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7-9 JUNE 1983(U) RANGE COMMANDERS COUNCIL WHITE SANDS
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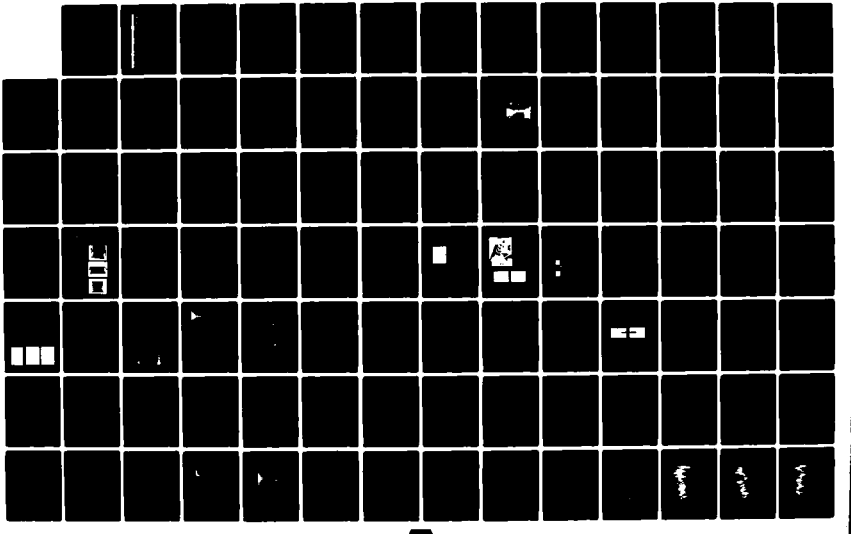

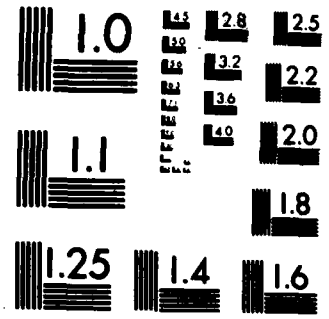

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TWELFTH TRANSDUCER WORKSHOP

7-9 JUNE 1983

MELBOURNE, FLORIDA

TELEMETRY GROUP

RANGE COMMANDERS COUNCIL

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KWAJALEIN MISSILE RANGE
YUMA PROVING GROUND

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(TITLE): Transducer Workshop (12th) Held at Melbourne, Florida on 7-9 June 1983.

(SOURCE): Range Commanders Council, White Sands Missile Range, NM. Telemetry Group.

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AD-P002 676	Test and Evaluation of Radioactively Contaminated Transducers and Transmitters.
AD-P002 677	Non-Self Generating Transducer Signal Conditioning Technique.
AD-P002 678	High Accuracy Temperature Measurement on a Diagnostic Canister for the Nevada Test Site.
AD-P002 679	New Application of Proximity Probe Measurement on Rolling Element Bearings.
AD-P002 680	Space Shuttle Main Engine Turbopump Transducer.
AD-P002 681	Utilization of Double Integration Methodology to Determine an Aircraft's Vertical Displacement.
AD-P002 682	An Angular Velocimeter for Aerospace Applications.
AD-P002 683	An Extended Range Pendulous Velocity Gage.
AD-P002 684	Weapon Chamber Pressure Measurement.
AD-P002 685	Soil Pore Gas Pressure Measurements at the Nevada Test Site.
AD-P002 686	Temperature Compensation and Shunt Calibration of Semiconductor Pressure Transducers.
AD-P002 687	Application of the Small Body Pressure Transducer.
AD-P002 688	Effect of Measurement System Phase Response on Shock Spectrum Computation.
AD-P002 689	Piezometer Probe Technology for Geotechnical Investigations in Coastal and Deep Ocean Environments.
AD-P002 690	Systems Approach to Measuring Short Duration Acceleration Transients.
AD-P002 691	Calibration of Vibration Pickups at High Frequencies.
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	6. PERFORMING ORG. REPORT NUMBER:
7. AUTHOR(s): Telemetry Group, Range Commanders Council, White Sands Missile Range, NM 88002	8. CONTRACT OR GRANT NUMBER(s):
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TWELFTH TRANSDUCER WORKSHOP

7-9 June 1983

MELBOURNE, FLORIDA

TRANSDUCER COMMITTEE
Telemetry Group
Range Commanders Council

Edited by

LeRoy Bates
and
Ken D. Cox

Published and Distributed by

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White Sands Missile Range,
New Mexico 88002

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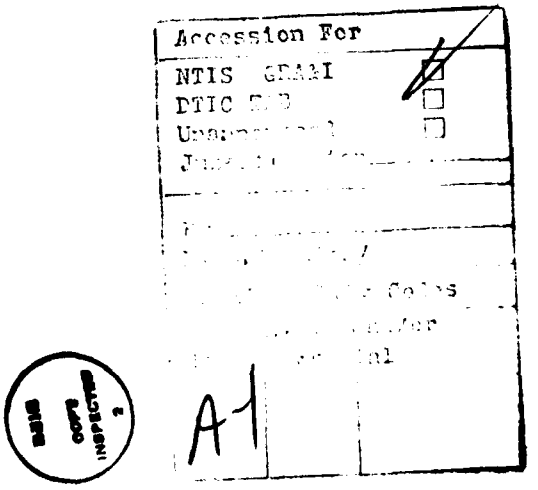

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WELCOMING ADDRESS

Colonel Thomas from Patrick Air Force Base gave the Welcome Address. Colonel Thomas substituted for Colonel Gardner who was attending an RCC meeting at Vandenberg Air Force Base in California.

Colonel Thomas is Director of Range Operations for Eastern Test Range. Following are some excerpts from his welcoming address:

"Patrick Air Force Base Eastern Test Range was established as a Long Range Proving Ground in 1949 by Congress. It is now part of the Eastern Space and Missile Center, which is responsible for all launch activities from Kennedy and Cape Canaveral, from a range safety point of view, providing metric data, etc. The DOD people launch payloads on the Tritan, occasionally on the Atlas and Delta, and now on the space shuttle.

Eastern Test Range is composed of instrumentation sites at Patrick Air Force Base; at Cape Canaveral, over on Kennedy Space Center; we have down range sites at the Grand Bahamas, Ascension Island, and Antiqua Island. When we are operating with the shuttle we link together with seven national ranges, including Kwajalein Missile Range, Edwards Air Force Base, and some of the Nasa facilities."

Colonel Thomas offered to assist on the arrangements for the tour at Kennedy Space Center.

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INTRODUCTION

The Twelfth Transducer Workshop was held in Melbourne, Florida, 7-9 June 1983. It was sponsored by the Vehicular Instrumentation/Transducer Committee of the Range Commanders Council (RCC), Telemetry Group (TG). The General Chairman was Ken D. Cox of the Naval Weapons Center (NWC), Code 6213, China Lake, California.

Workshop logistics were excecuted by a volunteer team as follows:

LeRoy Bates, Chairman, Vehicular Instrumentation/Transducer Committee and Treasurer, Naval Ship Weapons Systems Engineering Station, Port Hueneme, California.

William D. Anderson, responsible for paper call and selection, program assembly and program printing. Served as Vehicular Instrumentation/Transducer Committee Chairman until February 1983.

Colonel Thomas, substituting for Colonel Richard A. Gardner, USAF Deputy Commander for Eastern Test Range, Executive Committee Member (RCC), gave the welcoming address.

Richard Hasbrouck, responsible for accommodation arrangements, local brochure, and tour arrangements, Lawrence Livermore Labs, Livermore, California.

Homer E. Beckner, Jr., responsible for audio-visual and served as local contact, Patrick Air Force Base.

Ray J. Faulstich, responsible for session recorder and equipment, NATC, Patuxent River, Maryland.

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Steve Huehn, assembled Manufacturers Panel, Sandia National Laboratory (SNL).

Additional Committee Members: John Ach - AFWAL Wright Patterson

Dennis Henry - Physical Science Lab, New Mexico State University

Dick Krizan - AFFTC, Edwards Air Force Base, California

Larry Rollingson - Naval Weapons Center, China Lake, California

all who helped keep the program moving throughout the three-day workshop.

Jana McLeaughlin, Wright Patterson, Dayton, Ohio, who took shorthand notes and did the first rough draft of session discussions.

Session Chairmen: Fred Schelby - Sandia National Labs, Albuquerque, New Mexico

Norm Rector - Lawrence Livermore National Labs, Livermore, California

Bill Xavier - EG & G, San Ramon, California

Peter K. Stein - Stein Engineering Services, Inc., Phoenix, Arizona

Lawrence Mertaugh - Naval Air Test Center, Patuxent River, Maryland.

TELEMETRY GROUP FUNCTIONS AND GOALS

by
WILLIAM D. ANDERSON, CHAIRMAN

VEHICULAR INSTRUMENTATION/TRANSDUCER COMMITTEE, TG, RCC
NAVAL AIR TEST CENTER
PATUXENT RIVER, MARYLAND

The Range Commanders Council (RCC) is a group of 13 national ranges. The present members are White Sands Missile Range, Kwajalein Missile Range, Yuma Proving Ground, Pacific Missile Test Center, Naval Weapons Center, Atlantic Fleet Weapons Training Facility, Naval Air Test Center, Eastern Space and Missile Center, Armament Division, Western Space and Missile Center, Air Force Satellite Control Facility, Air Force Flight Test Center, and Air Force Tactical Fighter Weapons Center. The RCC was founded in August 1951. Its purpose and scope is to:

a. Develop operational test procedures and standards for present and future range use.

b. Discuss common range matters and resolve common problems in an organized forum.

c. Exchange information and control duplication.

d. Conduct joint investigations pertaining to research, development, procurement, and testing.

The Telemetry Group is a subgroup of the RCC and the Vehicular Instrumentation/Transducer Committee is one of the four committees of the Telemetry Group. The present members of the Vehicular Instrumentation/Transducer Committee, in addition to myself, are LeRoy Bates from the Naval Ship Weapon System Engineering Station, Port Heueme, California; Kenny Cox from the Naval Weapons Center, China Lake, California; Richard T. Hasbrouck from Lawrence Livermore National Laboratory, Livermore, California; and Charles E. Thomas from the Air Force Flight Dynamics Laboratory, Wright Patterson Air Force Base, Ohio.

As I indicated, one purpose of the RCC is to develop operational test procedures and standards for present and future range use. Two standards generated by the Telemetry Group which contain inputs from the Vehicular Instrumentation/Transducer Committee are RCC Document 106, Telemetry Standards, and RCC Document 118, Test Methods for Telemetry Systems and Subsystems. These documents are very useful and may be obtained from the RCC Secretariat. Government activities can obtain them free of charge by writing to the Secretariat, Range Commanders Council, White Sands Missile Range, New Mexico 88002. Non-government activities can obtain them from the Defense Technical Information Center, Cameron Station, Alexander, Virginia 22314.

The main efforts of the Vehicular Instrumentation/Transducer Committee, at present, involve supplying inputs to RCC Document 118. This document now has five volumes, Volume I, End-to-End Test Methods for Telemetry Systems, has one of our inputs titled "Test Methods for Transducer Based System Calibrations." It contains

calibration techniques to verify or calibrate the entire measurement system including the transducer signal conditioner, recording system and all interconnections.

The Vehicular Instrumentation/Transducer Committee is in charge of coordinating inputs for Volume V, Test Methods for Vehicle Telemetry Systems. This volume will be published this fall with chapters on "Telemetry Transducer Amplifier Test Procedures," "Thermal Transient Test Procedures for Pressure Transducers," "Vehicle Telemetry Power Supply Test Procedures," and "Vehicle Transmitter Test Procedures." Future upgrades will include chapters on "Vehicle Tape Recorder Test Procedures" and "Vehicle Multiplex System Test Procedures." The "Power Supply Test Procedures" will be published in pink sheet form in June or July and sent to Range members and industry for comments. The remaining chapters are rewrites of existing chapters from previous RCC 118 documents.

The Vehicular Instrumentation/Transducer Committee still has as one of its objectives fostering communications among transducer users and manufacturers. The Transducer Workshop is one method the committee uses to do that. Workshops have been sponsored by the Transducer Committee since 1960. This is the 12th Workshop. Another method that the Vehicular Instrumentation/Transducer Committee uses is the generation of a Directory of Transducer Users. This was first published after the 7th Transducer Workshop and new editions have been published after each workshop. This document lists personnel in each subscribing activity who are the primary contacts or users of transducers. We list contacts rather than all users at each activity to keep the document small. We plan to publish the 6th edition after this workshop. Anyone interested in having their activity included in the Directory should complete one of the Directory forms available in the present Directory or from any member of the Vehicular Instrumentation/Transducer Committee.

TELEMETRY GROUP COMMITTEES

Chairman, C. G. Ashley, PMTC
Vice Chairman, D. K. Manoa, WSMC

RF Systems
Data Multiplex
Recorders/Reproducers
Vehicle Instrumentation/Transducer

MEMBERS OF THE VEHICLE INSTRUMENTATION/TRANSDUCER COMMITTEE

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China Lake, CA 93555

TRANSDUCER COMMITTEE OBJECTIVES

This committee will inform the Telemetry Group (TG) of significant progress in the field of telemetry transducers; maintain any necessary liaison between the TG and the National Bureau of Standards and their transducers' program or any other related telemetry transducer efforts; coordinate TG activities with other professional technical groups; collect and pass on information on techniques of measurement, evaluation, reliability, calibration, reporting and manufacturing; and recommend uniform practices for calibration, testing and evaluation of telemetry transducers.

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TRANSDUCER WORKSHOP SUMMARY

Workshop Number	DATE	HOST	GENERAL CHAIRMAN	NUMBER ATTENDEES	RCC/TG TRANSDUCER CHAIRMAN
1	Mar 1960	Albuquerque New Mexico			
2	25-26 July 1961	Holloman AFB Alamogordo New Mexico	W. M. Sanders Holloman AFB New Mexico	46	Paul Polishuk Wright-Patterson Dayton, Ohio
3	21-23 June 1962	NBS Washington, DC	Arnold Wexler NBS Washington	106	Paul Polishuk Wright-Patterson
4	18-19 June 1964	Wright-Patterson Dayton, Ohio	Jack Lynch Patuxent River, MD	53	Jack Lynch NATC Patuxent River, MD
5	3-4 October 1967	NBS Gaithersburg, MD	Loyt L. Lathrop Sandia Lab Albuquerque, NM	106	Loyt L. Lathrop Sandia Lab Albuquerque, NM
6	22-24 October 1969	Langley Research Ctr. NASA Hampton, VA	Paul Lederer NBS Washington, DC	49	Loyt L. Lathrop Sandia Lab Albuquerque, NM
7	4-6 April 1972	Sandia Labs Albuquerque New Mexico	W. G. James AEFDL Wright-Patterson Dayton, Ohio	111	Pat Walter Sandia Labs First Manufacturers Panel Boo-Boos
8	22-24 April 1975	Wright-Patterson Dayton, Ohio	Pierre F. Fuselier Lawrence Livermore Labs Livermore, CA	74	Pat Walter Sandia Labs

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WORKSHOP NUMBER	DATE	HOST	GENERAL CHAIRMAN	NUMBER ATTENDEES	RCC/TG TRANSDUCER CHAIRMAN
9	26-28 April 1977	Fort Walton Beach Eglin AFB, FI	Kenny Cox NWC California	100	William Anderson Pax River, MD
10	12-14 June 1979	Colorado Springs Colorado North American Air Defense Company	Richard Hasbrouck Lawrence Livermore Labs Livermore, CA	106	William Anderson Pax River, MD
11	2-4 June 1981	Seattle, WA, Air Force Plant Representative Office, Det. 9	LeRoy Bates NSWSES Port Hueneme, CA	95	William Anderson Pax River, MD
12	7-9 June	Melbourne, Florida Patrick AFB	Kenneth D. Cox		William Anderson Pax River, MD

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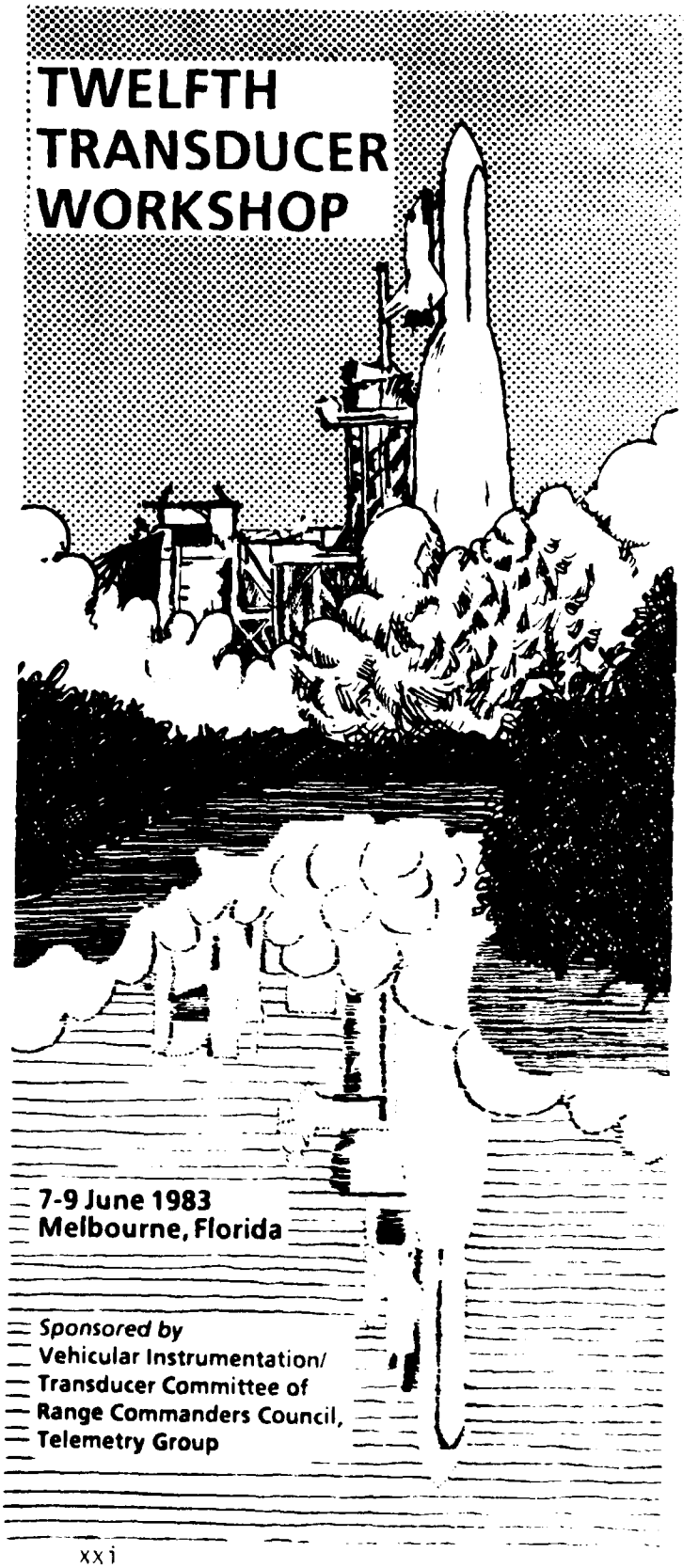

DEFINITION OF THE TRANSDUCER WORKSHOP

History:

The Workshop is sponsored by the Vehicular Instrumentation/Transducer Committee of the Range Commanders Council, Telemetry Group. The Eleven previous workshops, beginning in 1960, were held at 2 year intervals at, or near, various U. S. Government installations around the country.

Attendees:

Attendees are working-level people who must solve real life hardware problems and are strongly oriented to the practical approach. Their field is making measurements of physical parameters using transducers. Test and project people who attend will benefit from exposure to the true complexity of transducer evaluation and selection.

Subjects:

Practical problems involving transducers, signal conditioners, and readout devices will be considered separately and in systems. Engineering tests, laboratory calibrations, transducer developments and evaluations represent potential applications of the ideas presented. Measurands include force, pressure, flow, acceleration, velocity, displacement, temperature and others.

Emphasis:

1. A practical approach to the solution of measurement problems.
2. Strong focus on transducers and related instrumentation used in measurements engineering.
3. The ratio of discussion to presentation of papers is high.
4. Open discussion and problem solving through the sharing of knowledge and experience. Session chairman will present the speakers as a panel to stimulate discussions with and within the audience.

Goals:

To bring together those people who use transducers; to identify problems and hopefully suggest some solutions; to identify areas of common interest; and to provide a communication channel within the community of transducer users. Some examples are:

1. Improve the coordination of information regarding transducer standards, test techniques, evaluations, and application practices among the national test ranges, range users, range contractors, other transducer users, and transducer manufacturers.
2. Encourage the establishment of special sessions so that attendees with measurement problems in specific areas can form subgroups and remain to discuss these problems after the workshop concludes.
3. Solicit suggestions and comments on past, present and future Vehicular Instrumentation/ Transducer Committee efforts.

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PROGRAM

MONDAY, 6 JUNE 1983

2000 Social Hour, courtesy of the Vehicular Instrumentation/Transducer Committee
All attendees welcome.

TUESDAY, 7 JUNE 1983

0730 Registration

0800 Welcome: RICHARD A.GARDNER,Col USAF, Deputy Commander for Eastern Test Range. Executive Committee Member, RCC
Introductions: LEROY BATES, Chairman Vehicular Instrumentation/Transducer Committee, RCC/TG
KENNY COX, General Chairman Twelfth Transducer Workshop

0900 **Session 1: Transducer Systems**
Chairman: FRED SCHELBY, Sandia National Labs
Panel Members and Papers' Briefs (10-15 minutes each):

- **"Measurements on and with Non-Linear Systems - Problems and**

Approaches," PETER K. STEIN, Stein Engineering Services

- "Drift Prediction for a Roll-Stabilized Inertial Measurement System," VESTA I. BATEMAN, Sandia National Laboratories
- "Performance Evaluation of Sensors," PAUL S. LEDERER, Wilcoxon Research
- "Test and Evaluation of Radioactively Contaminated Transducers and Transmitters," R. C, STRAHM, EG&G Idaho, Inc,
- "Non Self Generating Transducer Signal Conditioning Techniques," RICHARD TALMADGE, Air Force Wright Aeronautical Laboratories

1015 BREAK

1030 Session 1 open discussion, with speakers sitting as a panel

1130 "Telemetry Group Function and Goals," LEROY BATES, Chairman, Vehicular Instrumentation/Transducer Committee

1200 LUNCH

1330 Session 2: Temperature, Displacement and Velocity
Chairman: SAM SPARTARO, Lawrence Livermore National Laboratory
Panel Members and Papers' Briefs (10-15 minutes each):

- "A High Accuracy Temperature Measurement on a Diagnostic Canister for the Nevada Test Site," DONALD GERIGH, Lawrence Livermore National Laboratory
- "A New Application of Proximity Probe Measurement on Rolling Element Bearings," TOM MCGAUVRAN, Bentley, Nevada
- "Space Shuttle Main Engine Turbopump Transducer," TOM J. PATTERSON, Rockwell/Rocketdyne
- "Utilization of Double Integration Methodology to Determine an Aircraft's Vertical Displacement," TERRY A. COLLOM, Naval Air Test Center
- "An Angular Velocimeter for Aerospace Applications," DR. P. W. WHALEY, University of Nebraska-Lincoln
- "An Extended Range Pendulous Velocity Gage," LAURENCE STARRH, Lawrence Livermore National Laboratory and ROGER NOYES, EG&G, Inc.

1500 BREAK

1515 Session 2 open discussion, with speakers sitting as a panel

WEDNESDAY, 8 JUNE 1983

0830 Session 3: Pressure
Chairman: BILL XAVIER, EG&G, INC.
Panel Members and Papers Briefs (10-15 minutes each)

- "Weapon Chamber Pressure Measurement," W. SCOTT WALTON, U.S. Army Aberdeen Proving Ground
- "Soil Pore Gas Pressure Measurements at the Nevada Test Site," LEE DAVIES, ROGER NOYES, JOHN KALINOWSKI and TED STUBBS, EG&G Inc.
- "Temperature Compensation and Shunt Calibration of Semiconductor Pressure Transducers," JOSEPH R. MALLON, JR., Kulite Semiconductor Products, Inc.
- "Applications of the Small Body Pressure Transducer," ROBERT E GEORGE, Ames Research Center
- "Precise Hydraulically Operated 100,000 Pound Force Transfer Standard," VERN E. BEAN and B E WELCH, National Bureau of Standards
- "Piezometer Probe Technology for Geotechnical Investigations in Coastal and Deep Ocean Environments," R. H. BENNETT and J. T. BURNS, Naval Ocean Research and Development Activity

1000 BREAK

1015 Session 3 open discussion, with speakers sitting as panel

1130 LUNCH

1300 Tour of Kennedy Space Center

1730 No-host social hour at hotel

1830 Banquet at hotel

2000 Session 4: Manufacturers' Panel
Chairman: PETER K. STEIN, Stein Engineering Services, Inc.

Panel Members:
WILCOXON RESEARCH - PAUL LEDERER
KISTLER-MORSE CORP.-WALTER KISTLER
VALADYNE ENGR. CORP. - MAX KOPP
RdF CORPORATION - FRANK HINES
GOULD, INC. - TOM PERRIN
PCB PIEZOTRONICS - ROBERT LALLY
BRUEL AND KJAER - JORGEN JENSON
SENSOTEC, INC. - JOHN EASTON

THURSDAY, 9 JUNE 1983

0830 **Session 5: Vibration and Shock**
Chairman: LAWRENCE MERTAUGH, Naval Air Test Center
Panel Members and Papers' Briefs (10-15 minutes each)

- **"A Systems Approach to Measuring Short Duration Acceleration Transients,"** FRED SCHELBY, Sandia National Labs.
- **"Calibration of Vibration Pickups at High Frequencies,"** B. F. PAYNE, National Bureau of Standards
- **"Shock Isolated Accelerometer,"** MARK GROETHE and ED DAY, S-Cubed
- **"Testing Techniques Involved in the Development of High Shock Acceleration Sensors,"** BOB SILL, Endevco Corporation
- **"Aircraft Ground Vibration Test Instrumentation System,"** DAVID BANASZAK and RICHARD TALMADGE, Air Force Wright Aeronautical Laboratories

1000 **BREAK**

1015 Session 5 open discussion, with speakers sitting as a panel

1130 **LUNCH**

1300 **Session 6: Informal Wrap-Up**
Chairman: LEROY BATES, Naval Surface Weapon System Engineering Station
This session is provided to encourage small group discussions between transducer users and vendors with regard to instrumentation problems and future needs.

1410 **BREAK**

1420 Closing Remarks - Vehicular Instrumentation/Transducer Committee

1500 **WORKSHOP CONCLUDES**

GENERAL INFORMATION

This Twelfth Transducer Workshop will be held 7-9 June 1983, at the Holiday Inn, Melbourne, Oceanfront, Florida. The hosting agency is Patrick Air Force Base.

Registration

The registration consists of two parts: a written "Murphyism" of one page or less, and a fee of $40.00.

A "Murphyism" can describe any measurement attempt that went astray, with the objective of learning from our errors and keeping our feet on the ground. It should be something generic, rather than common human oversight; something from which we can learn. The tone should be relaxed, with a sense of humor. The "Murphyism" should be anonymous and must not embarrass any person, organization, or company.

Advance registration is desirable. Please use the enclosed registration form, include a check or money order for $40.00 payable to the Twelfth Transducer Workshop, and mail to the Workshop by 15 May 1983. (Note: Purchase orders are not acceptable.)

The registration fee covers: coffee, tea, soft drinks and doughnuts; the Wednesday evening fixed-menu dinner at the Holiday Inn; and a copy of the minutes of the workshop. Late registration will be provided for at the Workshop registration desk in the hotel.

Hotel Accomodations

The official hotel for the Workshop is the Holiday Inn, Melbourne Oceanfront, P.O. Box 3775, 2600 A-1-A, Indialantic, Florida 32903. (305) 777-4100. A block of rooms has been reserved at the special rates indicated on the enclosed registration card. Hotel registrations must be received by 1 May 1983.

No formal program will be provided for wives or guests. However, they will be most welcome at the Social Hour on Monday and the dinner on Wednesday ($20.00 additional per guest for the dinner). Note: Final count for the banquet must be known by 11 am, 7 June.

Tour-Wednesday Afternoon

A tour of the Kennedy Space Center is planned for Wednesday, June 8, 1983. Since the tour size is limited to a maximum of 80 persons

(ages 13 and over welcome), participation will be on a "first registered, first accommodated basis" Transportation will be provided.

Format and Background

The traditional discussion format will be observed. Workshops are just what the name says: everyone should come prepared to contribute something from his knowledge and experience. In a workshop the attendees become the program in the sense that the extent and enthusiasm of their participation determines the success of the workshop.

Participants will have the opportunity to hear what their colleagues have been doing and how it went; to explore areas of common interest and common problems; to offer ideas and suggestions about what's needed in transducers, techniques, and applications. A few manufacturers, selected to represent a fair sampling of transduction methods and measurands, have been invited to the Twelfth Transducer Workshop. Give some thought (and write it down!) to the questions, comments, and topics you want to present to them, and make a copy and leave it at the registration desk on Tuesday morning.

TWELTH TRANSDUCER WORKSHOP
7-9 June 1983 - Cocoa Beach, Florida
REGISTRATION FORM

NAME: _____

ORGANIZATION: _____

STREET/MAIL CODE: _____

CITY, STATE/ZIP CODE: _____

TELEPHONE/EXT.: _____

I wish to take the Kennedy Space Center Tour: Self. _____ Number of Guests _____
I will have guests for the Banquet: No. Guests _____ (Do not include yourself.)

Please make checks and money orders in the amount of $40.00 payable to: Twelfth Transducer Workshop.
Please mail workshop registration fee, and "Murphyism" with this form by 15 May 1983 to:

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NOTES ON THE SESSIONS

The traditional format of the Transducer Workshop was observed. Each paper presentation was limited to 10-15 minutes and all papers in each session were given sequentially. Authors then sat as a panel to lead the discussions and to answer questions and receive comments on their work. Participation in the discussions was extensive and productive.

The discussion summary appearing at the end of each session was taken from notes and tape recordings in an effort to capture the interactive spirit of the workshop. Transcription for rough draft was done at Wright Patterson Air Force Base by Jana McLeaughlin; completed transcription was done by Linda King, Doris A. Cox, and Lynn Sword, all of the Naval Weapons Center, China Lake, California. Editing was done by Kenny D. Cox of the Naval Weapons Center and LeRoy Bates of NSWSES.

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CHANGES IN AGENDA

Welcome: Col. Thomas gave the welcome in place of Col. Gardner.

SESSION ONE: Went as planned.

SESSION TWO: Chairman, Norm Rector replaced Sam Spartaro in presenting Tom J. Peterson's paper.

SESSION THREE: Papers authored by Patrick L. Walter, Sandia National Laboratory, Albuquerque, New Mexico replaced papers authored by Vern E. Bean of National Bureau of Standards.

SESSION FOUR: Bill Russell replaced Max Kopp for Validyne Engineering Corporation. Tom Perrin for Gould, Inc., did not attend. Lee Myers replaced John Easton for Sensotec, Inc.

SESSION FIVE: Went as planned.

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SESSION I

TRANSDUCER SYSTEMS

Fred Schelby, Chairman

AD P002673

Measurements on and With Non-Linear Systems: Problems and Approaches

Peter K. Stein
Stein Engineering Services, Inc.
Phoenix, Arizona, U.S.A.

ABSTRACT

Whenever the relationship between two quantities is anything other than a straight line, time variations of one quantity at one set of frequencies will result in time variations of the other quantity at a different set of frequencies. NON-LINEAR SYSTEMS ARE FREQUENCY-CREATIVE. This is an inherent property of non-linear systems, and can, in fact, be used as a check on system linearity. This property of non-linear systems may be desired when new frequencies are to be created, such as in frequency multiplication, division or in modulators of all kinds. This property is undesired and can create havoc in those measuring systems in which any of the following criteria are to be met:

a. Frequency-content reproduction or spectral-content reproduction, for subsequent analysis as signatures, thumbprints, patterns, etc.;

b. Wave-shape reproduction with subsequent analysis of patterns,

c. Peak-to-peak reproduction of wave shapes, as in calibration signals with square waves of injected voltage or injected resistance changes (shunt calibration).

d. Integration of signals, and

e. Differentiation of signals. Some of the consequences of the frequency-creative ability of non-linear systems on the design of measuring systems will be developed in this paper and supported by examples taken from the author's experience and from the literature.

MEASUREMENTS ON AND WITH NON-LINEAR SYSTEMS: PROBLEMS AND APPROACHES

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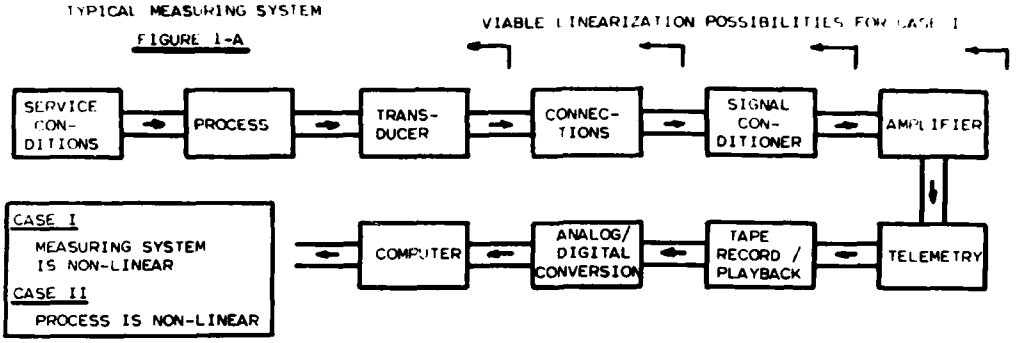
FIGURE 1

TYPICAL EXAMPLE OF A MEASUREMENT PROCESS WITH NON-LINEARITIES SOMEWHERE

TYPICAL MEASURING SYSTEM

FIGURE 1-A



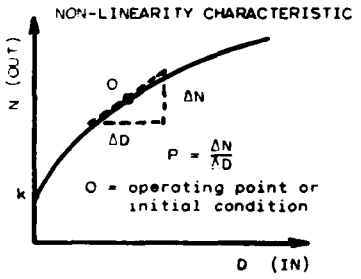


FIGURE 1-B

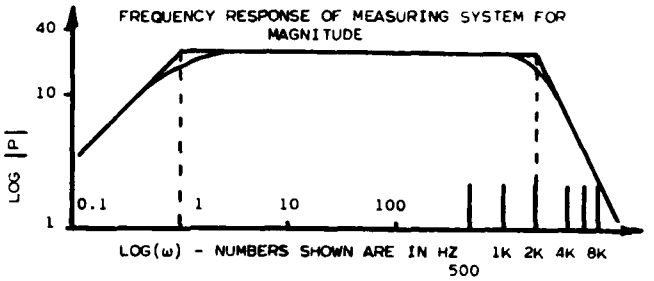


FIGURE 1-C

invoking the trigonometric equivalences for $Sin^2\omega t$, $Sin^3\omega t$, $Sin^4\omega t$ available from any trigonometry handbook.

The appearance of frequencies lower than the forcing frequency ω, such as DC (zero frequency) and doubly underlined, and of multiples or harmonics 2ω, 3ω and 4ω (singly underlined) in the expression for N represents the "creation" of frequencies which were not present in the original forcing function D. Note that the cubic nonlearity term, c, even creates an in-phase component at the same frequency as D with amplitude $(3/4).c.Sin\omega t$. The significance of these facts will be elucidated in the various sections below.

Dynamic Excitation - Slightly More Complex:

If the forcing function, D, is anything more complicated than $Sin\omega t$, the results are even more spectacular:

Let $D = Sin\omega_1 t + Sin\omega_2 t$ (4)

Then

$$N = k + a.Sin\omega_1 t + a.Sin\omega_2 t + \frac{1}{2}(b)(1-Cos2\omega_1 t) + \frac{1}{2}(b)(1-Cos2\omega_2 t) + b.Cos(\omega_1-\omega_2)t - b.Cos(\omega_1+\omega_2)t + \ldots(5)$$

with sum $(\omega_1+\omega_2)$, and difference $(\omega_1-\omega_2)$ frequencies appearing, which in turn will have harmonics if equation (5) were carried out further. It should be emphasized that these sum and difference frequencies present in N and not in D, are not harmonically related to those frequencies present in D.

The simple examples above, based on a power series approximation, do not provide for the possibility of sub-harmonics (*) or non-harmonically related frequencies below the forcing function frequency, although all these possibilities exist in real hardware. Several examples will be cited in this paper.

It should also be noted that the appearance of Cosine terms as a result of sinusoidal excitation is evidence of a phase shift.

(*) A function as simple as $N = \sqrt{1+D}$ would, for values of D less than 1, be capable of generating sub-harmonics.

MEASUREMENTS ON AND WITH NON-LINEAR SYSTEMS: PROBLEMS AND APPROACHES

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INTRODUCTION

Whenever the relationship between two quantities is anything other than a straight line, time variations of one quantity at one set of frequencies will result in time variations of the other quantity at a different set of frequencies. NON-LINEAR SYSTEMS ARE FREQUENCY-CREATIVE. This is an inherent property of non-linear systems, and can, in fact, be used as a check on system linearity. This property of non-linear systems may be desired when new frequencies are to be created, such as in frequency multiplication, division or in modulators of all kinds. This property is undesired and can create havoc in those measuring systems in which any of the following criteria are to be met:

a. frequency-content reproduction or spectral-content reproduction, for subsequent analysis as signatures, thumbprints, patterns, etc.;

b. wave-shape reproduction with subsequent analysis of patterns;

c. peak-to-peak reproduction of wave shapes, as in calibration signals with square waves of injected voltage or injected resistance changes (shunt calibration);

d. integration of signals

e. differentiation of signals

Some of the consequences of the frequency-creative ability of non-linear systems on the design of measuring systems will be developed in this paper and supported by examples taken from the author's experience and from the literature.

THE BASIC PROPOSITION

Suppose a non-linear relationship exists between two variables N and D as shown in Fig. 1-B. These quantities could be any variables encountered in engineering. In particular, however, there are numerous quantities which are expressed as ratios of two variables between which a non-linear relationship might exist:

$$P = \Delta N/\Delta D$$

determined at some operating point or at some initial condition, O. Such ratios P include:

a. almost all material properties

b. all transducer performance parameters such as impedance levels, transfer functions, etc.

c. all Latent Information Parameters as defined in the Unified Approach to the Engineering of Measuring Systems (STEIN, 1972A, 1973).

The problems discussed in this paper are, therefore, applicable to all such parameters or properties when subjected to dynamic conditions.

It is always possible, over a range of variables, to let the expression $N = f(D)$ be approximated by some function such as a simple algebraic power series, selected here only as an example:

$$N = k + a.D + b.D^2 + c.D^3 + d.D^4 \quad (1)$$

where k is a constant and a, b, c, d are numerical coefficients dependent on the nature of the relationship between N and D. It is quite possible, for example, to determine these coefficients as part of a calibration procedure on a computer-controlled test set-up and to present numerical values for these coefficients as part of the calibration data. This procedure is followed in the Transducer Laboratory at Lawrence Livermore National Laboratory in Livermore, California, USA.

For high-temperature platinum resistance thermometers a quadratic interpolation equation, and for standard (Pt-10%Rh) vs. Pt thermocouples, a 5th degree polynomial interpolation equation are sufficient (EVANS, 1977).

Dynamic Excitations - Simple Case:

For purposes of this paper, dynamic excitations shall include STEADY STATE or PERIODIC phenomena and TRANSIENT or APERIODIC phenomena, i.e., time-dependent. The simplest dynamic steady state phenomenon is a unit sine wave. Let the variable, D, undergo single-frequency unit-amplitude time-wise variations:

$$D = \mathrm{Sin}\omega t \quad (2)$$

then

$$N = k + a.\mathrm{Sin}\omega t + \frac{1}{2}(b)(\underline{1}-\mathrm{Cos}\underline{2}\omega t) + \frac{1}{4}(c)(3\mathrm{Sin}\omega t-\mathrm{Sin}\underline{3}\omega t) + \frac{1}{8}(d)(\underline{3}-4\mathrm{Cos}\underline{2}\omega t+\mathrm{Cos}\underline{4}\omega t) \quad (3)$$

Preliminary Conclusions:

In non-linear systems, or systems with non-linear components, the responses may contain:

- multiples or harmonics of frequencies or wave lengths contained in the forcing function;
- sub-multiples or sub-harmonics of frequencies or wave lengths contained in the forcing function;
- non-multiples or non-sub-multiples, apparently unrelated to any frequency contained in the forcing function, such as the excitation of modes of vibration in mechanical systems;
- sums and differences of frequencies or wave lengths contained in the forcing function, and these may have harmonics and sub-harmonics.

Any data analysis process which relies on the reproduction of frequencies, or wave lengths as in optical systems, will base its conclusions on erroneous data if the frequency content of N (which is perhaps the system output) is taken as representative of the frequency contant of D (which is perhaps the system input). Data analysis processes which demand:

- frequency/spectral content reproduction
- wave shape reproduction
- integration or differentiation
- peak-to-peak reproduction

are absolutely dependent on the linearity of the measuring system with which the data are acquired, or must rely on corrections. It will be seen that these are sometimes just not possible.

Note that, although the average over one period of the forcing function is zero, the average of Equ. (3) over one period of the forcing function is $k + (1/2)b + (3/8)d$, and that the average of Equ. (5) is also non-zero. Thus even the average of a distorted signal is a distorted average. This topic will arise again when flowmeters and filters are discussed.

APPLICATION

Figure 1-A illustrates a typical measuring system attached to a process excited by some service conditions, forcing function, inputs, stimuli, or whatever terminology is preferred. Two cases must be distinguished:

Case I: The measuring system is non-linear and creates frequencies at its output which were not present at the output of the process -- the input of the measuring system.

Case II: The process is non-linear, and creates frequencies at its output - the input of the measuring system - which were not present in its service conditions or excitation.

Case I: Non-Linear Measuring System

The output of whichever component in the system is non-linear will contain "created" frequencies of the nature shown in Equs. (3) and (5), which may well be harmonics which lie outside the passband of the measuring system, or DC levels which may be completely suppressed in an RC-coupled (AC-coupled) system. Thus if there were a 500 Hz component in the process output for the example shown in Fig. 1-C, the created harmonics would be progressively attenuated and phase shifted; any DC components would be totally suppressed. The computer, therefore, cannot receive the information it needs in order to correct the data according to the master equation, such as (3) or (5). Unless the computer is informed of the total system frequency response for magnitude and phase, it CANNOT correct the data; and what should it do about components which never reach it such as the postulated DC "created" signals which were totally suppressed !

For most real measuring systems, detailed enough knowledge of the frequency response for magnitude and phase is not always available, especially if magnetic tape recorders or telemetry components are part of the system. The problem is really even more complicated since the frequency response curves of non-linear systems depend on excitation amplitude (see later section).

Any linearizing which is done, should be done before the telemetry or the tape recorder, as shown in Fig. 1-A. Commonly used linearization schemes exist which operate in any of the four components identified: the transducer, the connection, the signal conditioner, or the amplifier, and will be discussed.

The Frequency Response of Non-Linear Systems"

In correcting dynamic data acquired with non-linear systems, the problems of the frequency response of non-linear systems will appear.

There are many possibilities for non-linearity behavior. Two of the major ones are shown in Fig. 2: hardening and softening behavior. The frequency-response curves for such systems present hooked characteristics with jump pheno-

tend as the vertical-slope region of the curve is reached for either increasing or decreasing frequency. This is one of the reasons why in rotating machinery there are often sudden jumps in vibration amplitude, either from lower to higher or vice versa. WIRT (1962-A) shows examples for small gas turbine.

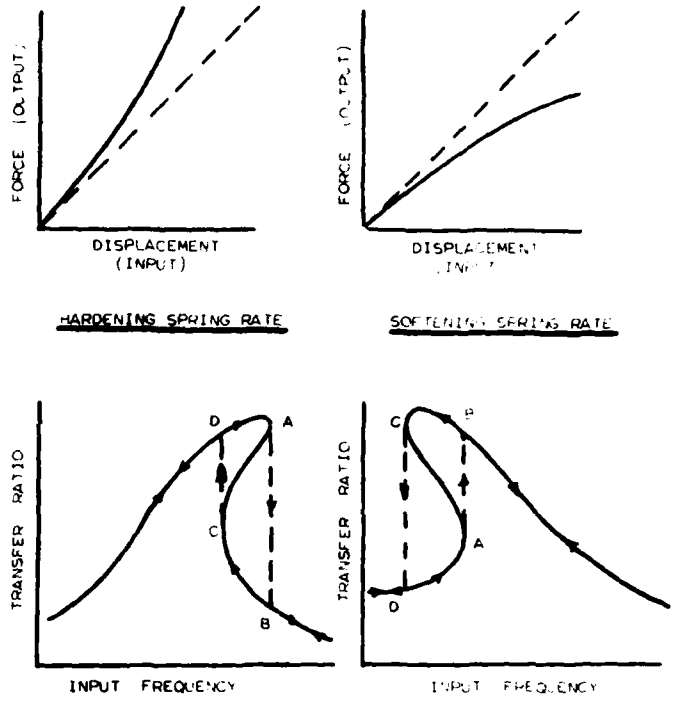
There are four variables for non-linear system frequency response:

- input amplitude
- output amplitude or transfer ratio (out/in)
- input frequency
- output frequencies since non-linear systems create frequencies.

Fig. 3 shows several possibilities of slicing this 4-dimensional space with 3-dimensional displays from WHETSEL (1968) who tested a cantilever beam vibrating against shaped supports to turn it into a hardening spring.

As will be seen in later sections, the correction of dynamic data acquired with non-linear systems presents almost insurmountable problems.

FIGURE 2 MAJOR TYPES OF NON-LINEARITIES



The frequency response curves for non-linear systems are hooked and exhibit "jump" phenomena. For increasing frequencies, there will be sudden jump from A to B with a corresponding sudden decrease or increase in response amplitude. For decreasing frequencies there will be a jump from C to D.

Linearizing Possibilities

It is well known that non-linear systems can be linearized and that the problems identified above might be circumvented if the difficulties identified in Fig. 1-C are also circumvented. To illustrate the possibilities of linearization in the four portions of the measuring system identified in Fig. 1-A, just a few examples will be cited here from the field of thermometry.

Linear Sensor: It is possible to obtain linear resistance thermometers so that linearization is not necessary if the rest of the system is linear, from manufacturers such as SWEMA (*), MOTOROLA, MIDWEST COMPONENTS, ANALOG DEVICES among others.

(*) The specific products referenced and manufacturers' addresses are given in the bibliography in a separate part.

Linearized Sensor: Many resistance thermometers are, however, non-linear such as Platinum, Nickel or Balco. Fig. 4 illustrates Nickel and Balco from (ANON 1976). It might be possible to linearize the sensor by fabricating it in portions from different temperature sensitive alloys for which the non-linearities will cancel, as in the "CLTS" Cryogenic Linear Temperature Sensor, invented by John Telinde of McDonnell-Douglas and made under license by the MEASUREMENTS GROUP. Its principle is illustrated in Fig. 5 and the sensor is made up of different portions of Manganin and Nickel to achieve linearization. The sensor is meant for cryogenic applications since above 200°F (93°C) the heat treatment history of the Manganin is changes and the linearization scheme is compromised. Heat treatment history change means change in resistance-temperature coefficient (STEIN, 1972-C).

SEVERAL THREE-DIMENSIONAL DISPLAYS OF FOUR-DIMENSIONAL SPACE

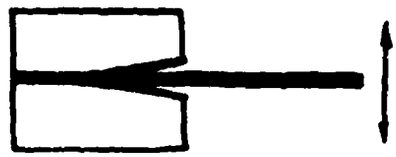
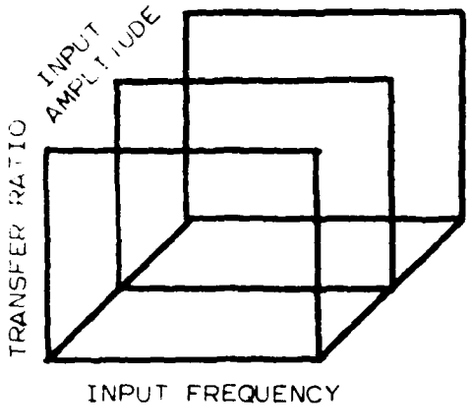
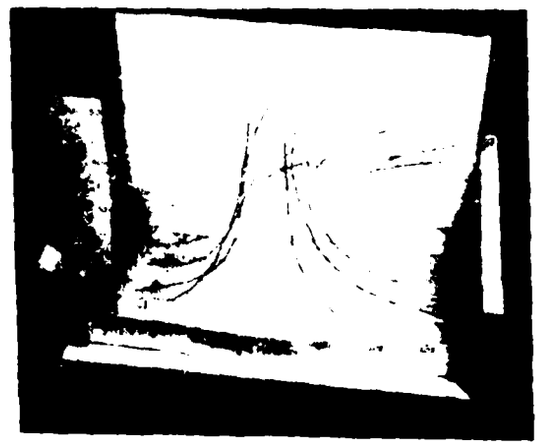


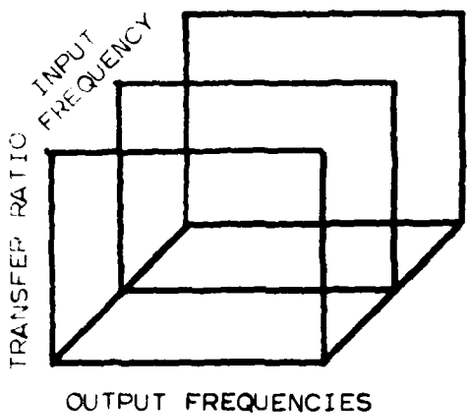
FIGURE 3

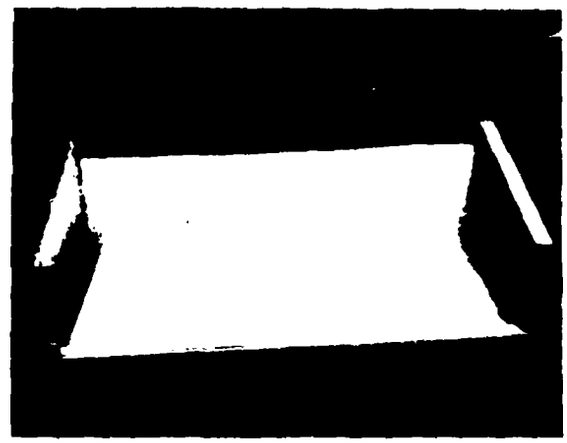
A Cantilever beam vibrating against a shaped support is a non-linear system for which there are at least 4 parameters:

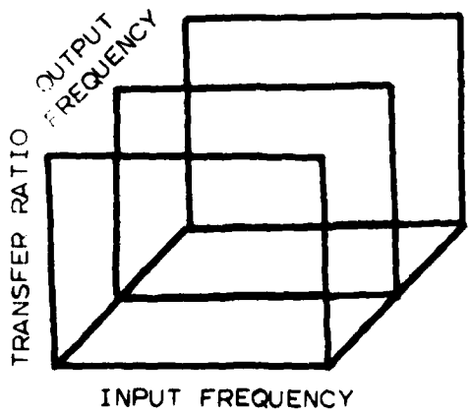
- INPUT AMPLITUDE
- OUTPUT AMPLITUDE or TRANSFER RATIO
- INPUT FREQUENCY
- OUTPUT FREQUENCIES

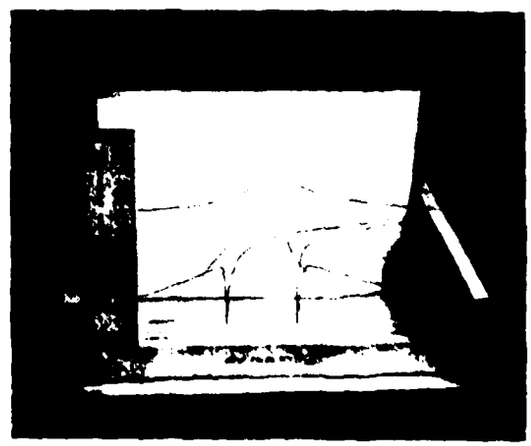








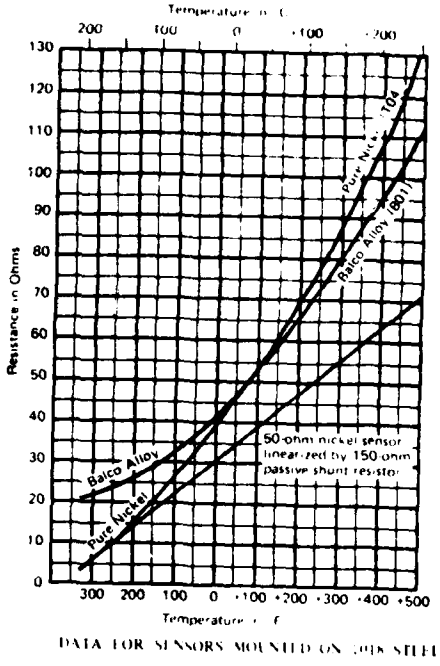




Linearizing in the Connections: It is possible to linearize a Nickel temperature sensor by placing across it a parallel resistance, temperature insensitive, and of a value about 3 times that of the sensor (ANON, 1976) with results as illustrated in Fig. 4. Commercial linearizing and matching networks for that purpose and for purposes of adapting resistance thermometers to standard millivolt/volt signal conditioning are available from many sources including the MEASUREMENTS GROUP. It should be noted that different lot numbers of nickel have different resistance-temperature characteristics and may require different matching networks.

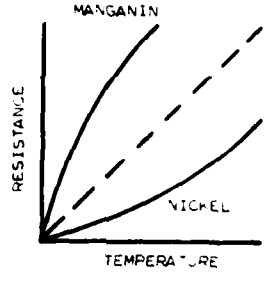
Linearizing in the Signal Conditioning: Wheatstone bridges (Fig. 6) with single "active" arms (i.e., one sensor) are highly non-linear in their relationship between resistance change in the sensor and bridge output, e. Their non-linearity can be adjusted by varying the ratio of the resistance in the arms across the power supply: R_2/R_1 (STEIN, 1961-B, 1963). Thus a nickel resistance thermometer in arm R_1 with a resistance about 3 times its value in R_2 will produce a bridge non-linearity almost completely off-setting the non-linearity of the thermometer (ANON, 1976). It is also possible to linearize a Wheatstone Bridge with a single "active" arm, R_1, by controlling the supply voltage, V, to the bridge in such a manner that the current through the sensor, R_1, remains constant. Under constant-current conditions in the sensor, the bridge will be linear (STEIN, 1961-B). The MEASUREMENTS GROUP Model 2300 Signal Conditioner can achieve this arrangement by means of remote sensing the voltage across R_2. ZHUQIAN (1981) actually adds twice the bridge output back to the supply voltage to achieve the same effect.

Linearizing in the Amplifier: Linearizing amplifiers are very common in thermocouple applications and in many other measuring systems. It should be emphasized that the problems discussed in connection with Fig. 1-C must always be kept in mind and that they become increasingly more important the further away from the initial transducer the linearization is accomplished.



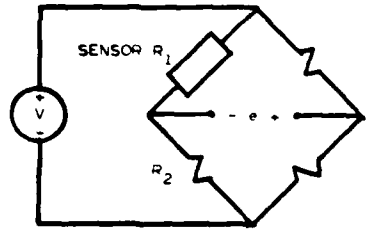
DATA FOR SENSORS MOUNTED ON 304K STEEL

FIGURE 4: RESISTANCE-TEMPERATURE CHARACTERISTICS



PRINCIPLE OF THE CRYOGENIC LINEAR TEMPERATURE SENSOR.

FIGURE 5



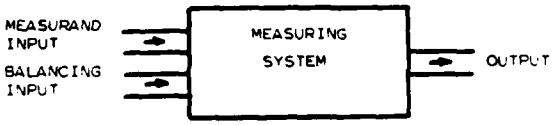
WHEATSTONE BRIDGE FIGURE 6

System Linearity:

In a discussion of system linearity, the ports between which the linear behavior is desired and/or achieved, must be carefully specified, since every measuring system will be linear between some ports and highly non-linear between others. Thus, for example referring to Fig. 7, a null-balance system will be highly linear between the (Unknown) Measurand-Input and the Balance Controls, but between either of thoseand the null detector at the Output, the characteristics will be, and should be, highly non-linear. Similarly in a well-designed unbalance system, the relationship between the Measurand Input and the Output will be linear, but the relationship between the Balance Control and either of the other ports will be highly non-linear. For a discussion of this topic and the development of a new generalized concept from which the criteria for unbalance and null-balance systems can be derived see STEIN (1971B).

FIGURE 7

PORTS ON A GENERALIZED MEASURING SYSTEM



Case II: Non-Linear Process:

If the process is non-linear, then the frequencies which enter the measuring system are not necessarily related to the frequencies in the input to the process. If knowledge of the forcing function is desired, then an interpretation of the process output (its response) is fraught with the same dangers discussed above for non-linear measuring systems. Any data-shaping processes such as tracking filters, may be quite ill-advised unless carefully thought out, for two reasons:

a. The major, damage-producing responses of the process to its service conditions may not be at the frequency of those service conditions. This is especially true of sinusoidal vibration tests on "shake" tables, and of rotating machinery where responses will exist at many frequencies other than the excitation frequency or the rotational speed.

b. The tracking filter would also acquire the frequency "created" by the cubic term in the non-linearity: $(3/4).c.\sin\omega t$ from Equ. (3), which is of the same frequency as the forcing function and in phase with it !

The author is well aware that in many rotating machinery applications tracking filters are used very often in strain and vibration measurements from his four-year experience in that industry. Given the situation described above, however, it is necessary for the measuring system designer to organize the system in such a way that these non-linear effects, suppressed by the tracking filter, are not totally lost, fostering a false sense of security. Thus, tracking filter combs, not always tracking multiples of engine speed, may be necessary.

Examples which follow will illustrate very simply some of the situations described above.

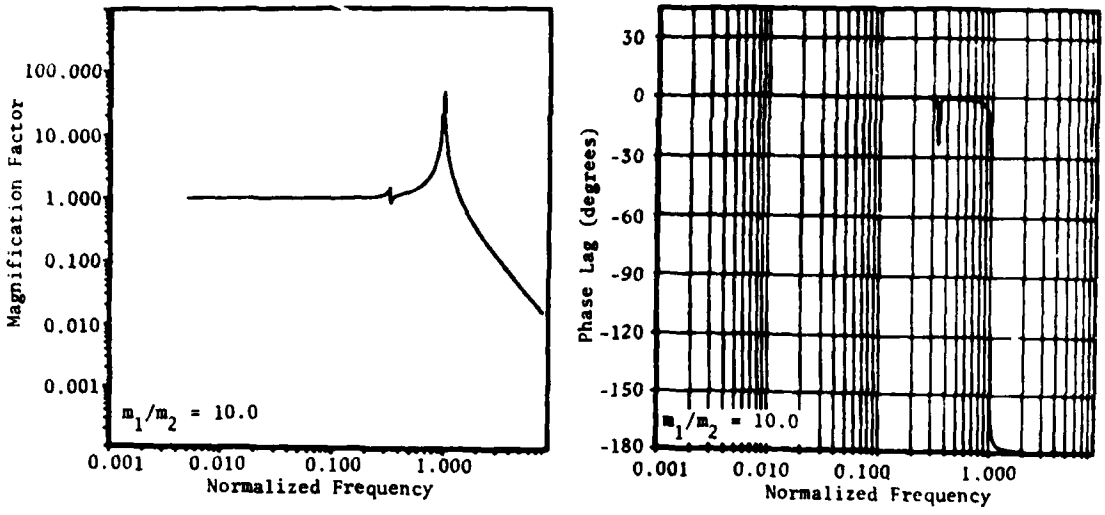
Tracking Filters: In view of the foregoing discussion, it would appear that the appropriate place for a tracking filter is at the INPUT to a sinusoidal vibration exciter (in the case of a mechanical system), i.e., at the excitation to the process in Fig. 1-A. This will avoid the problem exhibited in Fig. 7.5 from WALTER (1978B). There the wave shape driving the vibration exciter during an accelerometer calibration contained a small amount of third harmonic distortion. When that tiny amount of third harmonic lay on the accelerometer high-"Q" resonance, it found a huge dynamic magnifier, and gave a spurious indication of a resonance. That spurious indication appeared in the data at one-third of the true accelerometer resonance, since that is the frequency at which the fundamental of the excitation was located when the 3rd harmonic was at the accelerometer resonance. The phase-shift curve shows a similar spurious indication.

Joints as Contributors to Non-Linearity, Hysteresis and Creep: Mechanical joints of any type, including:

Rivets
Spot welds
Bolts - Screws - Nails

especially gasketed joints, but even welded joints, are contributors to non-linearity in the relationship between input forces and resulting displacements, velocities, accelerations, or strains,

FIGURE 7.5: TWO DEGREE OF FREEDOM SYSTEM AMPLITUDE RESPONSE FOR INPUT SINE WAVE CONTAMINATED WITH A SMALL AMOUNT OF THIRD HARMONIC



whether in tension/compression or bending. Is there a real mechanical structure without joints of the type listed above ? Even in static measurements, the assumption that strains should return to zero when the forces on a structure are removed, is unwarranted. The slipping, sliding and local distortions which are inevitable in any joint may be responsible for residual, frictionally-induced forces remaining distributed in the joint and causing non-return to zero strain.

The concept of loads equally shared by a group of rivets/bolts/screws is a fond hope of democracy among these components, of which they are blissfully unaware. Thus, incidentally, checking a strain gage installation integrity by whether or not it returns to its original reading after loads are removed, may not be a fair check at all.

Examples 1 and 2 illustrate problems in dynamic measurements in structures with joints. Some data for static tests on rivet patterns are given by SMITH (1962) in Fig. 8, and a fascinating study by HOOKER et al. (1974) discusses mounting methods for cantilever-beam-based transducers.

It is axiomatic that good transducer design involves the absence of joints in the mechanical-flexure portion of the transducer. Everything is machined out of one solid piece as much as possible. HOOKER (1974) discusses a

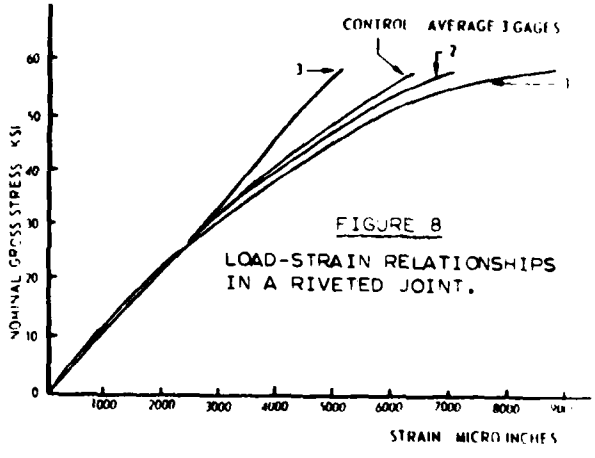
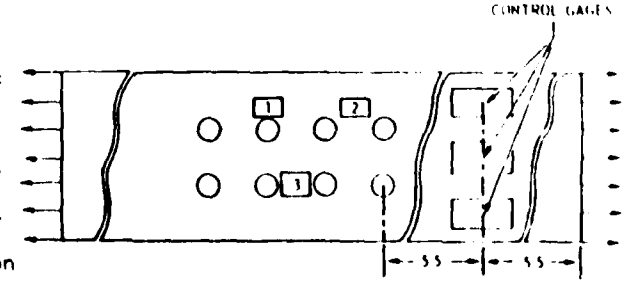


FIGURE 8
LOAD-STRAIN RELATIONSHIPS IN A RIVETED JOINT.



BASIC ELEMENT OF A BOREHOLE DEFORMATION GAGE (HOOKER et al. 1974)

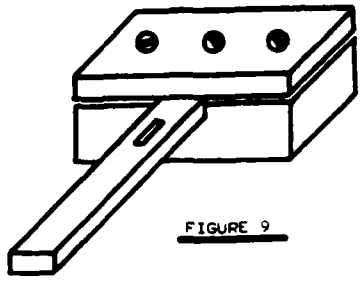


FIGURE 9

Creep performance with the mount as shown was very bad and depended on the tightening torque of the screw passing through the strain-gaged beam. Without the central screw performance was much improved. A beam made integral with the mount showed a creep performance 90% less than even that.

cantilever-beam-based bore-hole deformation gage which measures the change in diameter of c borehole in rock mechanics studies and is made of several pairs of the kind of beam shown in Fig. 9. The original mounting configuration is shown in the figure, and exhibited very large creep, which was extremely sensitive to the tightening torque of the central mounting screw which passed through the beam. When that mounting screw was removed, and only two screws were used to hold the beam, the performance dramatically improved. "This led to the machining of the transducer and gage body from a solid piece of metal . . . Creep was reduced by an average of 90% over that of the gage with the clamp-block-mounted transducer." (HOOKER et al., 1974, p.3) Creep, hysteresis and non-linearity in a transducer are interrelated quantities and the presence of one indicates the presence of all, especially if there are joints in the mechanical hardware.

Transducer mounts such as used for accelerometers, are also joints, and may cause problems. WALTER (1978A, 1978B) illustrates the same acelerometer being calibrated with different attachment methods, with the results shown in Fig. 10. The mount may not only affect the frequency response characteristics of the transducer, but may dominate it, such as with its own resonances (ANON, 1975).

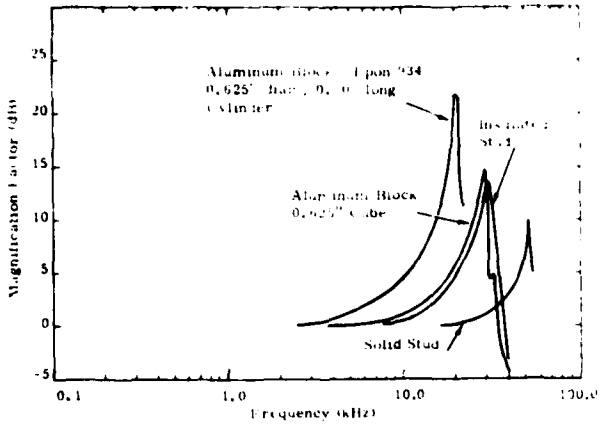


FIGURE 10: EFFECTS OF MOUNTING METHOD ON ACCELEROMETER FREQUENCY RESPONSE

When accelerometers are to be used at temperature extremes for measuring low-frequency, low-level accelerations in the presence of high-frequency, high-amplitude vibrations, certain special effects must be considered. The internal pre-load on any compression-stacked quartz crystals in the accelerometer (or other piezoelectric elements) becomes a function of the differential thermal expansion between the quartz and the metallic pre-load fixture. Non-linearities may be caused by excessive or insufficient pre-load. The same is true of the mounting fixture for the accelerometer and the pre-load it exerts on the mounted accelerometer. Furthermore, any dimensional change of metallic portions due to phase changes at those temperatures must be considered. In addition, the spring constant of the mount must remain constant or else non-linearities are introduced because of the mounting method itself. These problems are discussed and illustrated by WASHBURN (1969) for cryogenic applications.

Strain-distribution studies through riveted, bolted, spot-welded or seam-welded structures are most efficiently carried out with the photoelastic coating technique. Typical of the work done in this area are studies by ZANDMAN (1960) and ZANDMAN et al (1962).

Any instrumented structure with joints, whether test specimen or transducer, should be suspected of non-linearity, hysteresis and creep, and dynamic data treated accordingly.

ILLUSTRATIVE EXAMPLES

Ten case studies will be briefly discussed: five for non-linear PROCESSES and five for non-linear MEASURING SYSTEMS. They are selected to show a broad range of often-unsuspected problems associated with the engineering of measuring systems, which the designer must face in order to obtain data that can, in fact, be interpreted.

Non-Linear Processes: Case Studies

Example 1: Magnetic and Mechanical Non-Linear Systems: Harmonics and a Sub-Harmonic.

As part of a student experiment in noise documentation and suppression (magnetic fields interfering with mechanical strain measurement)(STEIN 1971A), it was discovered that not only harmonics, but also a sub-harmonic could be generated in a stable, predictable and controllable manner. The specimen is shown in Fig. 11 -- a CENCO Model 85102 String Vibrator to which strain gages are attached, two on top and two on the bottom, one pair regular single-grid strain gages and one pair of non-inductive, bifilar wound gages as shown. The electro-magnet with a DC magnet inside it is excited at line frequency (50 or 60 Hz) but produces magnetic forces at all harmonics except the 6th, up to the 10th harmonic of line frequency (600 Hz in the US)(MUZZY, 1965; ROBERTS, 1969).

The non-linearity of the magnetic excitation is hereby documented: one frequency in, more than one frequency out. The lower photo shows the response of the single-grid gages acting here as magnetic-field sensors, without any voltage applied to the bridge (no current through the gages), and for which the frequency content is shown and interpreted as the frequency content of the driving magnetic forces. It is precisely this self-generating electromagnetically induced voltage which is the noise level on the dynamic strain measurement. The mechanical strains exist at all the frequencies at which there is a dynamic, magnetically-induced force applied to the beam (i.e. harmonics from 60 to 600 Hz except 360 Hz), as well as at all the eigenvalues, resonances or modes of vibration, of which the first five are excited by the periodic impact of the beam on the felt pad which covers the electromagnet.

The problem of noise suppression therefore involves signals and noise in overlapping frequency ranges, correlated to each other through the magnetic excitation, and with signals being much smaller than the noise, (See STEIN, 1975, 1971A, 1979 for solutions).

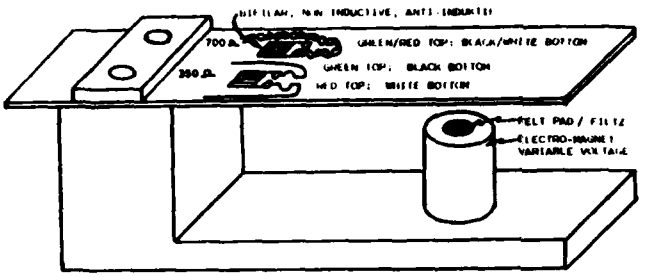
When the electromagnet is excited at slightly less than line voltage, there is a clear sub-harmonic generated, which is not in the magnetic field, but is present in the mechanical response as seen in the top photo, Fig. 11. PUST (1971) shows that a system of non-linear characteristics similar to the beam, with an operating point as shown in the figure, is capable of generating sub-harmonics. The adjustment of the exact operating point is achieved by changing the driving voltage on the electromagnet.

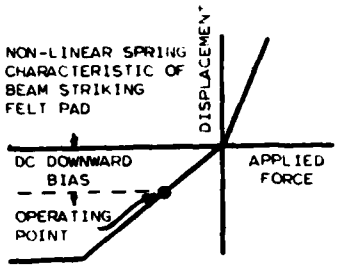
It is postulated that the non-symmetrical clamp providing a longer moment arm for upward deflections than for downward deflections, coupled with a dramatic change in the force-deflection curve when the beam hits the felt pad, provides the requires non-linearity characteristic (shown in straight-line-approximation in Fig. 11) for sub-harmonic generation as illustrated by PUST (1971).
The bottom trace on the photo provides both information on the frequency content of the magnetic field excitation, and also a time scale, since it is a 60 Hz repetition rate. The top photo is obtained from the non-inductive strain gages, for which the output at zero bridge supply is almost zero, as shown on the photo; i.e., any magnetically induced self-generating voltages are cancelled within the gage grid. Note the net downward bias of the beam towards the magnet as shown on the top photo with its zero-signal trace. It is the negative operating point which is controlled by adjusting the driving voltage on the electromagnet.

Example 2: Generation of Harmonics Near Rivet Holes.

As part of a Master's Thesis on vibrations of rotating bladed structures, BOLLETER (1968) discovered that near the riveted mounting brace of the Sears, Roebuck fan blades being investigated, there appeared to be frequency-doubling and tripling. This phenomenon was subsequently investigated by BUNN (1968) in a Senior Project which won the ASME National Student Papers Competition First Prize that year.

Fig. 12 illustrates the system. The excitation was a closed-loop, self-excited arrangement in which the output from one of the several strain gages





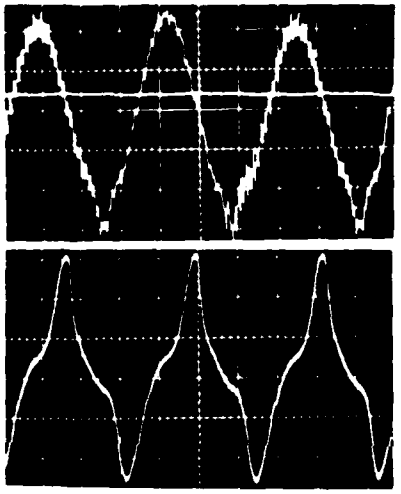
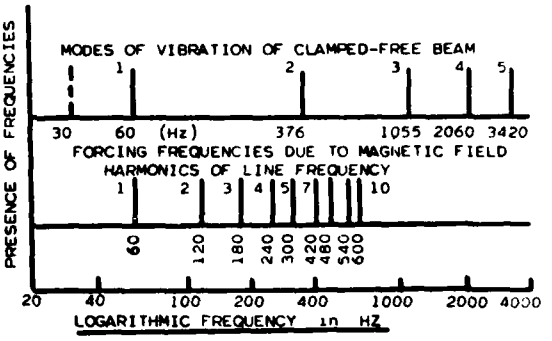


FIGURE 11



mounted on the fan blade was used to feed the small electromagnetic vibration exciter which was attached to the stationary fan blade shown spring mounted in a supporting structure. Fig. 12 shows the 3 mounting springs, the vibration exciter and the blade with the strain gages. Traces on the photos show, from top to bottom:

The responding strain gage output
The out from the strain gage being used to provide the forcing function
The input to the vibration exciter.

Frequency doubling and tripling are clearly evident -- in fact, it would appear that the fatigue-damage-creating strains are at triple the forcing frequency ! A tracking filter at the measuring system output, tuned to forcing function or engine speed would completely mask that life-sapping phenomenon ! Various mechanisms to account for such harmonic generation are shown in the figure. Vibrations were initiated by simply striking the blade with a fingernail. The positive feedback, self-regenerating system quickly built this "unit impulse" input up into steady-state vibrations.

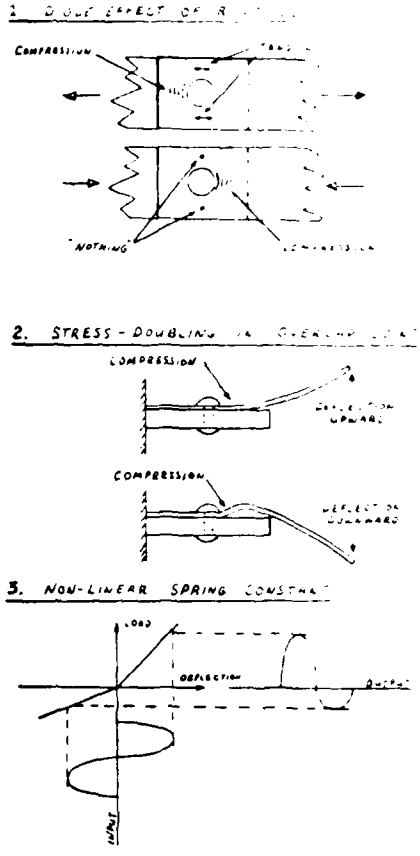
Example 3: Sub-Harmonic Generation in a Gas Turbine.

One of the more spectacular and unusual cases of sub-harmonic-caused problems was on a model of small gas turbine which had been reduced in size from a very successful and popular larger unit. The larger unit had never experienced serious problems, and it was a surprise, therefore, when the scaled down version exhibited occasional units which "growled". The diagnostic vibration pattern of a "growler" was a dominant frequency component in the third-octave-band associated with 320 Hz center frequency. The linearized theoretical design staff was not willing to recognize that

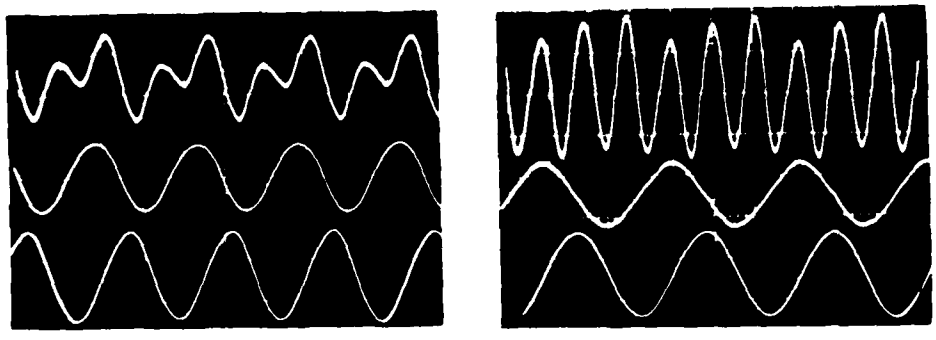
FIGURE 12: HARMONIC GENERATION IN A BLADED, NON-ROTATING STRUCTURE

INSTRUMENTED FAN BLADE

POSSIBLE NON-LINEARITY MECHANISMS



FREQUENCY MULTIPLICATION

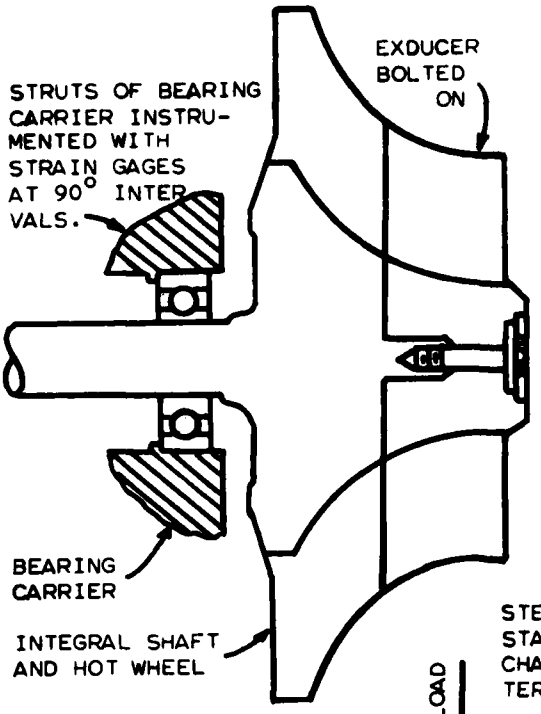


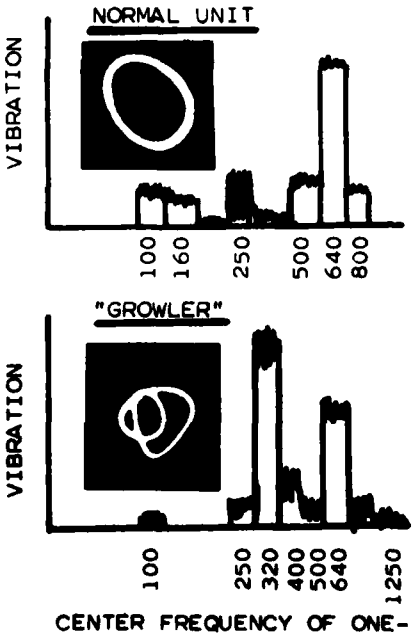
TRACE AND IDENTITY		FREQUENCY DOUBLING	FREQUENCY TRIPLING
TOP:	RESPONSE GAGE	Gage 5 10 με/cm 5 mv/cm	Gage 3 10 με/cm 5 mv/cm
MIDDLE:	FORCING GAGE	Gage 3 64 με/cm 10 mv/cm	Gage 1 12.8 με/cm 2 mv/cm
BOTTOM:	VIBRATION EXCITER INPUT VOLTAGE	2 v/cm. No specific phase relationship with upper two traces may be deduced since it is a second exposure.	
HORIZONTAL AXIS: TIME		5 msec/cm. All channels coupled DC, single-ended, all photos on this page.	

FORCING FUNCTIONS AND RESPONSES OF GAGES NEAR RIVETED JOINTS

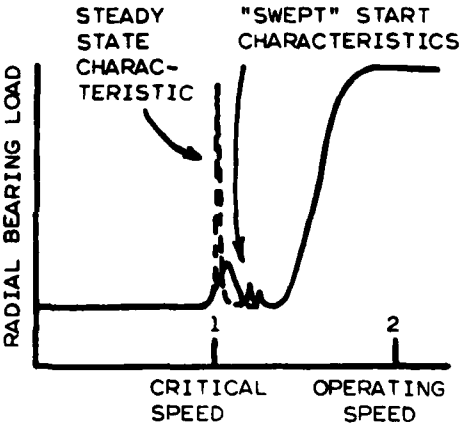
FIGURE 13

SUB-HARMONIC GENERATION IN A GAS TURBINE





ABOVE: VIBRATION SPECTRUM AND STRAIN GAGE X-Y PLOTS FOR NORMAL UNITS AND "GROWLERS"



ABOVE: RADIAL BEARING LOAD AS FUNCTION OF ENGINE SPEED AS INDICATED BY THE STRAIN GAGES.

NOTE: The "swept" start avoids the steady-state resonance but since critical speed is exactly half of operating speed, a sub-harmonic finds a ready-made mechanical amplifier of very high "Q" or dynamic magnifier. The bearings are the non-linear component.

dominant "growl" frequency as one-half of shaft speed, for which the 3rd-octave center frequency was 640 Hz. The only fix which worked often enough to be practical was a disassembly of those "growlers", a scrambling of the parts among several turbines, and a rebuild. When the Instrumentation Engineering group was finally commissioned to investigate the problem, it was decided to mount strain gages at 90 degree intervals on the bearing carrier struts and to follow the radial loads experienced by the bearing from the rotating assembly by means of a Lassajous figure of a cross-plot from 90-degree-apart located strain gages on the carrier.

Fig. 13 shows the radial load Lissajous pattern as seen on normal units, together with their frequency pattern, and on the "growlers" with their frequency patterns, and documented beyond any doubt the presence of a sub-harmonic vibration, not possible in linear systems. Since both strain gage channels were also played through hi-fi stereo sound equipment as well as being visually monitored on a CRO and recorded on magnetic tape, the ear immediately diagnosed half of shaft speed by comparing the outputs from the two loudspeakers. For acoustic, aural monitoring of data, sometimes for immediate solution to the engineering problem, see WIRT (1962C).

The unusual part of this common phenomenon was that the operating turbine speed was exactly twice the critical speed of the rotating assembly, so that this sub-harmonic, once generated, found itself a very highly resonant mechanical amplifier, and thus dominated the vibration spectrum. That steady-state resonance had been avoided by sweeping through it rapidly on start-up (See Figure 13), and was now steady-state excited ! Among the choices of economically reducing these vibrations, the following were discarded:

a. change the operating speed of the turbine - not possible
b. change the critical speed of the rotating group - expensive
c. change the non-linear spring responsible for sub-harmonic generation, i.e., the bearing - not economical.
d. add damping at critical speed - not economical.

WIRT (1962A) who had interpreted the works of Toshio Yamamoto as they applied to this problem, suggested that the balancing procedure used for the rotating group be changed. Practice was a combined balance of the assembled exducer and turbine-wheel-shaft, thus providing the possibility of separate unbalances at operating speed and temperature, especially since these parts did not touch along their periphery. Theywould provide a driving-force unbalance larger than expected. A change to SEPARATE balancing of each of the components before assembly - exducer and turbine-wheel-shaft, solved the problem at essentially zero cost. For additional deta ls about the instrumentation used, see STEIN (1961A, 1964).

Example 4: The Impedance of Non-Linear Systems

WIRT (1977) investigated the acoustic impedance of certain materials to be used in an environment of very high level and essentially-random sound pressure. He found that when using single-frequency sinusoidal excitation to measure the frequency response of these impedances, there was a very serious effect on the value of the impedance depending on whether or not the operating random signal was superimposed on the sinusoidal excitation.

He found that high-amplitude, random excitations to a non-linear component appear to bias its entire impedance characteristics into a totally different performance range. Only when he applied the high-level, random excitation during the impedance measurement, using small-signal, single-frequency excitation essentially as a "tracer" signal for impedance measurement purposes, did he succeed in matching the measured impedance of the material with the actual performance in service. The response of the material to that tracer has to be carefully and very-narrow-band filtered, tracking the excitation "tracer" frequency. The procedure is akin to determining the properties of a system at the in-service operating conditions, with small-signal-deviations from that operating point. Normally we visualize this as being done for amplitudes. Wirt shows that this is also true of frequency spectra.

Fig. 14 shows his preliminary evaluation on standing wave patterns observed in the presence and absence of broad-band bias sound pressures, and Fig. 15 the dramatic change in the impedance plot for one of the many acoustic materials which he evaluated, and for several of which he holds design patents. The standing wave apparatus developed for that purpose, and the process itself are both patented (WIRT 1974 , 1976). The proce-

FIGURE 14: STANDING WAVE PATTERNS OBSERVED IN THE PRESENCE AN. ABSENCE OF BROADBAND BIAS NOISE

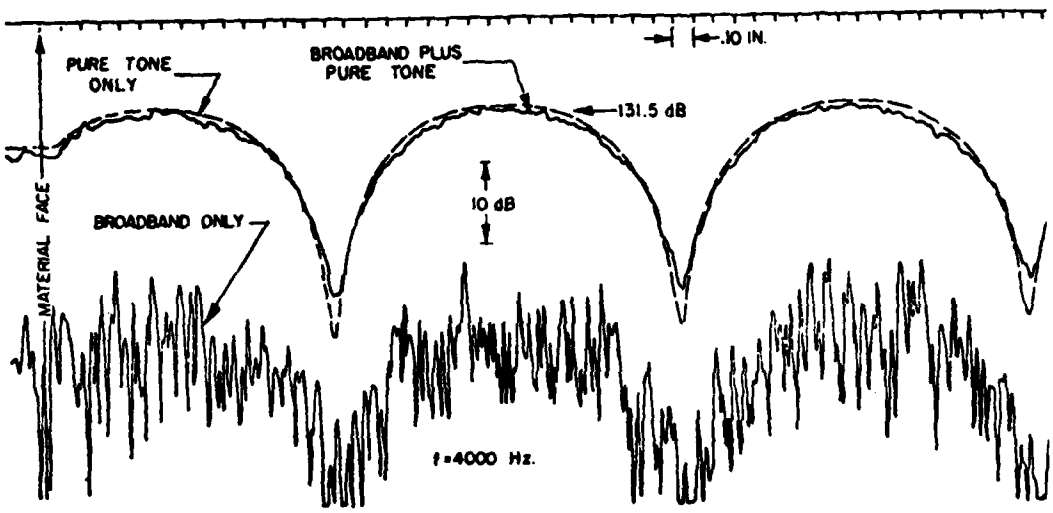
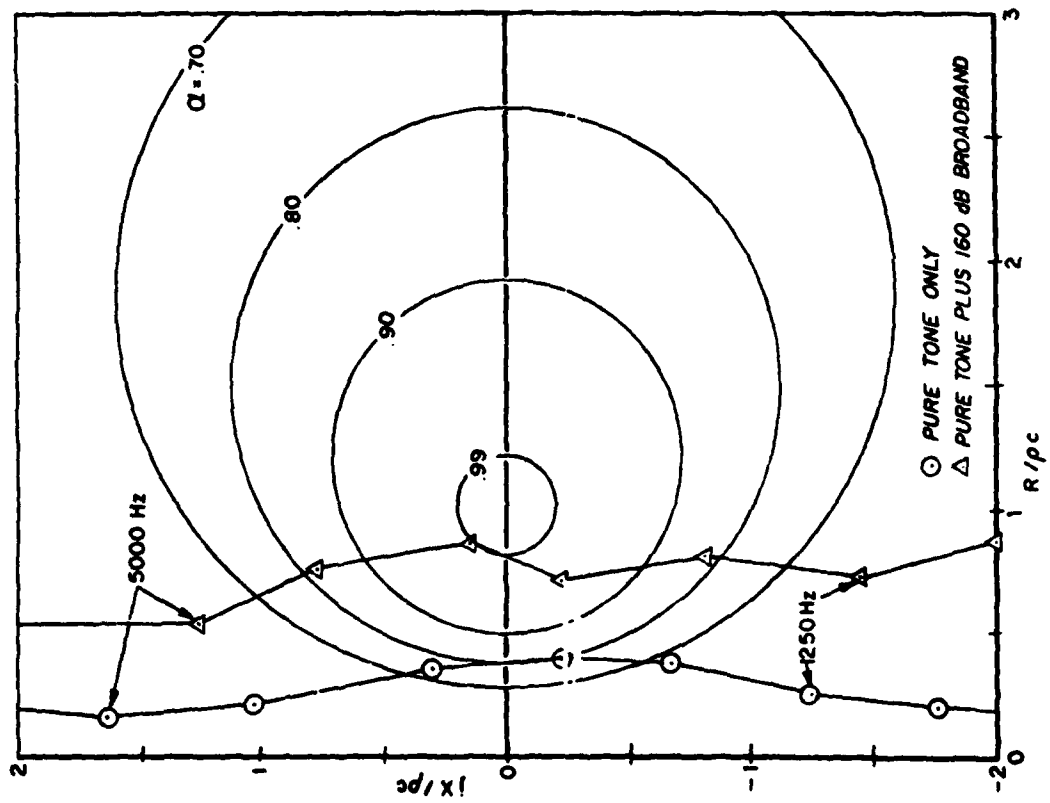


FIGURE 15: THE IMPEDANCE OF A TEN PERCENT OPEN AREA PERFORATE OVER A ONE-INCH AIR SPACE IN THE PRESENCE AND ABSENCE OF A 160 dB BIAS NOISE



dure applies to all impedance measurements in all disciplines, and also for transfer functions as Examples 7 and 8 will show in electrical systems.

Example 5: Modulation Processes in Gear Trains.

In gear trains, the frequency spectrum of the vibration usually contains frequencies not related by any simple harmonic manner to tooth counts, blade counts, rotation speeds, or torsional excitations. WIRT (1962B) showed that, in fact, many of the phenomena to which gears are subjected, tend to modulate the basic tooth-mesh-frequency assumed in traditional analyses to be the main driving mechanism for vibrations. It is even possible for tooth-mesh-frequency to have totally disappeared into the side-bands through the modulation process. The modulation process results in sum and difference frequencies between the component phenomena, which may in turn have harmonics and sub-harmonics, until a very complicated frequency spectrum results.

Modulation is a non-linear multiplication process in which two originally sinusoidal frequencies at the input, such as ω_1 and ω_2, emerge at the output in terms of $n(\omega_1 \pm \omega_2)$ where n is usually an integer multiple, but may also be a fraction if other non-linear components such as bearings complicate the problem. See also WIRT (1962A) in his explanation of the works of Toshio Yamamoto as they pertain to rotating machinery vibrations.

Wirt's then newly developed theory of how gear vibrations are caused, permitted the following logical path towards diagnosing the cause of gear train problems:

1. Postulate a variety of mechanisms which may be present in the gear train, such as:

a. error in pitch diameter contact, which may be symmetrical or unsymmetrical about zero error, or which may be always of the same sign (i.e., the pitch diameters may always intersect or never touch).

b. that there are torsional inputs on one of the shafts.

2. From these postulates, and knowing the configuration of the gear train, compute the side bands possible due to the assumed modulation processes for all the gears involved. This generates a spectrum of frequencies for which each is diagnostic of a specific "disease" in the gear train.

3. Acquire vibration or sound pressure data on the gear train.

4. Frequency analyse the data with a very, very narrow-band analyzer.

5. Compare the predicted possible frequencies with those actually present.

6. Work back through the postulates to determine which of the assumed mechanisms is present in that gear train and must therefore be responsible for the vibration -- i.e. diagnose the "disease".

For the gear train shown in Fig. 16 and the observed frequency spectra at various load levels on the gear train, Wirt was able to identify the cause responsible for the particular vibratory phenomenon which had made some serial numbers of that gear train unacceptable.

Note that until recently, conventional wisdom had the cause of gear vibrations identified as the tooth mesh frequency, but that this 4000 Hz tooth-mesh frequency for the 40-tooth gear turning at 100 rotations/second is conspicuous only by its absence in this case! The real information is all in the side-bands. Wirt puts the case that the demodulation of the vibration, treating it as a 4000 Hz carrier system, and the subsequent frequency analysis of that demodulated signal, is the way to solve gear vibration problems. He successfully did so. A recent publication on this topic is by RANDALL (1982) which summarizes past work and puts it into the modern Cepstrum Analysis context.

The irony that the older assumption of tooth-mesh-frequency as the main driving force could, in fact, be experimentally verified, was treated by STEIN (1979) where he showed that the selection of a filter not narrow-band enough (Fig. 16), would indeed verify a false theory. The 6% bandwidth filter shown in Fig. 16 would indeed give a reading when set at 4000 Hz, not because there is a frequency component there (there isn't), but because the closely-spaced side-bands which ARE there, would be gathered by the too-wide filter skirts to create a reading. Gear vibration is still a deterministic process, but requires extremely narrow-band filtering to separate often closely-spaced side-bands, as can be seen in Fig. 16.

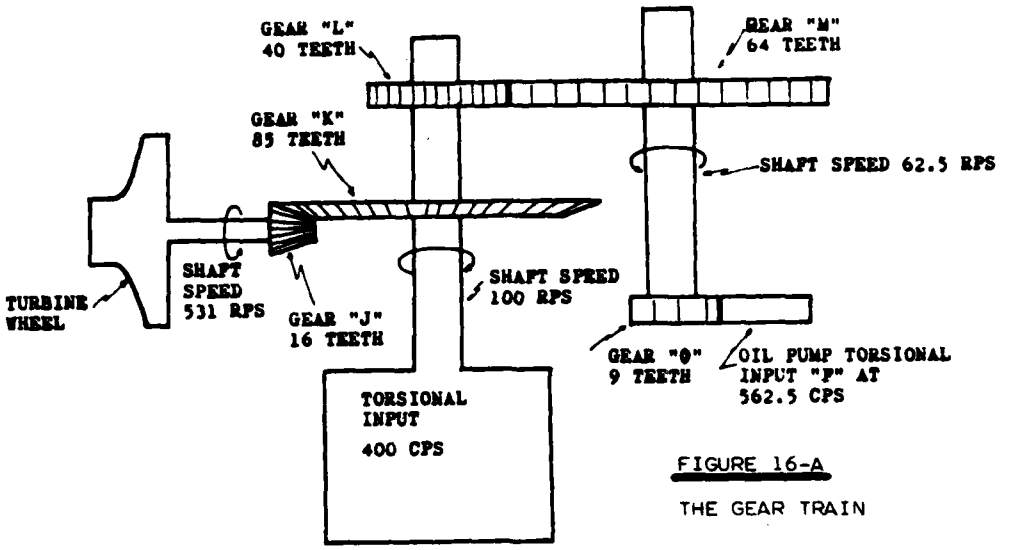


FIGURE 16-A

THE GEAR TRAIN

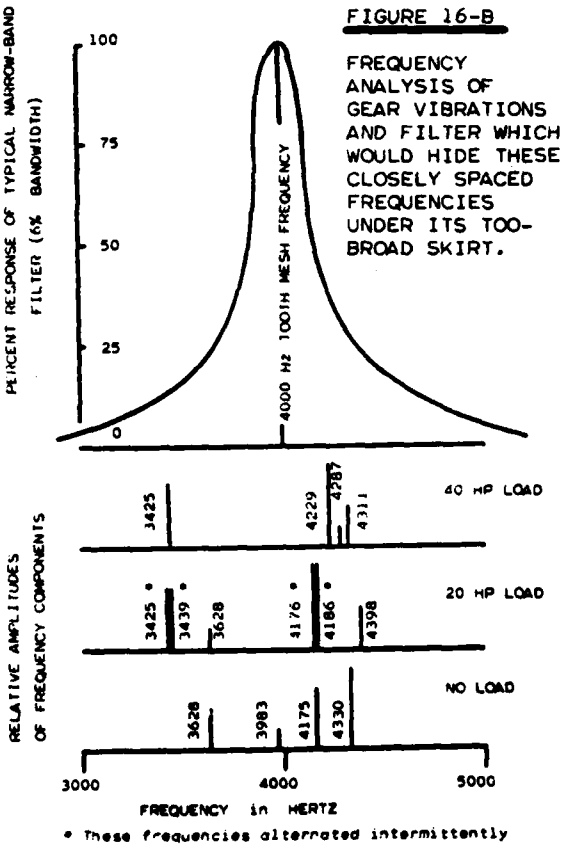


FIGURE 16-B

FREQUENCY ANALYSIS OF GEAR VIBRATIONS AND FILTER WHICH WOULD HIDE THESE CLOSELY SPACED FREQUENCIES UNDER ITS TOO-BROAD SKIRT.

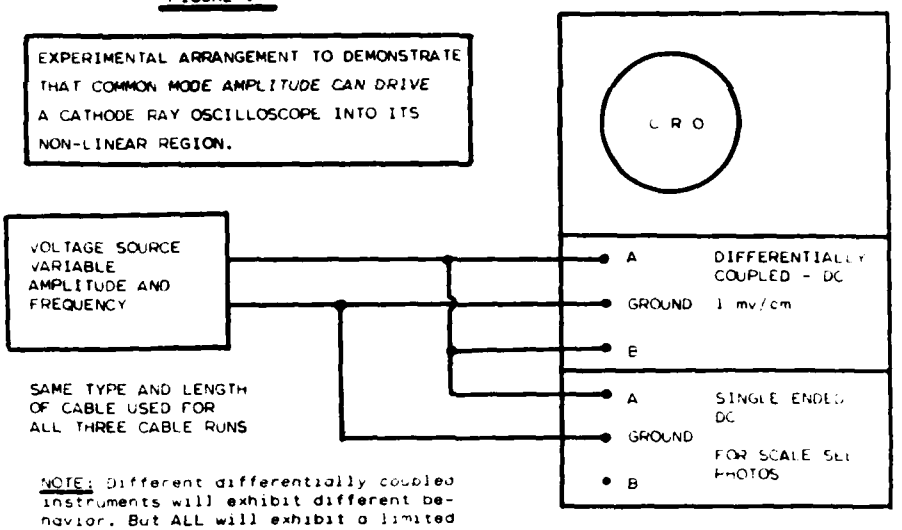
Non-Linear Measuring Systems: Case Studies

Example 6: Harmonic Generation in Differentially Coupled Systems.

The function of every differentially coupled system, from thermocouples with their "hot" and "cold" junctions, through differential pressure, force, torque, moment, optical birefringence, vibration, and voltage measuring systems is to measure the difference between two quantities independent of their average value - the common mode. Although the common mode is supposed to be rejected in the measuring system, its value may drive the differentially coupled component non-linear. The mechanism was investigated by BOYD (1963) and is explained by STEIN (1972B). It can be illustrated on every oscilloscope by means of the simple test set-up shown in Figure 17. For a Tektronix 502 CRO the demonstration is particularly spectacular since its common mode limit is only 2 volts, not even enough for direct use with a strain-gage-based Wheatstone bridge fed from a 6-volt supply, for which the common mode would be 3 volts when differentially coupled to the CRO. It should be noted that the phenomenon holds for ALL differentially coupled systems, and is especially dangerous for differential pressure measurements (WALTER, 1979 cited in STEIN, 1972B, and SCHELBY, 1981). In the 502 CRO the common-mode-induced non-linearity occurs in a stage after the position and balance controls, so that the demonstrations illustrated in Fig. 18 can be made. This is not true for most other situations.

FIGURE 17

EXPERIMENTAL ARRANGEMENT TO DEMONSTRATE THAT COMMON MODE AMPLITUDE CAN DRIVE A CATHODE RAY OSCILLOSCOPE INTO ITS NON-LINEAR REGION.



NOTE: Different differentially coupled instruments will exhibit different behavior. But ALL will exhibit a limited linear region above which problems such as those illustrated here, will occur.

FIGURE 18

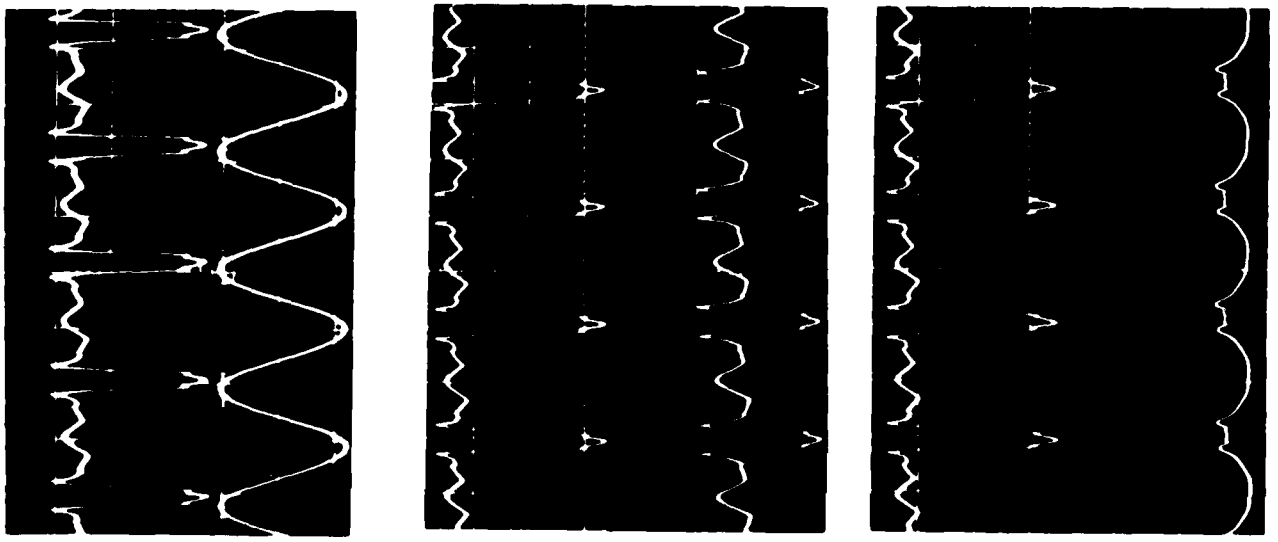


PHOTO 2: FREQUENCY CREATION IN A NON-LINEAR SYSTEM

Top: Differentially coupled DC, 1 mv/cm response

Bottom: Single ended DC 10v/cm common mode sine wave being subtracted from itself by the top channel. 1 kHz.

Time Axis: 0.5 msec/cm

The CRO has evidently been driven non-linear by the common-mode signal.

PHOTO 3: POSITION-SENSITIVE WAVE SHAPE AS NON-LINEARITY INDICATION

The top display from Photo 1 is moved up and down by means of the position control of the top CRO channel. A change in wave shape signified violation of the law of superposition. The CRO has been driven non-linear by the differential coupling.

PHOTO 4: WAVE SHAPE CHANGE WITH TRANSFER RATIO CHANGE INDICATES NON-LINEARITY

Both traces are the same signal. The top trace is at 1 mv cm., the bottom at 100 mv cm. -- 1/100 the gain, sensitivity or transfer ratio. The wave should appear 1/100 the size of the top trace. The fact that it does not, indicates a non-linear system which is driven by the law of superposition.

In Fig. 18 the top photo shows the common mode on the bottom trace and the output from the differentially coupled channel on the top trace. Note that the common mode voltage of 20 v peak-to-peak exceeds the specified limit by 10 to 1. The non-linearity of the system is beyond shadow of doubt for three reasons:

Top Photo: One frequency in, more than one frequency out.

Center Photo: Violation of the law of superposition: when the trace is moved up and down on the screen with the position control (or the balance control), its wave shape changes.

Bottom Photo: Violation of the law of linearity: the same signal displayed at 100 mv/cm and 1 mv/cm is not a scaled version of itself. (See also p. 24)

There is yet another way, not illustrated, to show non-linearity: decrease the input (common mode) and note that the output does not decrease proportionately by that amount.

Methods for checking whether or not this phenomenon exists DURING any particular test involving differentially coupled systems, by pushing a check-switch, are given by STEIN (1972B) and are highly recommended in all such situations, since the common mode often exceeds its linear limit, which, for most ΔP-transducers, for example, is not stated; nor is the concept applied to most differentially coupled measurements commonly made. (See p. 25)

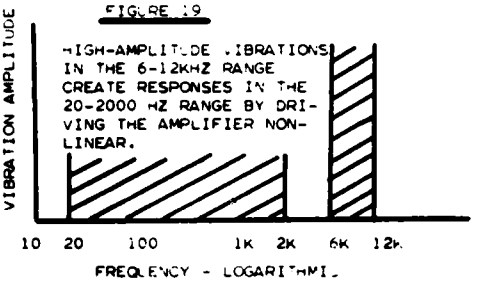
Example 7: High Frequency Overload Creates Low Frequency Distortion

MONFORT (1978) documents a spectacular case of accelerometer outputs at high-frequency, high-amplitude vibration levels driving an amplifier into its non-linear, distorted range, whereupon it creates distortions for LOWER frequencies which contaminate the measurements to be made in that low-frequency range (Fig. 19).

"Vibration measurement made in the MK12A flight program have shown high acceleration levels are present at high frequencies on the R/V shell structure. Further evaluation of the flight data in the form of power spectral densities has also revealed that during periods of excessive vibration, there is significant energy in the low frequency region (20 to 2000 Hz) which are well above system specifications. The GE position on this flight data has been that: measured low frequency (20-2000Hz) shell data is not valid due to the fact that high-level, high-frequency data (6-12KHz) is overloading the vibration sensor amplifier which results in distortion of the vibration signal producing false low-frequency signals." (R/V = re-entry vehicle).

The rest of the paper documents that this is indeed the mechanism, and suggests ways of dealing with the problem. The problem appears to be governed by the same mechanism found by WIRT (1977) in his investigation of the impedance of non-linear systems: high-frequency, high-amplitude signals may change the operating point of a non-linear system to a degree that results in serious distortion of the data at all frequencies. (Ex. 4).

FIGURE 19

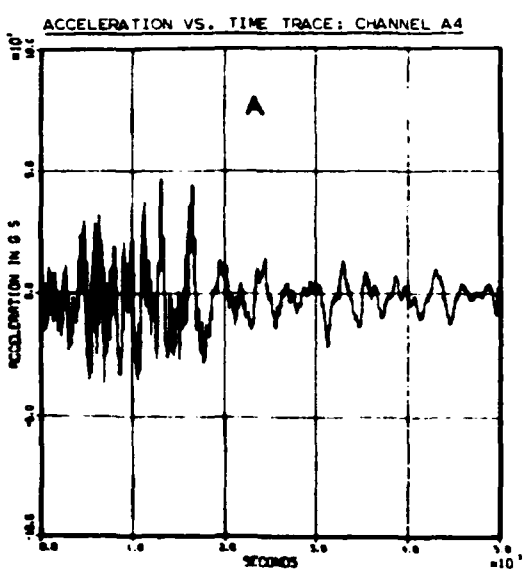


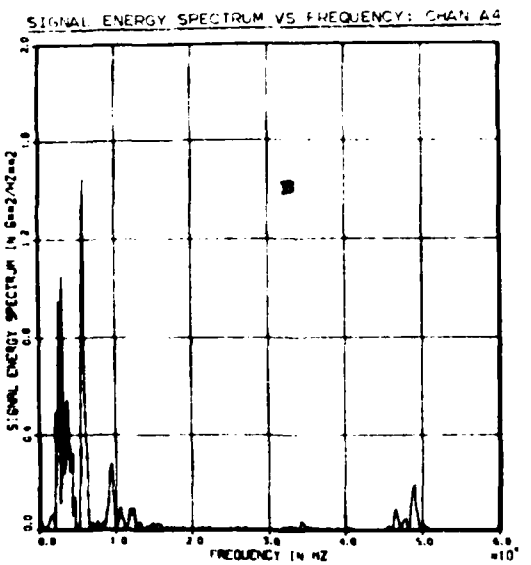
Example 8: Transient Measurements with Highly Resonant Transducers

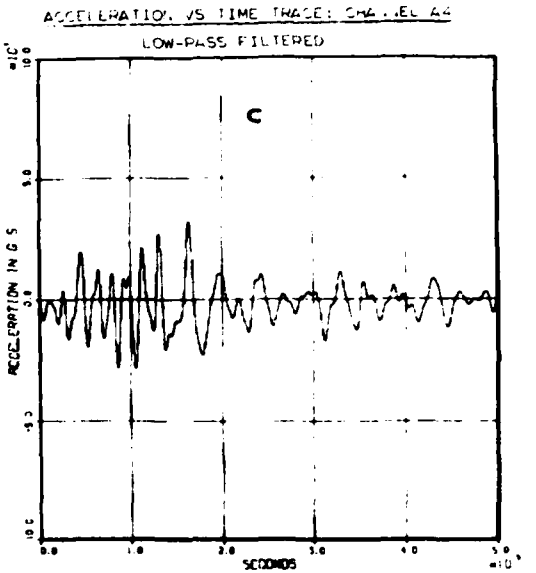
WALTER (1978A, 1978B, 1979) discusses the problems of validating and extracting meaningful data from highly resonant transducers such as accelerometers, pressure transducers and load cells, when subjected to impulsive transient excitations. Among his many contributions and conclusions is the following:

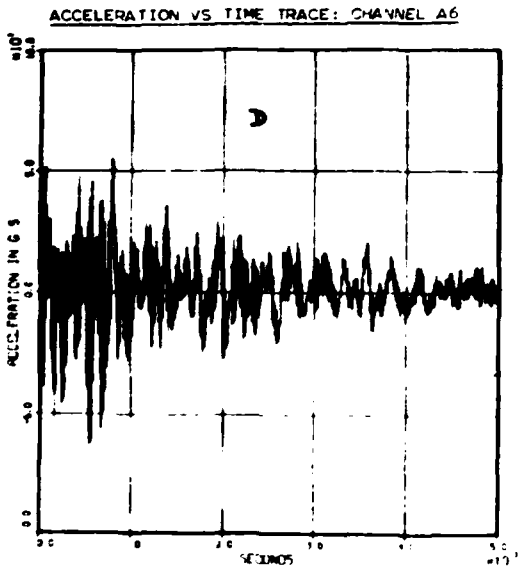
So long as the measuring system has remained linear and distortion free, the transducer resonant characteristics may be accounted for in the deconvolution process, provided there is some distance in the frequency domain between these resonances and the data. If the system has been driven non-linear, then no interpretation of the record is possible, since harmonics and sub-harmonics may be created, and the measuring system may be biased into a completely different operating range by the overload -- a process discussed in this paper in Examples 4 (WIRT 1977) and 8 (MONFORT, 1978).

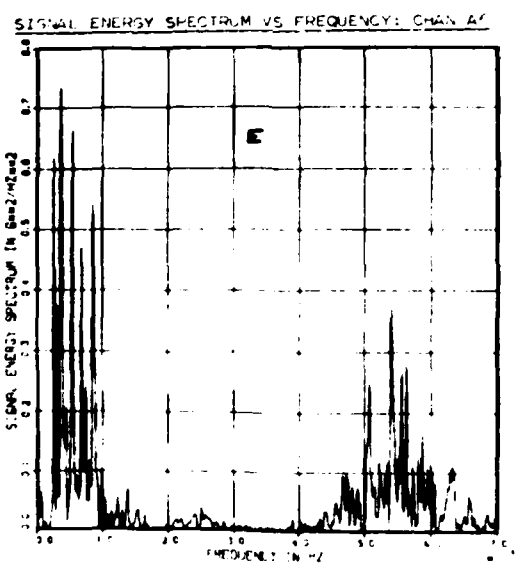
As one example he cites three accelerometers mounted on the same shell structure on a re-entry vehicle being tested in the laboratory to simulate the impul-

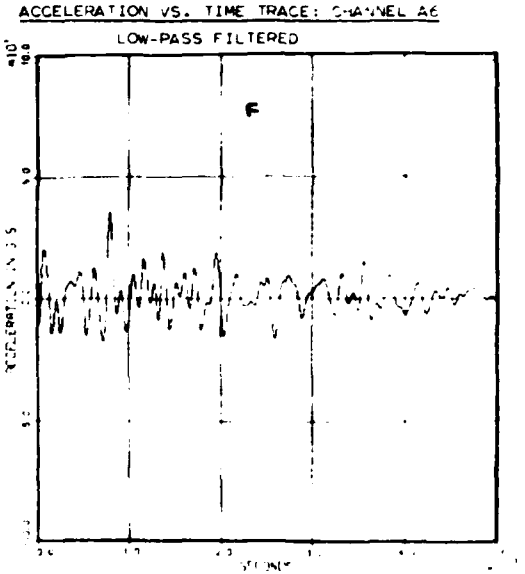

ACCELERATION VS. TIME TRACE: CHANNEL A4
A
SECONDS

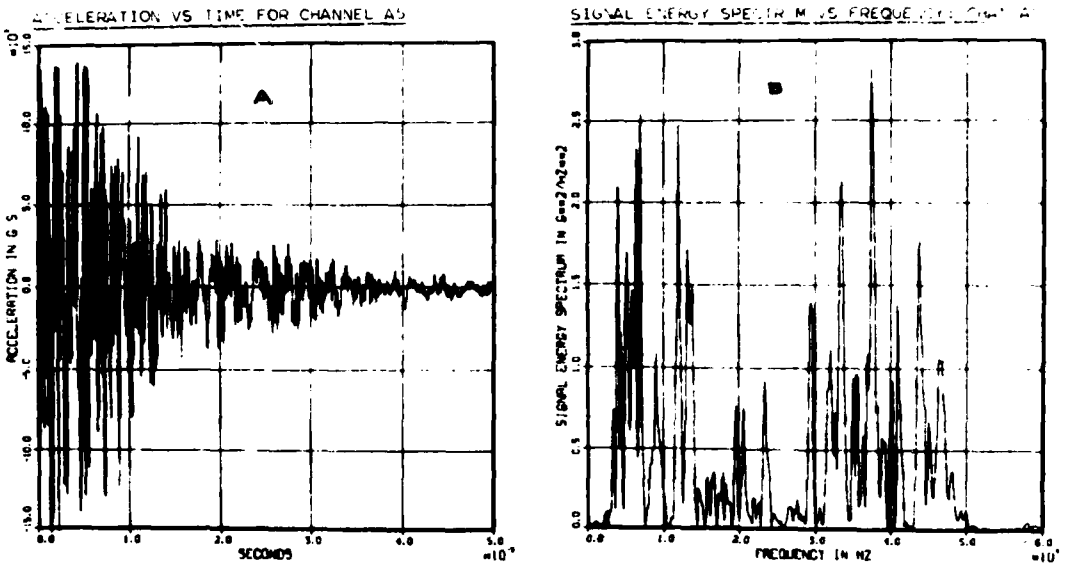

SIGNAL ENERGY SPECTRUM VS FREQUENCY: CHAN A4
B
FREQUENCY IN HZ


ACCELERATION VS TIME TRACE: CHANNEL A4
LOW-PASS FILTERED
C
SECONDS


ACCELERATION VS TIME TRACE: CHANNEL A6
D
SECONDS

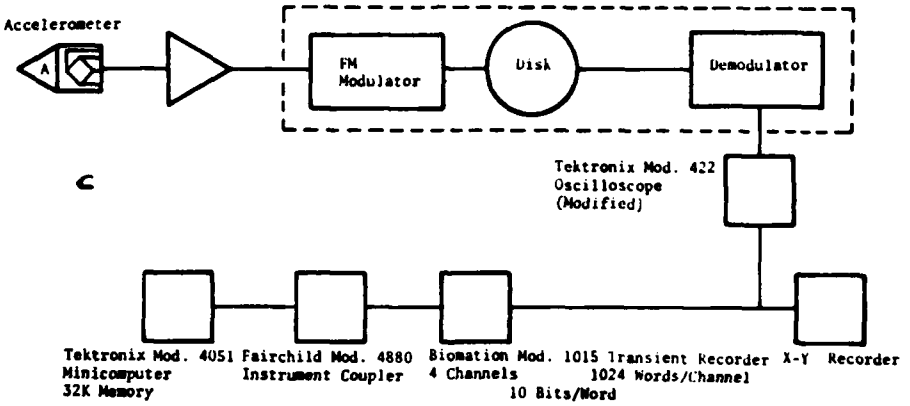

SIGNAL ENERGY SPECTRUM VS FREQUENCY: CHAN A6
E


ACCELERATION VS. TIME TRACE: CHANNEL A6
LOW-PASS FILTERED
F



Dynamics Amplifier Mod. 7600
D-C Coupled
1 MHz Response
0 to 10V Output

Sandia Laboratories Disk Recording System
16 Channels 2 MHz/Channel Response
28 msec Record Time 125 mV to 25V Input



INSTRUMENTATION SYSTEM FOR RECORDING AND DIGITIZING ACCELEROMETER CHANNELS A4, A5, A6

MAGNITUDE OF TRANSFER FUNCTION OF NON-RECURSIVE LOW PASS FILTER WITH ZERO PHASE SHIFT

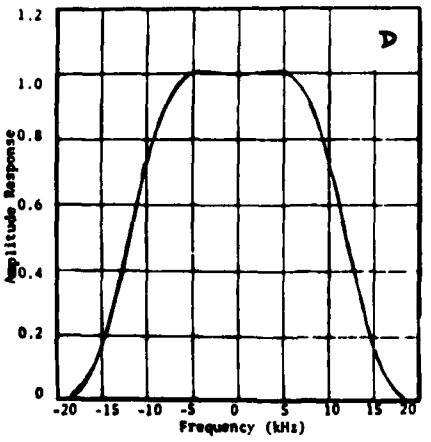


FIGURE 21

sive shock loading on re-entry by means of a light-initiated sheet explosive covering one-half of the vehicle and set off through exploding wires., (WALTER 1978A, 1978B). The records are shown in Figs. 20, 21 as Channels A4, A5, and A6 in close proximity on the inner part of the same shell, with A5 between A4 and A6. For A4 and A6 the original records are shown in Fig. 20A and 20D. The energy spectral density showing clear separation between the structure vibrational frequencies below 15 KHz, and the accelerometer resonances between 40 and 70 KHz, so that a filtering operation is permissible, as shown in Figs. 20B and 20E. The results are traces which are valid data for structural vibrations, Figs. 20C and 20F. Note that the filtering technique, so often automatically applied, has been justified.

For Channel A5, Fig. 21A and 21B, it is seen that the over-driven accelerometer-amplifier combination has resulted in a total intermingling of structural vibration frequencies and accelerometer resonances, presumably through the frequency-creating ability of non-linear systems, and through the possible biasing of the entire system characteristics by the high-frequency overload on the amplifier (see also WIRT 1977, MONFORT 1978). There is no way in which data on structural vibrations can be retrieved from a record such as A5, although provably so, the operation could be performed on the other two records of accelerometers in close proximity on the same structure.

The instrumentation set-up for the tests is shown in Fig. 21C and the non-recursive low-pass filter with zero phase shift which was used, in Fig. 21D.

As to why three accelerometers in close proximity on the same structure should experience such different excitations/responses, the answer lies in the extreme sensitivity of highly resonant systems to the sequence and timing of the impulse-loading-induced reflections which may superpose in or out of phase when they reach each transducer. Figs. 22A and 22B illustrate the response of the same transducer to an initial blast load and two subsequent reflections which arrive back at the transducer, but with slightly different timing. In Fig. 22A the reflections arrive at 0.21 and 0.30 arbitrary time units after the initial blast; in Fig. 22B they arrive at 0.20 and 0.30 time units. The solid trace through the

FIGURE 22: LINEAR SECOND ORDER SYSTEM RESPONSE TO EXPONENTIAL TRAIN (Damping Ratio: 0.01 of critical. Natural Period: 0.02.

Fig. 22A: Pulses start at t=0, 0.21, 0.30

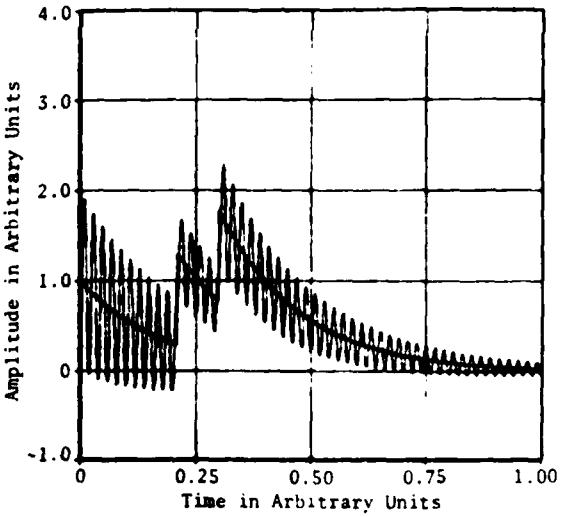
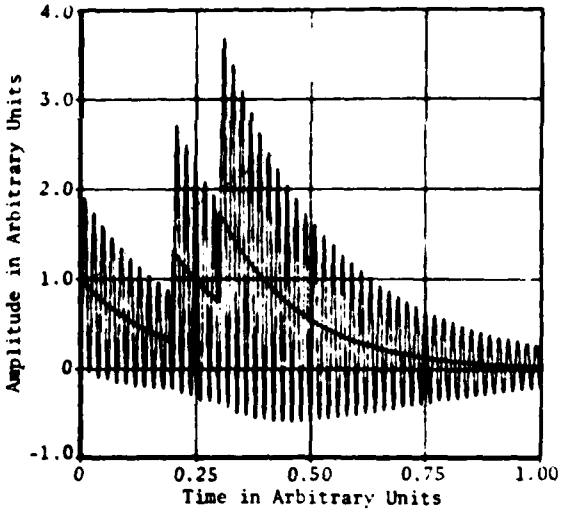


Fig. 22B: Pulses start at t=0, 0.20, 0.30



transducer responses is the actual blast loading input. It is easy to see that in one case the measuring system might remain in its linear, distortion-free range whereas in the other case it might be over-driven, giving rise to the phenomena already discussed. The above is a computer modelled study for illustration only

It is therefore NOT POSSIBLE to assume ANYTHING a priori about the possibility of any single channel on a transient test remaining in its distortion-free linear range. The early-time, travelling-wave, material-response-dominated excitations to the transducers can not be predicted by any model which might also predict the overall later-time structural responses. The types of checks which Walter developed are therefore required before any attempt can be made at data correction or deconvolution.

His findings are in overall agreement with the Unified Approach to the Engineering of Measuring Systems on which his work is based, which holds that it is not possible to GUARANTEE to obtain valid data in any particular test situation, but which has developed theories and practices by which measuring systems can be so designed that the documentation as to the data validity are inherently contained in the data themselves, and in the documentation and analysis process. "Are the data valid ?" can indeed be answered - guaranteed - after the test, and in a definitive manner.

Because documenting system linearity is so important in transient testing, measuring systems and transducers should have their frequency responses for magnitude and phase evaluated at least at two input amplitudes. Unless the curves obtained are identical for both amplitudes, the system is non-linear and should not be used for dynamic testing (WALTER, 1978A, 1978B.).

Case 9: Momentum-Based Fixed-Area Flow Meters

Orifices, venturis and nozzles are momentum-based fixed-area flow meters (see, for example MOFFAT 1973) for which the governing equation is:

$W = \rho.A.V$ where W = mass flow rate; ρ = density; A = area; V = velocity. In practical hardware, the final equation reduces to:

$W = K\sqrt{P}$ where K is a factor for the particular meter and flow conditions, and P is the pressure drop across the flow meter.

If a fluctuating flow, ΔW is superimposed on a steady flow W, a pressure drop ΔP will be produced:

$W + \Delta W = K\sqrt{P + \Delta P}$

To illustrate the problem, let

$\Delta W = \Delta W_o.\sin\omega t$

substituting this forcing function into the above equations and solving for ΔP; and removing all sinusoidal or cosinusoidal terms which would average out to zero over a period of the fluctuation:

$$\Delta P_{average} = \frac{1}{2}\left(\frac{\Delta W_o}{K}\right)^2$$

In other words, there is a DC component to the pressure drop which is created by the sinusoidally fluctuating flow. (See Equ. 3 for the DC component which arises when a sine wave is squared). Thus flow meters of the orifice, nozzle and venturi type, which are non-linear in the relationship between input flow and output pressure drop, will always read HIGH under pulsating (dynamic) flow, even when readings are averaged over a period of the flow fluctuation.

Linear flow meters such as the laminar flow meter, will give correct average results under pulsating flow conditions. A linearized momentum-based fixed-area flow meter might also by-pass the problem. A candidate unit would be the FOXBORO Model 823 d/p Cell (see Bibliography) which operates on the vibrating wire principle in which the frequency of vibration of a stretched wire, which is proportional to the square root of the pressure drop, is the flow-proportional readout:

$W = K_1.f$ f = frequency of wire vibration, and hence

any flow fluctuations will be linearly converted to frequency fluctuations without any residual DC pressure levels discussed above. This assumes that the pressure fluctuations actually reach the flow meter ports equally and that the frequency response of the connecting lines and the meter for magnitude and phase are in ranges that avoid the problems identified in Fig. 1-C. Swirl-type and instability-type flowmeters are also devices which emit a frequency of signal proportional to flow-rate, and similar comments apply.

Case 10: Capacitive Proximity Displacement Measurement.

Displacement measurement by non-contacting capacitive means is usually a highly non-linear process, since:

$V = K.\varepsilon.\frac{A}{D}$ where C = capacitance, K is a constant, ε = dielectric constant, A = plate area and D = distance between plates. If, however, the capacitive reactance rather than the capacitance is measured:

$$X_c = \frac{1}{j\omega C} = \frac{D}{j.\omega.K.\varepsilon}$$ proportional to D and linear. A candidate instrument which uses this principle is the HiTEC Proximic displacement system.

METHODS OF VERIFYING SYSTEM LINEARITY

Given the importance of maintaining a provably linear measuring system during dynamic tests, some of the techniques for incorporating into the measuring system, methods for verifying its linearity, will be discussed. The revolve around three fundamental principles:

Law of linearity
Law of superposition
Law of frequency-creation

Law of Linearity

Formally stated, the law says that: If Q is the response of the system to a forcing function f(t), then n.Q will be its response to n.f(t), where n is some numerical factor. Checks based on that proposition, in increasing order of applicability, might be:

a./Decrease the measurand by a factor, n. Observe if the system output shrinks by that same factor and if the wave shape is maintained proportionately. If the wave shape of the dynamic signal changes, then the system is non-linear. This is perhaps the least practical check although it is sometimes possible.

b./ Decrease the design-controlled input to the transducer by a factor n, and make observations similar to those described in (a). Since the input is design-controlled, the system designer can provide for this check. For a non-self-generating response such as the resistance changes in a strain-gage-based transducer, the design-controlled input is the bridge supply voltage. In changing that voltage, however, care must be taken not to confuse linearity problems with self-heating problems (STEIN, 1978). For a self-generating response the design-controlled input is governed by transducer geometry, material properties and manufacturing methods and is more difficult to modify. Some ingenious techniques, have, however, been developed for special cases. The terminology used in this section is that of the Unified Approach to the Engineering of Measuring System and of its six-terminal Unified Transducer Model as described by STEIN (1972A, 1973 for example).

c./ Decrease the transfer ratio, (gain, sensitivity, calibration factor) within the measuring system by a factor, n, and make the same observations as in (a). Note that only non-linearities forward of that transfer ratio control can thus be documented. If the system has been driven into its non-linear, distorted range before that control, then check (c) would not indicate that condition.

Law of Superposition:

Formally stated, the law says that: If Q_1 is the response of the system to forcing function $f_1(t)$, and if Q_2 is the system response to $f_2(t)$, then (Q_1+Q_2) will be the system response to $f_1(t) + f_2(t)$.

Checks based on this proposition would include the superposition on top of a dynamic signal, of a DC level by one of the means described below. As the LEVEL of the dynamic signal is changed, its WAVE SHAPE should not. If it does, then non-linearity around that operating point has been documented beyond shadow of doubt. This check corresponds to moving the operating point in Fig. 1-B.

a./ Change the level of the dynamic measurement, an unlikely but sometimes viable possibility.

b./ Change the balance point of the system. Since most measuring systems have balance controls, either in a bridge or on an amplifier or oscilloscope, this condition can be implemented easily.

c./ Change the reference value to which any differential measurement may be tied. Thus in a gauge-pressure transducer vented to atmosphere at one port, it is possible to introduce a small change in that reference pressure, which should then feed through the entire measuring system as a corresponding change in level. This can also be used for calibration during a test while recordings of the dynamic pressure applied to the measurand-port are still being made. This method is due to GE in Evendale, Ohio, but has not been published, only verbally presented at a Range Commanders' Council Transducer Workshop discussion. The principle is general, and in thermocouple systems, for example, the ice-bath reference temperature can temporarily be switched to some other reference temperature to see if the wave shape of the signal changes and if this difference in reference levels feeds through as a calibration signal.

d./ Inject a known level of signal artificially. Electrically this is done either by voltage insertion as in thermocouples, or resistance injection as in the shunt calibration technique for impedance-based transducers. The introduction of such a level change should, again, not alter the WAVE SHAPE

of the dynamic signal being observed. These injected signals also serve as calibration means, and often two checks can be made simultaneously. With very rapid switching or very steep rise times for the injected signal, that can also be used to document the rise time of the measuring system and thereby its frequency response.

Fig. 18 shows Linearity Check (c) and Superposition Check (a) in use, as well as the law of frequency-creation.

Law of Frequency Creation

As established at the beginning of this paper (Equs. 1-5) any system for which a single frequency excitation results at the output in anything other than that single frequency, is non-linear beyond shadow of doubt. Thus, on magnetic recordings it is common practice to introduce, for example a 1 volt rms, 1 KHz sine wave before and after the test. If on playback a sine wave is obtained, the system was linear, if it is 1 KHz, the tape speed is correct, and if it is 1 volt rms, the transfer ratio settings are correct.

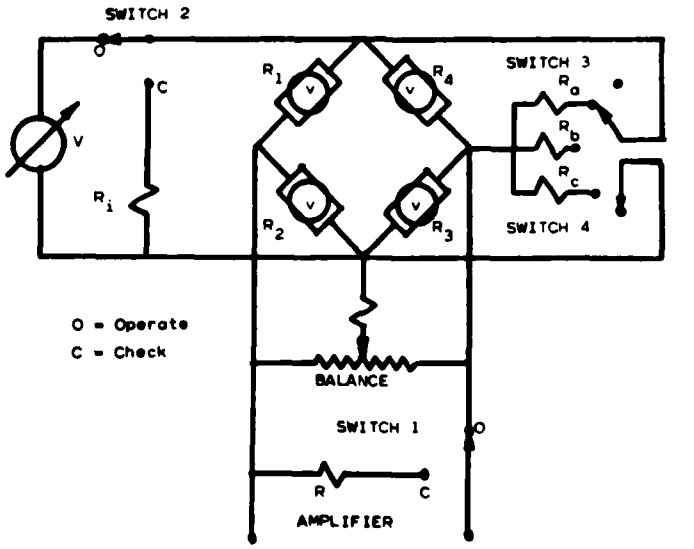
Typical Execution of these Checks:

Fig. 23 illustrates some of the checks discussed in this paper. It should be emphasized that the noise documentation and suppression process must precede the linearity documentation. Noise documentation and suppression are discussed by STEIN (1972A, 1972B, 1973A, 1973B, 1972D, 1970, 1975, 1977).

Switch 1: checks the ability of the subsequent component (amplifier) to reject the common mode from the bridge, if it is differentially coupled. In the C position, Switch 1 provides the amplifier a zero voltage, at the impedance level R of the bridge, and at the common mode voltage which exists during operation - half the bridge supply voltage. The system output during that check should be zero. Note that in Example 6 this was not the case. Switch 1 is one of the check switches to be used to guard against the Example 6 problems.

Switch 2: checks the ability of the transducer to respond in a self-generating manner, by producing voltages, v, within the bridge arms. Note that in Example 1, for the single-grid strain gages, the lower photo in Fig. 11 was obtained under this condition. This check is to be avoided in certain trans-

FIGURE 23: SOME CHECKING METHODS INCORPORATED INTO A CIRCUIT



ducers very sensitive to the current level in the bridge arms because of self-heating problems, such as semiconductor-based transducers. Other checks are available for self-generating responses.

Switches 3 & 4: illustrate the application of three shunt calibration resistors across adjacent bridge arms: Switch 3 to shunt them across arm R_4 and Switch 4 to shunt them across arm R_3. If the resistors R_a, R_b, R_c are so selected as to give uniformly increasing amplitudes of injected resistance change, then a 6-point linearity check and calibration is obtained when these switches are actuated. In addition, the wave shape of the signal should not change during such actuation, if the signal is being recorded during this period.

Supply Voltage, V: is indicated as variable to follow the (b) check for the Law of Linearity.

Balance Control: The balance point may be changed to utilize Superposition check (b).

Note that not all these checks will necessarily be used all of the time, nor that these are all the checks possible or recommended. Fig. 23 is only an example of several checks which can be made and which should be incorporated periodically on every dynamic test.

CONCLUSIONS

It is seen that non-linearities both in processes and in measuring systems are very wide-spread and occur in all disciplines. Measurements on non-linear processes demand certain precautions and special planning for the measuring system. Non-linear measuring systems should not be used for dynamic measurement problems. Documentation of system linearity should be planned for by the measurement engineers and demanded by the test requestor. If the measuring system remained linear, then the dynamic data may be subject to a correction procedure.

Since measuring systems for dynamic processes must be linear, it is quite permissible to mathematically model measuring systems with the assumption of linearity -- every effort must be made to make the measuring system obey this assumption. This means that linear differential equations are an adequate and respectable tool for the analysis of dynamic measuring systems. Not so for processes, and the paper has pointed to quite a number of processes often assumed linear which in reality are not.

Furthermore, it is the author's conviction that the topic discussed in this paper should form an integral part of the UNDERGRADUATE education of every engineer, theoretical or experimental. It is not necessary to burden the undergraduate student with cumbersom non-linear differential equations. It IS necessary to expose them to the problems which may be encountered in the real world, which is not linear, homogeneous, isotropic, ergodic, nor Gaussian.

Case 11: Non-Linearities due to Extraneous Influences

A measuring system may be linear with respect to the variable to be observed (the measurand), but non-linear with respect to some other environmental factor. Thus an undesired environment-response combination may create unsuspected frequencies. An example is illustrated in Fig. 24. Its application is to any measurement with resistive transducers in magnetic fields, such as strain gages or resistance thermometers in motors, generators, induction heeters or transformers, welders, etc.

Specimen: For demonstration purposes a 1/16" thick aluminum plate with four strain gages is used, all of the same gage length (1/4 inch) and of the same grid geometry. The gages are:

Gage 1: Constantan, single grid, 120 ohms, leads twisted and shielded.

Gage 2: Constantan, single grid, 120 ohms, leads parallel, unshielded.

Gage 3: Constantan, dual grid, bifilar, non-inductively connected grids one on top of the other, 240 ohms, leads twisted and shielded.

Gage 4: Isoelastic, "D" alloy, single grid, 350 ohms, leads twisted and shielded. Only gage 4 is used in the tests described here.

Environment: Magnetic fields generated by a Radio Shack Tape Degausser Eraser (about 750 Gauss near the center and with very high gradients in space); household stud finder with gimbaled magnet of unknown strength.

Effects: The magnetic fields create two different effects:

a. Electromagnetic induction according to the relationship: $e = k.N.A.\partial\phi/\partial t$ where e = induced voltage, k = constant, N = number of turns, A = area perpendicular to the magnetic fluex ϕ. This self-generating response is an undesired response to an undesired environment and is illustrated in Fig. 24-D. It would be the same for gages 1, 2, and 4 since it depends only on geometric factors and not on a material property of the gage grid. It could be eliminated by a carrier system -- a non-DC design-controlled input, (STEIN, 1975), or by mutual compensation such as in a non-inductively connected grid arrangement as in Gage 2 in Fig. 24. But alternate methods are possible as shown in Fig. 26.

b. Magneto-resistive responses, i.e. desired responses (resistance changes) stimulated by an undesired environment (magnetic fields). These responses would even pass through every carrier system and are illustrated in Fig. 24 A, B, C to the scale of 100 $\mu\varepsilon$/div equivalent. The only differences in these photos is the location of the magnetic field with respect to the gage -- i.e., the spatial gradient distribution of magnetic field in which the sensors finds itself. The magneto-resistive relationship is non-linear:

$$\Delta R/R = K_1.\Delta\phi + K_2.\Delta\phi^2 + K_3.\Delta\phi^3 + \ldots$$

and hence a sinusoidal magnetic field, $\Delta\phi$, will create harmonics according to Equ. (3). It happens that Isoelastic (36Ni, 56Fe, 8Cr, 0.5Mo, RTM John Chatillon & Sons) is magnetoresistive. So are Nickel and Balco, materials common in resistance thermometry. The effect is a DC effect, which electromagnetic induction is not. A DC magnet household stud finder placed over Gage 4 produced a 100$\mu\varepsilon$ equivalent static zero shift. Note that Photos Fig. 24 A, B, C represent the superposition of the self-generating induction and non-self-generating resistive effects.

STEIN (1977) discusses magnetoresistive responses in strain gages and temperature sensors at length and cites literature to indicate that even Constantan (55Cu, 45Ni) exhibits magnetoresistive behavior at low temperatures and high magnetic fields, but not at room temperature and moderate fields. This is due to the small but variable iron contant used to control resistance-temperature coefficient. Karma-type alloys (73Ni, 20Cr, + Fe, Al, RTM Driver-Harris) are less magnetoresistive and the (92Pt, 8W) alloys even less so.

The danger of the frequency-creation due to magneto-resistive responses is two-fold.

a. The ELECTROMAGNETIC INDUCTION effect may have been successfull eliminated, but the MAGNETORESISTIVE effect forgotten.

b. Any 60Hz noise levels may have been treated by inserting a 60Hz rejection filter, which here will not eliminate the created frequencies at harmonics of 60 Hz, and which will unwittingly contaminate even a carrier-type system.

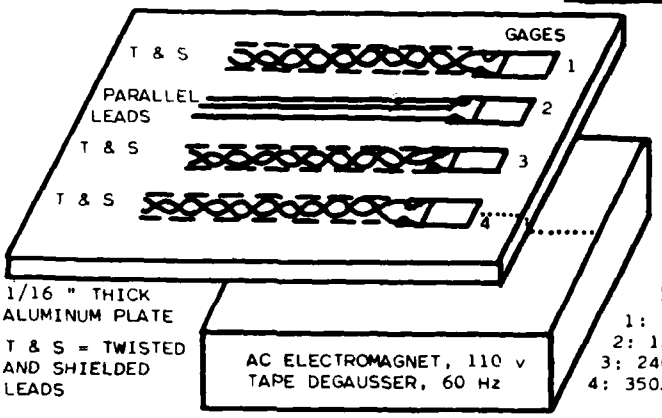
In addition to the effects described above, the magnetic AC field will also heat the specimen and gages due to eddy currents. Fig. 26 illustrates the thermally-induced zero shifts vs. time for this particular test specimen. The Constantan gages would have been self-temperature compensated for that aluminum alloy, and only thermally-induced real strains would have been evident.

The instrumentation used to obtain the

ELECTROMAGNETIC AND MAGNETORESISTIVE RESPONSES OF STRAIN GAGES IN MAGNETIC FIELDS

FIGURE 24

MECHANICAL ARRANGEMENT

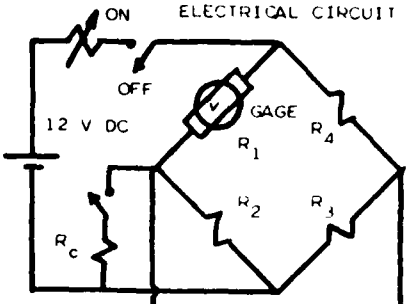


1/16 " THICK ALUMINUM PLATE

T & S = TWISTED AND SHIELDED LEADS

AC ELECTROMAGNET, 110 v
TAPE DEGAUSSER, 60 Hz

ELECTRICAL CIRCUIT

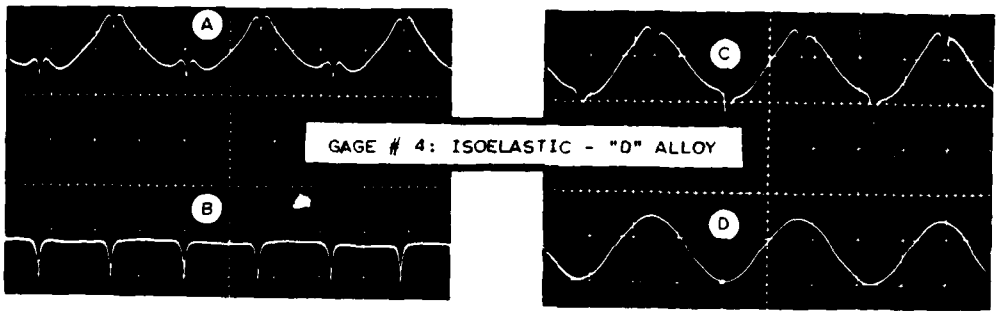


GAGES
1: 120Ω CONSTANTAN
2: 120Ω CONSTANTAN
3: 240Ω CONSTANTAN
4: 350Ω ISOELASTIC

BALANCE
AMPLIFY
DISPLAY
ON METER OR CRO

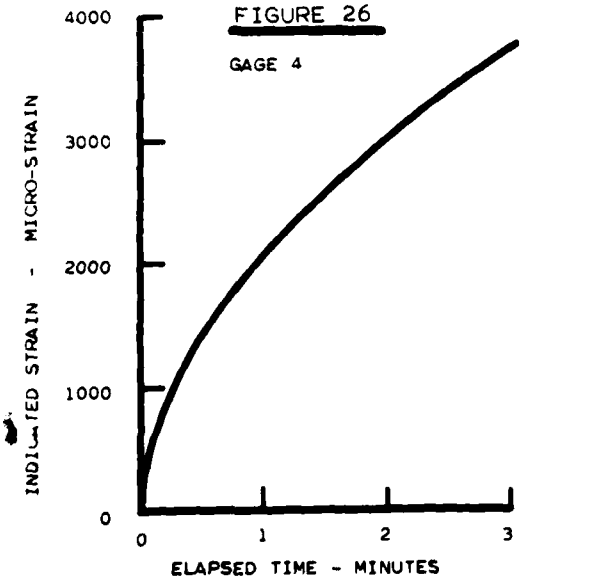
PHOTOS, A, B, C: BRIDGE POWER ON, ELECTROMAGNET ON
100 με / DIV VERTICAL SCALE
5 msec/cm HORIZONTAL SCALE

PHOTO D:
BRIDGE POWER OFF, ELECTROMAGNET ON
SAME SCALES AS PHOTOS A, B, C.



ZERO-SHIFT DUE TO ELECTROMAGNETIC HEATING

FIGURE 26



ARRANGEMENTS FOR CANCELLING THE SELF-GENERATING ELECTROMAGNETIC INDUCTION EFFECT

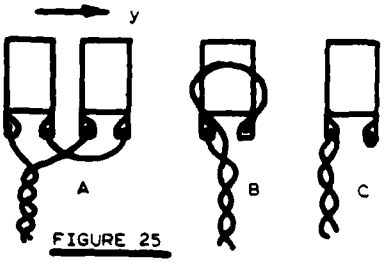


FIGURE 25

Fig. 25-A: Two sensors connected in a non-inductive manner. (If $\partial\phi/\partial y \rightarrow 0$)

Fig. 25-B: Return wire loop is made to act as the compensating mechanism.

Fig. 25-C: Two gages on top of one another are non-inductively coupled.

data in this section were an Ellis BAM-1 signal conditioner (MEASUREMENTS GROUP) and a Tektronix 502A Oscilloscope.

BIBLIOGRAPHY

ANONYMOUS
1975 Appendix B. Boo-Boo 15, Proc. Range Commander's Council 8th Transducer Workshop, White Sands Missile Range, NM 88002, 1975
1976 Bondable Resistance Temperature Sensors and Associated Circuitry, TN-140-3, Measurements Group, Inc. Raleigh, NC, 1976

BOLLETER, Ulrich, PhD
1968 On the Experimental Study of Rotating Blade Vibrations. Master's Thesis, Lab for Measurement Systems Engineering, Arizona State Univ., June 1968. Also published summary: Rotating Blade Vibrations, Measurements & Data, Sep.-Oct. 1968, pp. 81-84.

BOYD, Keith E.
1963 Common Mode Rejection Ratio for Tektronix 502 CRO, Graduate Project, Lab. for Meas. Systems Eng. ASU, Tempe, AZ May 1963.

BUNN, Maurice H.
1968 On Some Non-Linear Phenomena in Mechanical Vibrations, Lf/MSE Senior Project, ASU, Spring 1968. Summary published: Measurements & Data, July-Aug. 1968, 106-109.

EVANS, J.P.
1977 Note on the Relation between Resistance Thermometer, Thermocouple and Radiation Temperature Scales, 630-1064°C. Metrologia 13, 171-172.

HOOKER, Verne, James AGGSON, David BICKEL
1974 Improvements in the Three Component Borehole Deformation Gage and Overcoring Techniques, US Bur. Mines, RI 7894, 1974.

MOFFAT, Robert J. Ph.D.
1973 Introduction to Flow Rate Measurement. Copyrighted lecture notes, presented at the Measurement Systems Engineering Short Courses 1973 to date; also from R. J. Moffat, Stanford Univ., Stanford, CA 94305.

MONFORT, A.
1978 Type III Flight Vibration Amplifier Investigation. Memo to N. Satin General Electric Co., Re-Entry & Environmental Systems Div., No. U-RR-78-93-427, Philadelphia, PA August 4, 1978.

MUZZY, Joel
1965 Diagnosis and Suppression of Electromagnetically Induced Interference in Dynamic Strain Measurement. Lf/MSE, ASU, Spring, 1965

PUST, Ladislav
1971 Subharmonic Vibrations of Strongly Non-Linear Mechanical Systems, Mecanique Appliquée, Rev. Roumanian Sciences & Technology, Vol. 16/1, 91-100, Bucarest, 1971

RANDALL, R. B.
1982 Cepstrum Analysis and Gearbox Fault Diagnosis, Brüel & Kjær Application Notes, Ed. 2, Nærum, Denmark

ROBERTS, Jackson H.
1969 Vibration Measurement in a Hostile Environment: Case Study of Interference Control, Lf/MSE Project, ASU, Jan. 1969.

SCHELBY, Fred
1981 Evaluation of Valiayne DP-22 Pressure Transducers for Measuring Excess Pore Pressure. Sandia National Labs internal Memo to Karen Grube, Dec. 14, 1981, Albuquerque, NM

SMITH, Clarence R.
1962 Strain Gages, Their use in Airplane Stress Analysis. Convair, San Diego, CA, publication, n.d. *Cited with figure in Chapter 21*, Measurement Engineering Vol. II, The Strain Gage Encyclopaedia, by Peter K. Stein, SES, Inc. 1962, op.

STEIN, Peter K. listed separately

WALTER, Patrick L., PhD.
1978A Limitations and Corrections in Measuring Dynamic Characteristics of Structural Systems, Illustrations to accompany lectures at the Measurement Systems Dynamics Short Courses, SES, Inc. 1st ed. 1978, 2nd ed., 1979. Lf/MSE Publ No. 73.
1978B Limitations and Corrections in Measuring Dynamic Characteristics of Structural Systems, Sandia Doc. SAND 78-105, Oct. 1978, PhD dissertation ASU. Sandia National Laboratories, Albuquerque, NM

Abbreviations used in this bibliography:
Lf/MSE = Laboratory for Measurement Systems Engineering, now at Stein Engineering Services, Inc., Phoenix, AZ
ASU = Arizona State University, Tempe, AZ
SES = Stein Engineering Services, Inc. 5602 E. Monte Rosa, Phoenix, AZ 85018

WALTER, Patrick L., PhD,(Continued)
1979 Assessment of Instrumentation for 5-Tube Boiling Heat Transfer Experiments, Sandia Labs Memo, Feb. 28, 1979, Albuquerque, NM. (Cited in STEIN, 1972B)
1981 Deconvolution as a Technique to Improve Measurement System Data Integrity. Experimental Mechanics August 1981, 309-314.

WALTER, Patrick L., Harold D. NELSON
1979 Limitations and Corrections in Measuring Structural Dynamics Experimental Mechanics, Sept. 1979, 309-316.

WASHBURN, B. W.
1969 Vibration Measurements at Cryogenic Temperatures and High Acceleration Levels. Proc. 6th Transducer Workshop, Range Commander's Council Document 112-70, 123-139, 1969, White Sands Missile Range, NM 88002

WHETSEL, J. Elwin
1968 Transfer Characteristics of a Nonlinear Vibratory System. Master's Thesis, Lf/MSE, ASU, Oct. 1968

WIRT, L. Spencer
1962A The Precessional Primer. Strain Gage Readings, Vol. V/1, April-May 1962, 7-20. Also Chapter 16, Measurement Engineering Vol. I, by P. K. Stein and contributing authors, 1st ed., Jan. 1962, SES, Inc. Distributed as excerpts at all Measurement Systems Courses operated by SES, Inc. since 1962.
1962B An Amplitude Modulation Theory for Gear-Induced Vibrations: Case Study. Strain Gage Readings, V/4 Oct-Nov. 1962, 3-9. Also Ch. 17 in Measurement Engineering Vol. I (see above). Distributed as excerpt at all Measurement Systems Courses operated by SES, Inc.
1962C Acoustics as an Aid in Measurement Engineering. Ch. 10 in Measurement Engineering Vol. I, see above. Distributed as excerpt at all Measurement Systems Courses operated by SES, Inc., since 1962.
1977 Measurement of the Impedance of Non-Linear Systems, Lf/MSE Publ. 68, March 1977.
1974 US Patent 3,824,842. Apparatus and Methods for the Measurement of Acoustic Absorption and Impedance July 23, 1974. (With Duane L. MORROW)
1976 Method for Measuring Impedance U.S. Patent 3,960,004, June 1, 1976 (with Duane L. MORROW)

ZANDMAN, Felix
1960 Stress Analysis of a Guided Missile Test Section with the Photoelastic Coating Technique. SESA Proc. XVII/2, 135-150, 1960

ZANDMAN, Felix, M. WATERS, S. REDNER
1962 Stress Analysis of a Rocket Motor Case with the Birefringent Coating Method, Proc. SESA, Vol. 19/2, 215-221, 1962

ZHUQIAN, Zhou
1981 Linear Bridge for Platinum Thermometer on Low Temperature Monitoring. Paper at Transducer Temp-Con '81, Wembley, England, June 1981. Proc. from Trident Intern. Exhibits Ltd., 21 Plymouth Rd. Tavistock, Devon, PL19 8AU, UK.

MANUFACTURERS

ANALOG DEVICES INC.
P.O.Box 280, Norwood, MA 02062
Two-terminal IC Temperature Transducer.

FOXBORO, CO.
38 Neponset Ave., Foxboro, MA 02035. Model 823 and 821 GM/GH series pressure transmitters. TI-37-75a, TI-37-76a

HiTEC CORP.
Nardone Industrial Park, Westford, MA, 01886. Proximic non-contacting displacement measuring system.

MEASUREMENTS GROUP, INC.
P.O.Box 27777, Raleigh, NC 27611
Product Bull. PB-104, CLTS
Product Bull. PB-105-6, Temperature Sensors and LST Matching Networks. 2300 Signal Conditioner.

MIDWEST COMPONENTS INC.
P.O.Box 787, Muskegon, MI, 49443
Tempsistor temperature sensor

MOTOROLA SEMICONDUCTOR PRODUCTS INC.
Box 20912, Phoenix, AZ 85036
MTS 102, 103, 105 series silicon temperature sensors.

SWEMA
P.O. Box 20, S-12305 Farsta, 5, Sweden. Cuproswem linear resistive temperature sensor.

Publications by STEIN

The publications listed below and cited in this paper are available from the Laboratory for Measurement Systems Engineering (Lf/MSE) as Publication Numbers shown for each reference. Stein Engineering Services, Inc. (SES, Inc.) 5602 East Monte Rosa, Phoenix, Arizona 85018, USA.

STEIN, Peter K.

1961A Strain-Gage-Based Shaft Whirl Instrumentation in Gas Turbines, Strain Gage Readings, IV/3, 3-13 Aug-Sep. 1961. Lf/MSE Pub. 51

1961B Strain-Gage-Based Computers Strain Gage Readings, IV/4, 17-50, Oct-Nov. 1961. Lf/MSE #47

1963 The Constant Current Concept for Dynamic Strain Measurement, Strain Gage Readings, VI/3, 53-72, Aug.Sept. 1963, also in BLH Measurement Topics 6/2, 1-12, Spring 1968, BLH Electronics, Waltham, MA. Also in Instruments & Control Systems, 38/3, 154-55, May 1965 in abstract. Lf/MSE Publ. 46

1964 Characteristics of High-Speed Assemblies Determined by Their Reactions on Stationary Gas Turbine Parts. Presented at 2nd Intern. Experimental Stress Analysis Congress, Paris, France April 1962. Instruments & Control Systems, Vol. 37/11, Nov. 1964, 132-39. Lf/MSE No. 52

1970 The Response of Transducers to Their Environment: The Problem of Signal and Noise. Shock & Vibration Bull. 40/7. 1-15, 1970 Proc. 6th Transducer Workshop, RCC Doc. 112-70, pp. 91-106, White Sands Missile Range, NM 1970. Jnl. Environmental Sciences, May-June 1971, 10-17. #17.

1971A The Response of Transducers to Their Environment: The Problem of Signal and Noise - A Comprehensive Undergraduate Experiment. Lf/MSE Publ. 38, Fall '71.

1971B The Concept of a "System Operating Surface" as a Fundamental Measuring System Characteristic. IEEE Trans. Instrumentation & Measurement, Nov. 1971, 183-191

1972A A New Conceptual and Mathematical Transducer Model: Application to Impedance-Based Transducers such as Strain Gages. VDI Ber. 176, 221-236, 1972. Düsseldorf, Germany. Lf/MSE 34

1972B The Measurement of Differential Quantities; Problems and Approaches. Lf/MSE Publ. 43, June 1972

1972C Sensors/Detectors/Transducers: The Basic Measuring System Components. Proc. 1972 Joint Measurement Conf. ISA, Raleigh, NC, 1972, pp. 63-91

1972D A Unified Approach to Handling Noise in Measuring Systems. AGARD NATO LS-50: Flight Test Instrumentation, Neuilly-sur-Seine, France 1972, pp. 5-1 to 5-11. Lf/MSE 56.

1973A A New Conceptual Model for Components in Measurement/Control Systems: Practical Application to Thermocouples. Proc. 5th Intern. Symp. on Temperature, ISA, Raleigh NC, 1973, pp. 1991-2007. Lf/MSE 29.

1975 Information Conversion as a Noise Suppression Method. Lf/MSE # 66, Jan. 1975

1973B Environment-Response Combinations in Measuring System Components and the Role of Statistics. ACTA IMEKO 1973, Paper B-120, Budapest, Hungary, June 1973. Lf/MSE # 61.

1977 Spurious Signals Generated in Strain Gages, Thermocouples and Leade. Proc. 9th Transducer Workshop, Range Commanders' Council, White Sands Missile Range, NM 1977, Lf/MSE # 69.

1978 Transducers in Temperature Gradient/Transient Environments. VDI Ber. 312, pp. 29-36, Düsseldorf, Germany, 1978. Lf/MSE # 72.

1979 Our Engineering Education, The Not-So-Scientific Method. Proc. 11th Measurement Science Conf., Jan. 1982, San Diego, CA. Lf/MSE Publ. 74, Dec. 1979.

APPENDIX:

Many of the case studies cited here were either student experiments in the third-year Measurement Systems Engineering course which the author taught for 18 years as Professor of Engineering, o was a Senior or Graduate student project for the BS, MS or PhD degree with a Measurement Engineering Major. Those projects were subsequently used as demonstrations or laboratories in the undergraduate courses. There were a total of six courses, each meeting 4 hours a week for lectures and 2 hours a week for labs, from Junior to post-graduate levels. During those 18 years there was one PhD, over 40 MSE and over 200 BSE Measurement Majors. A total of 950 students who took at least the first course, might be called Measurement-Oriented, Measurement-Aware or Measurement-Conscious engineers.

It is the author's firm conviction that ALL engineers, whether destined for theoretical or experimental careers, must have a basic understanding of measurement systems. In fact, pure theoretical analysts are often at the complete mercy of the data offered to them in terms of material properties, service conditions, boundary conditions, etc., which go into their theoretical models. See STEIN (1979) for case studies of the inordinate waste of time, effort, manpower and resources which can result.

Sources of the examples are:

Examples 1 and 6

From a student experiment conducted from 1959 through 1977 in the author's laboratory at the junior level. Several undergraduate projects were carried out to develop it to its final phase: MUZZY (1965), ROBERTS (1969) for Ex. 1, and BOYD (1963) for Ex. 6.

Example 2

The phenomenon was found by Dr. Ulrich Bolleter during his Master's Thesis (BOLLETER 1968) investigating the vibrations of a rotating bladed structure (Sears Roebuck Fan Blade) and investigated thoroughly as an undergraduate project by BUNN (1968) for which he was awarded the first prize, nationally, in the 1968 ASME Student Papers' Contest.

Examples 3 and 5

Projects on which Wirt and Stein cooperated during their joint tenure in the Instrumentation Engineering Group at AiResearch Manuf. Co. of Arizona, of which Stein was Group Leader.

Example 4

From Wirt's text material and presentation at the annual Measurement Systems Engineering Short Courses in Phoenix, Arizona, sponsored by the author's organization since 1962.

Examples 7 and 10

From the literature

Example 8

From WALTER (1978A), his doctoral dissertation with Stein as Chairman until his resignation from the faculty. Papers based on this work have since appeared and are cited as applicable.

Example 9

From Moffat's lectures at the annual Measurement Systems Engineering Short Courses in Phoenix, Arizona.

Figure 3

From a Master's Thesis,(WHETSEL 1968) on the dynamics of non-linear systems.

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The author acknowledges with gratitude, the contributions of his past students in educating him, and of his co-workers and co-lecturers in doing the same.

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Drift Prediction for a Roll-Stabilized Inertial Measurement System

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Abstract

A roll-stabilized inertial measurement system is being developed by Sandia National Laboratories. This system will measure three orthogonal body angular rates and three orthogonal body accelerations and will calculate three Euler angles for attitude control of small rocket systems and/or large rocket payloads in flight. An analysis of the predicted drift in the Euler angles has been undertaken to aid in the definition of computational hardware characteristics (such as gyro resolution and gyro sample frequency) and to assess the performance of the system over typical trajectories. The method of analysis uses two different techniques to calculate Euler angles and to compare the results. The first technique results in a "true" Euler angle which is calculated by a Bortz equation (a method to relate vehicle body coordinates to earth coordinates). The second technique simulates the in-flight calculations by including effects of drift from the truncated Bortz algorithm, quantization, and random gyro drift. The comparison results in drift as a function of time for the three Euler angles, roll, pitch, and yaw. Examples of predicted drift over typical trajectories are presented.

I. Introduction

A miniature roll-stabilized inertial measurement system (Mini-Rims) for attitude measurement and control is being developed at Sandia National Laboratories. The system consists of 2 two-degree of freedom, dynamically-tuned rotor gyros and 3 single-degree of freedom accelerometers which are mounted on a roll-stabilized gimbal. This configuration was used initially at Sandia for spinning sounding rockets applications in the early 1960's and isolates the sensors from high roll rates (up to 10 rps). At that time, a miniature attitude reference system (MARS) with 2 free gyros mounted on a roll-stabilized gimbal was designed at Sandia and ultimately manufactured by a commercial source. MARS has been used for a variety of vehicle instrumentation applications over the past twenty years. A comparison of MARS and Mini-Rims characteristics is shown in Figure 1.

The goals of the Mini-Rims program are three-fold. First, the design requirements of the potential users must be satisfied. These include: an improved (over MARS) accuracy of 2-3 deg./hr.; a minimum size which accommodates 9 in. diameter vehicle applications; environmental constraints; and minimum cost. Secondly, two prototypes are to be developed by August of this year (1983). One prototype (non-computational version) is for attitude measurement and telemeters data for post flight processing. The other prototype is for attitude

measurement and control and processes data for the calculation of Euler angles by an on-board computer. Thirdly, a commercial manufacturing source is to be developed.

The prototypes are starting their environmental tests and will also undergo performance tests. Since the prototypes are flight-worthy, it is anticipated that Mini-Rims will fly in a vehicle-development application within the year.

A systems-level description of the hardware is given in Section II. In Section III, the drift prediction analysis is presented. Conclusions and future work are described in Section IV.

II. Hardware

The configurations for the non-computational version and the computational version are shown in Figures 2 and 3, respectively. The non-computational version consists of an inertial measurement unit (IMU) which is supported by a vibration isolator and four electronics boards, (the gyro servo board, the gyro analog-to-frequency converter board, the inverter board, and the resolver board). The IMU contains the sensors, gimbal, and torque motor. The Mini-Rims prototypes have two Incosym Mod V dynamically-tuned rotor gyros and three Sundstrand Minipal Model 2180 accelerometers. One gyro measures pitch and roll, and the other gyro measures yaw and roll. The pitch and yaw gyros and the accelerometers operate

in a strapdown mode (ungimballed) since the gimbal is roll-stabilized. The redundant roll axis is used to stabilize the gimbal, and its output is fed into the inverter board to servo the gimbal. The roll, pitch, and yaw outputs are used to servo the gyros. The torquer current is proportional to the angular rates input to the gyros and is converted to pulses by a reset-integrator type analog-to-frequency converter. The output from the gyros are then pulses whose frequency is proportional to angle increments. The output from the resolver indicates the relative position between the gimbal and the vehicle body and is used with the analog gyro outputs in an analog computer on the resolver board to obtain three orthogonal body rates. The analog accelerometer outputs are also input to the resolver board and combined with the resolver output to obtain three orthogonal body accelerations.

The computational version contains the same IMU and electronics boards except that an accelerometer analog-to-frequency (A/F) converter board is substituted for the resolver board. The A/F converter board yields a pulse output for the accelerometers which is suitable input to the computer input/output (I/O) board. The I/O board accumulates pulses for both the gyro and accelerometer outputs and inputs them into the computer. The computer (SANDAC) is a MC68000-based airborne computer designed by Sandia. It is configured as shown in Figure 4.

III. Drift Prediction Analysis

The gyro outputs in the form of pulses are used to calculate Euler angles for attitude measurement and control. Euler angles are the angles about the roll (x), pitch (y), and yaw (z) axes which relate the position of the vehicle at one time (for example, at launch) to the position of the vehicle at another time (for example, the target) during the flight. These angles are used in a direction cosine matrix, $\underline{C}$ (a square, 3x3 matrix), to relate the coordinates of the vehicle at two different positions during the flight, or

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_T = \underline{C}_L^T \begin{bmatrix} x \\ y \\ z \end{bmatrix}_L$$

where; T = Target and
L = Launch.

The method chosen to calculate the direction cosine matrix is the J. Bortz (1)* method of direction cosine matrix updates in strapdown systems as

$$\underline{C}_L^T (t+\Delta t) = \underline{C}_L^T e^{\underline{\Phi}}$$

where:

$$e^{\underline{\Phi}} = \underline{I} + \frac{\sin\phi}{\phi} \underline{\Phi} + \frac{1-\cos\phi}{\phi^2} \underline{\Phi}^2$$

$\underline{I}$ = 3x3 identity matrix,

$\underline{\phi}$ = orientation vector = $\left[\phi_x, \phi_y, \phi_z\right]^T$,

ϕ = magnitude of the orientation vector

*Numbers in parentheses refer to references at the end of the paper.

$$= \sqrt{\phi_x^2+\phi_y^2+\phi_z^2}\ , \text{ and}$$

$$\underline{\Phi} = \begin{bmatrix} 0 & -\phi_z & \phi_y \\ \phi_z & 0 & -\phi_x \\ -\phi_y & \phi_x & 0 \end{bmatrix}.$$

The orientation vector is found by solving the vector differential equation:

$$\dot{\underline{\phi}} = \underline{\omega} + \frac{1}{2}\,\underline{\phi}x\underline{\omega} + \frac{1}{\phi^2}\left[1 - \frac{\phi\sin\phi}{2(1-\cos\phi)}\right]\,\underline{\phi}x\underline{\phi}x\underline{\omega}$$

where: $\underline{\omega}$ = angular velocity vector = $\left[\omega_x, \omega_y, \omega_z\right]^T$.

The vector differential equation will yield the correct orientation vector if the exact angular velocity vector is available for input. However, to reduce the computation load on the airborne computer and to accommodate the available data which is $\underline{\Delta\Theta}$ (angle increments in the form of pulses), an algorithm which approximates the vector differential equation has been derived (2) as

$$\begin{aligned}\underline{\Delta\phi}\ (M-2 \rightarrow M) = {} & \underline{\Delta\Theta}\ (M) + \underline{\Delta\Theta}\ (M-1) \\ & - 2/3\ \left[\underline{\Delta\Theta}\ (M) \times \underline{\Delta\Theta}\ (M-1)\right] \\ & + 1/2\ \left[\underline{\phi}\ (M-2) \times (\underline{\Delta\Theta}(M) + \underline{\Delta\Theta}\ (M-1))\right]\end{aligned}$$

where: M = value at current gyro sample,

M-1 = value at previous gyro sample,

M-2 = value at two previous gyro samples, and

$\underline{\Delta\Theta}$ = gyro angle increments = $\left[\Delta\Theta_x, \Delta\Theta_y, \Delta\Theta_z\right]^T$.

The value of $\underline{\phi}$ (M-2→M) is

$$\underline{\phi}\ (M\text{-}2\rightarrow M) = \underline{\phi}\ (M) + \underline{\Delta\phi}\ (M\text{-}2\rightarrow M)$$

The $\underline{\Delta\phi}$ values are calculated every other gyro sample for eight gyro samples, and then the value of $\underline{\phi}$ is used to update the direction cosine matrix. The following paragraphs consider drift contributions to the resultant Euler angles due to hardware and software limitations when the previously described calculations are performed in flight.

The first drift determined in the analysis is that which occurs from the use of the algorithm instead of the vector differential equation. This drift was determined by the use of a 20° sin $(2\pi t)$, where t is time in seconds, input to the pitch axis because this allows an analytical expression for ω. The drift is found by the comparison of direction cosine matrices calculated with $\underline{\phi}$ from the two different methods, the vector differential equation and the algorithm. The resulting algorithm drift in the pitch axis is a sinusoid which varies from 0 to -0.13° in magnitude at a frequency of 1 Hz (2π rad/sec).

The second drift determined in the analysis is the drift which occurs from the use of A/F converters. The gyro outputs are quantized by the A/F converters into values of 50 arc-sec/pulse (0.0139 deg./pulse) and 100 arc-sec/pulse (0.0278 deg./pulse) for the two maximum A/F frequencies for Mini-Rims of 4096 Hz and 8192 Hz, respectively. The drift is found by the comparison of two direction cosine matrices

calculated with different $\underline{\phi}$. One $\underline{\phi}$ uses quantized pulse values, and the other $\underline{\phi}$ uses analog $\underline{\Delta\theta}$ values. This quantization drift was calculated for a trajectory shown in Figures 5-7. A roll angle input is not shown because the gimbal is roll-stabilized. The resulting drift for the three axes is shown in Figures 8-10 for 50 arc-sec/pulse quantization and Figures 11-13 for 100 arc-sec/pulse quantization. Because of the irregular variation in the drifts, it is not possible to determine a drift rate (a constant slope) for any of these calculations. However, it is apparent that the drift variation is somewhat less for the 50 arc-sec/pulse quantization.

The third drift determined in the analysis is that from the random drift in the gyros. The gyro drift for one axis is assumed to be exponentially correlated from one sample to the next (3) as

$$R_g(j,k) = \sigma^2 \exp -(\beta T |j-k|)$$

where: $R_g(j,k)$ = expected error between samples j and k from one axis,

σ^2 = variance of gyro drift (deg./hr.),

β = inverse of the correlation time $\left(\text{sec}^{-1}\right)$,

T = time between gyro samples (sec.) and

j,k = gyro samples (0,1,2...).

The drift between two separate axes is assumed uncorrelated (zero). If the drift model for a gyro output from the x-axis is $\Delta\Theta_x + \varepsilon_{gx}$, where ε_{gx} is the random gyro drift (and likewise for the other three axes), then the expected drift in $\underline{\phi}$, $\underline{\varepsilon}_{\phi}$, may be calculated. A drift for each axis and each of the gyro samples over an eight gyro sample sequence must be substituted into the four equations in the $\underline{\phi}$ calculations for a direction cosine matrix update. In this way, the effect of a random gyro drift rate is traced through a calculation sequence. The result is a drift, $\underline{\varepsilon}_{\phi}$, which is a function of the random gyro drift, $\underline{\varepsilon}_g$, and an eight gyro sample sequence, or

$$\underline{\varepsilon}_{\phi}^2 = \sigma^2 \, \underline{G} \, \underline{A} \, \underline{G}^T$$

where: $\underline{G}$ = a 3 x 24 matrix derived from the eight $\underline{\phi}$ equations, and

$\underline{A}$ = a 24 x 24 matrix derived from the eight $\underline{\varepsilon}_g$ substituted into the eight $\underline{\phi}$ equations.

The resulting drifts in the roll, pitch, and yaw Euler angles which result from the input trajectory of Figures 5-7 with an A/F quantization of 50 arc-sec/pulse are shown in Figures 14-17. A random gyro drift of 1°/hr. was assumed and the data is sampled at 100 Hz (0.01 sec. gyro sample interval or 0.08 sec. direction cosine matrix update interval).

A spectral analysis has been performed on the results shown in Figures 14-16. The only significant frequency content is at 1 Hz. This is the frequency of oscillation in the pitch and yaw axes which occurs over the first 20 seconds of flight.

IV. Conclusions and Future Work

The algorithm drift as compared to the quantization and random gyro drifts is relatively insignificant. The quantization drift can be minimized with the use of 8192 Hz for the maximum A/F frequency. This requirement can be implemented with minimal hardware and software impact. The largest drift results from the random gyro drift. Although this drift will be minimized in most cases because of the short duration of flights, it will be the largest source of drift.

The effects of acceleration (g) sensitive drift and g^2 gyro drift have not been analyzed. Other flight trajectories may have significant g and g^2 inputs so that these drifts must be considered. A model for these gyro drifts is to be implemented and analyzed over more severe trajectories.

The availability of on-board computational capability associated with inertial mesurement systems affords the potential for increased accuracy, simplicity, and reliability in flight vehicle attitude measurement and control systems. When this capability is implemented, however, an assessment of hardware and software parameters which influence its performance must be made.

References

1. J. E. Bortz, "A New Mathematical Formulation for Strapdown Inertial Navigation," IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-7, No. 1 (January 1971), pp. 61-66.

2. Watts, A. C. and R. D. Andreas, "A Single Gimbal/Strapdown Inertial Navigation System for Use on Spin Stabilized Flight Test Vehicles," IEEE Paper No. CH1597-A/80 /0000-0250 (1980).

3. Gelb, Arthur, et. al., Applied Optimal Estimation, M.I.T. Press (1974), p. 81.

CHARACTERISTIC	MARS	MINI-RIMS (NON-COMPUTATIONAL)	MINI-RIMS (COMPU-TATIONAL)
VOLUME	162 $IN.^3$	218 $IN.^3$	341 $IN.^3$
WEIGHT	8.5 LBS.	11 LBS.	17.5 LBS.
DRIFT	20-30 DEG./HR.	2-3 DEG./HR.	2-3 DEG./ HR.
POWER	32 WATTS	45 WATTS	75 WATTS
OUTPUTS:			
BODY ANGLES	YES	YES	YES
BODY RATES	NO *	YES	YES
BODY ACCELERATIONS	NO *	YES	YES
EULER ANGLES	NO	NO	YES
ATTITUDE CONTROL AND TIMING FUNCTIONS	NO *	NO	YES

*These three functions may be added to MARS with separate components (100 cu. in. and 4.5 lbs.) for a total of 262 cu. in. and 13 lbs. (exclusive of cabling and interconnections).

Figure 1: A Comparison of MARS and Mini-Rims Characteristics.

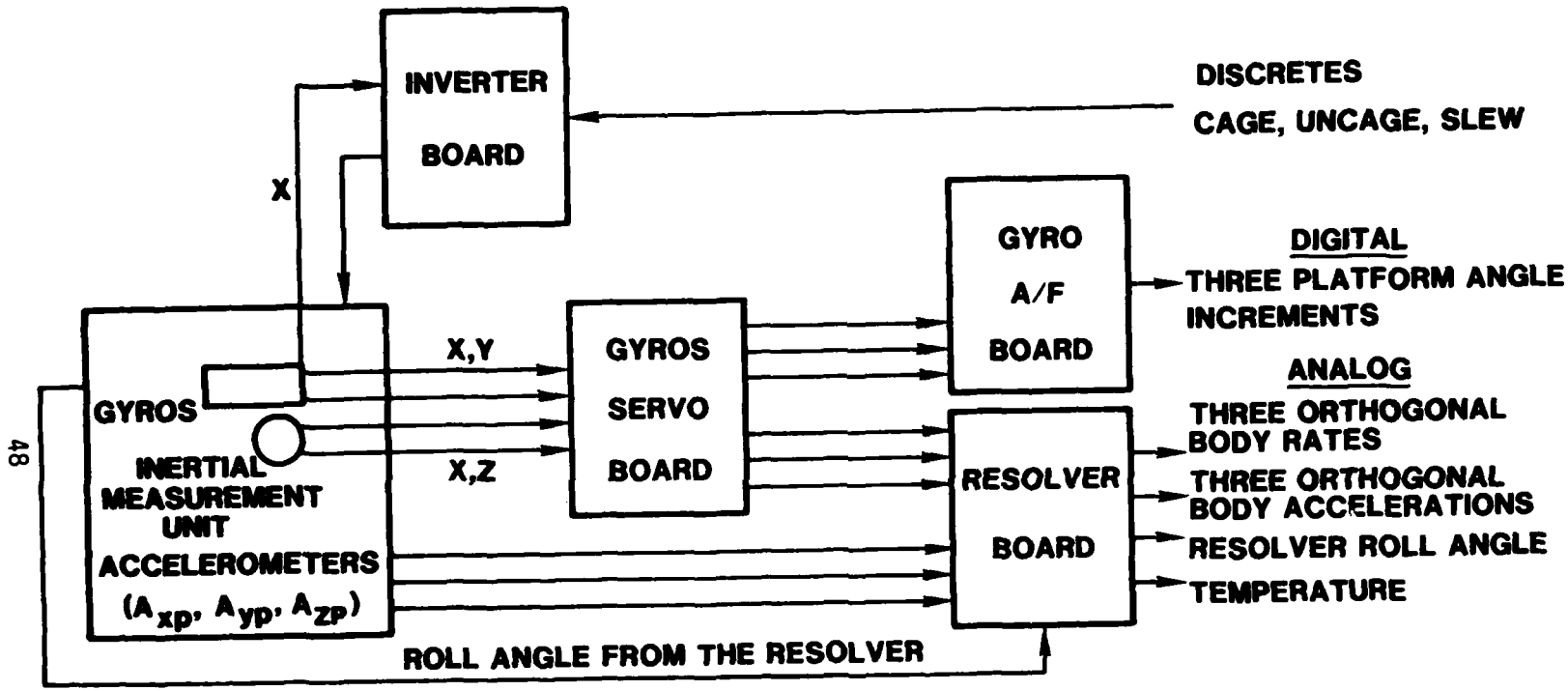

Figure 2. Block Diagram for Mini-Rims Non-Computational Version.

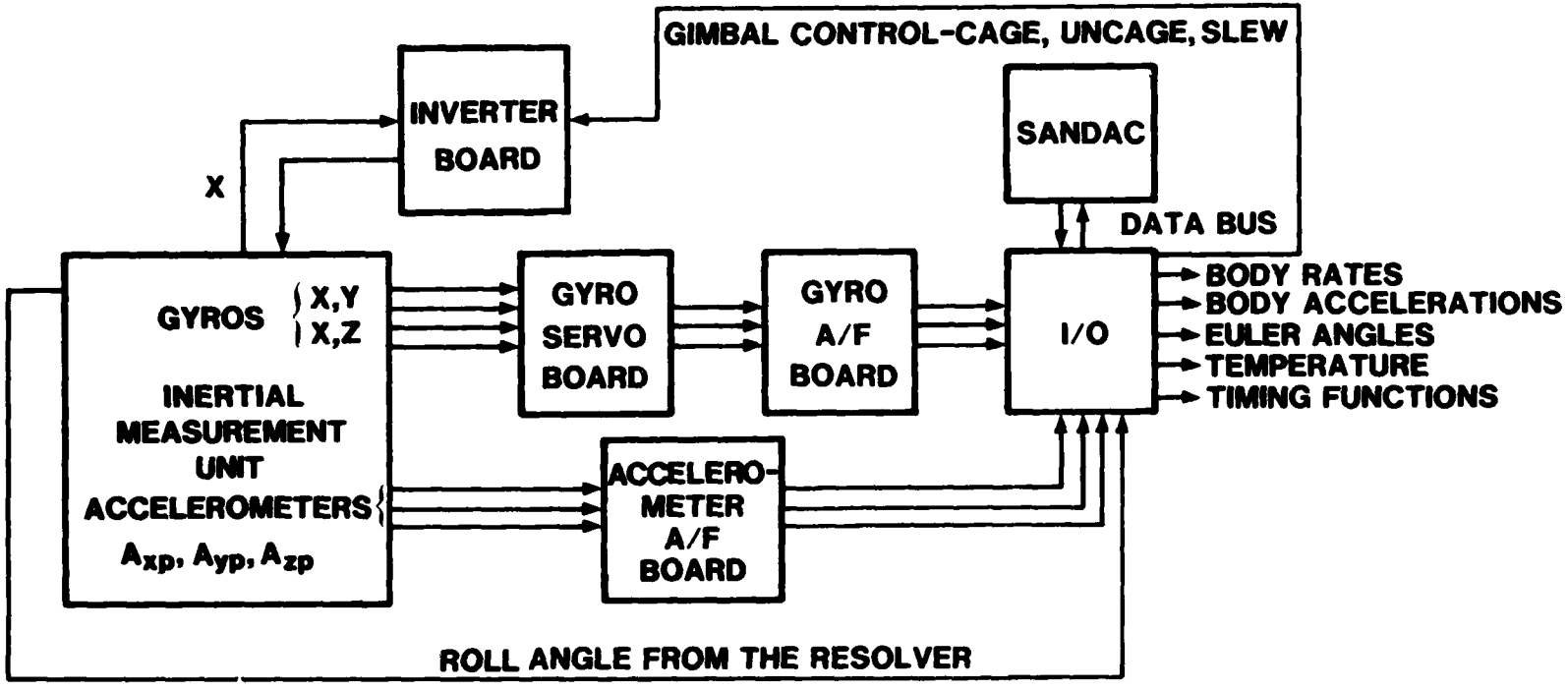

Figure 3: Block Diagram for Mini-Rims Computational Version.

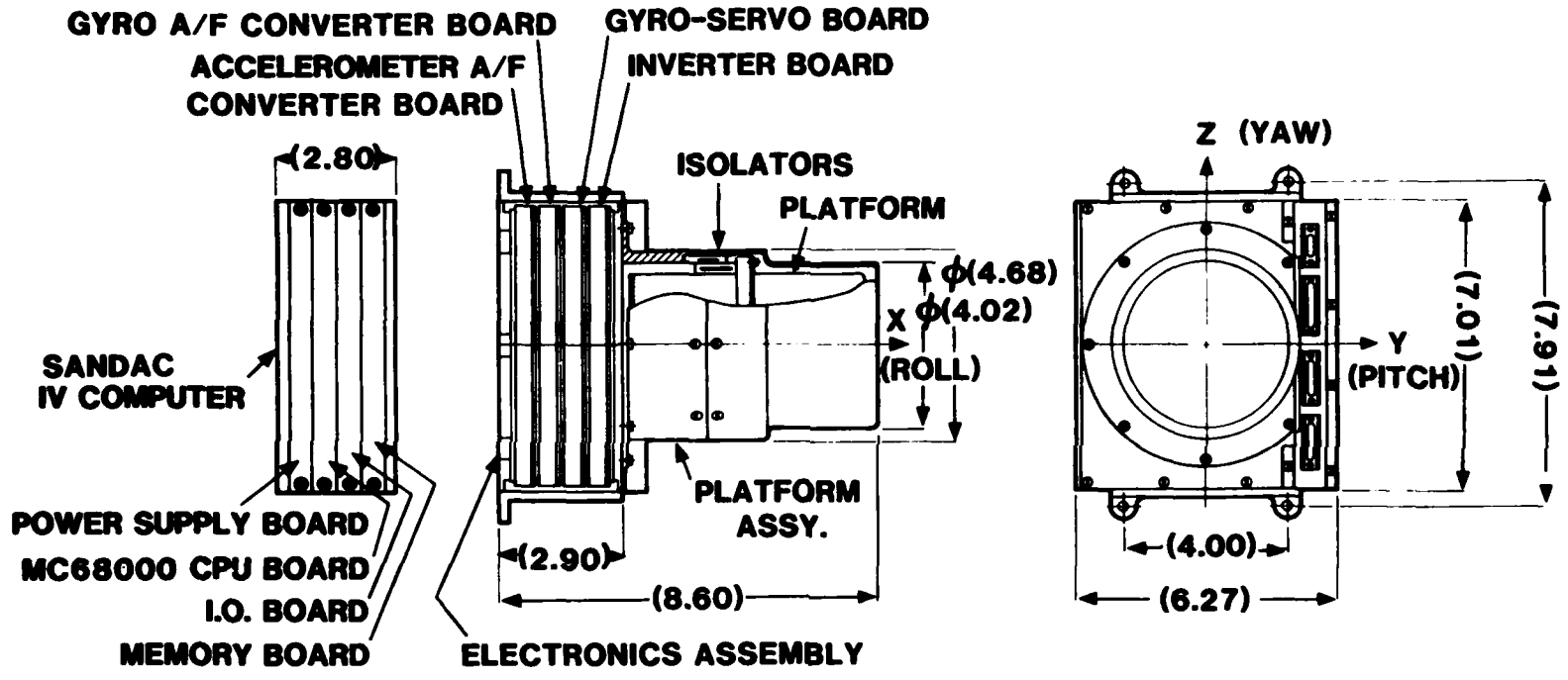

FIGURE 4. MINI-RIMS COMPUTATIONAL VERSION SCHEMATIC

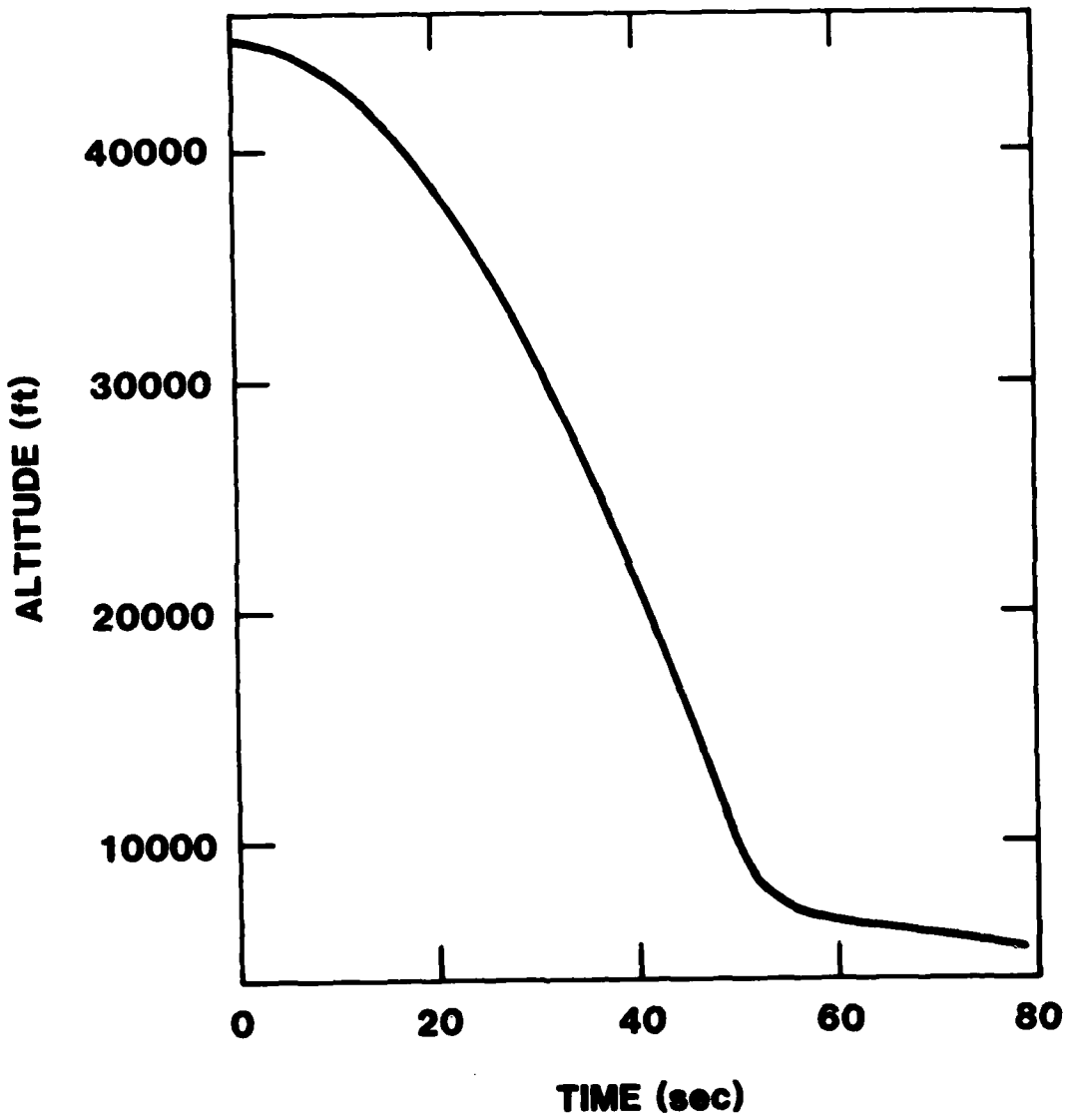

Figure 5. A Typical Bomb Altitude-Time History.

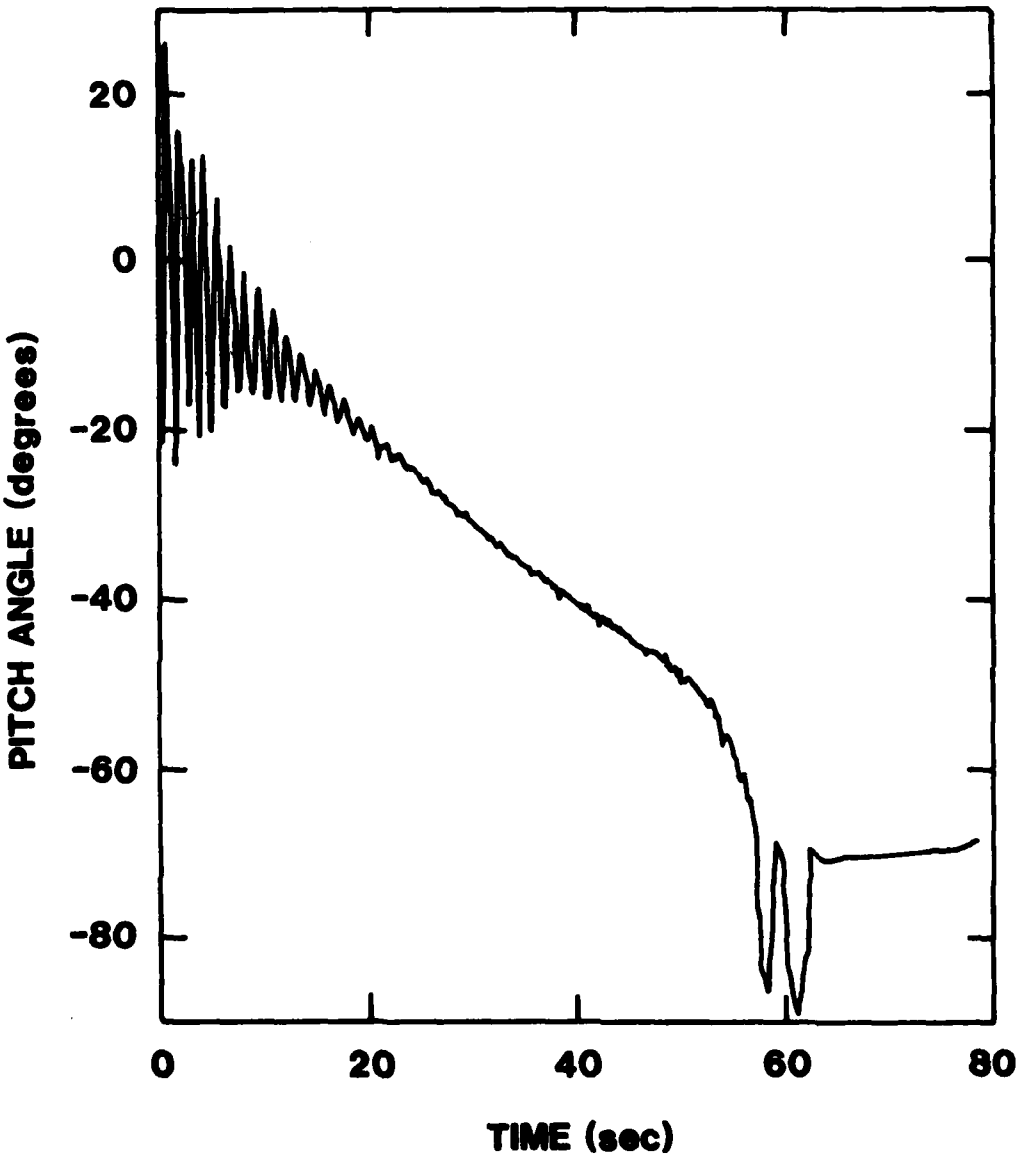

Figure 6. A Typical Bomb Pitch Angle-Time History.

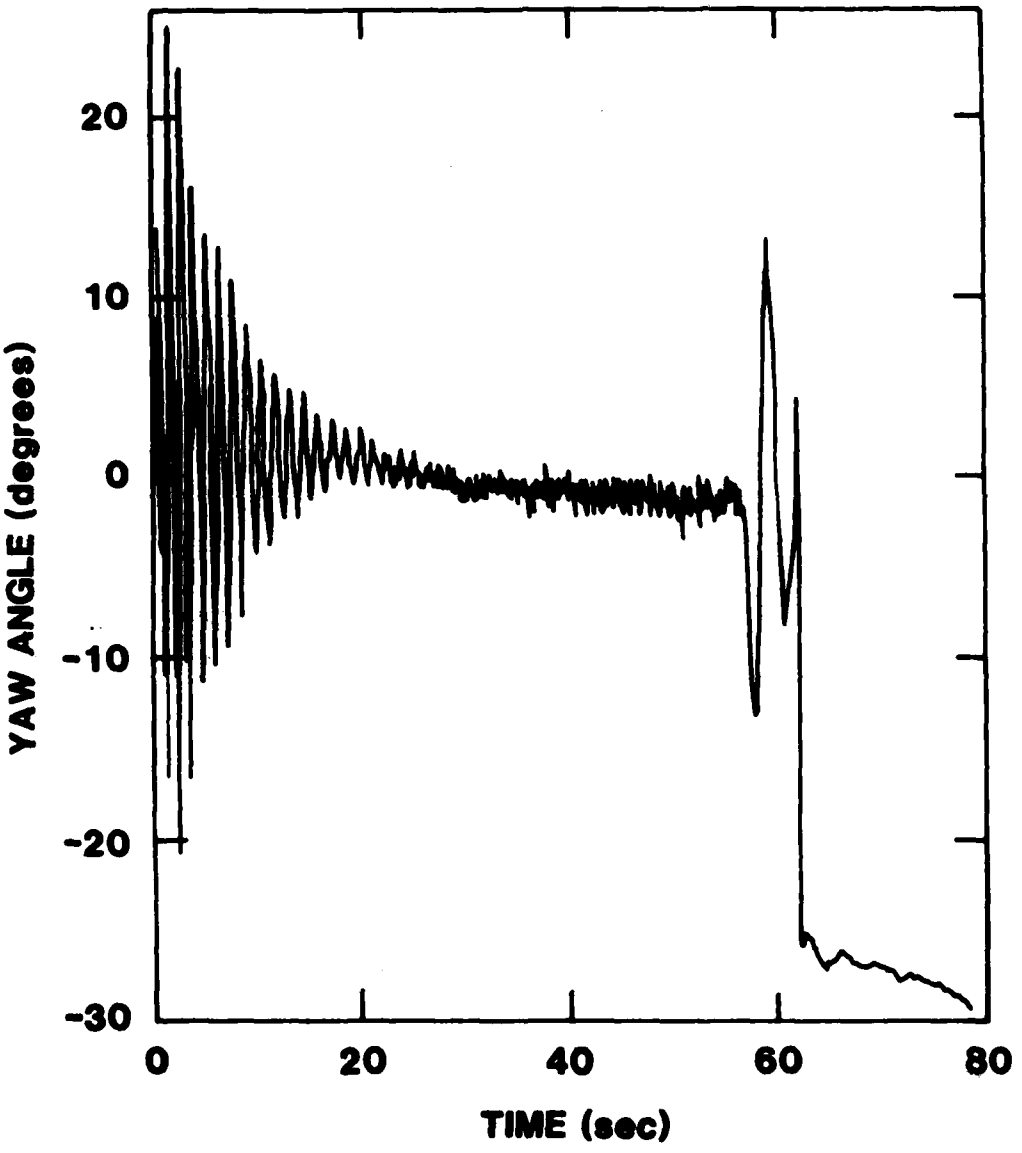

Figure 7. A Typical Bomb Yaw Angle-Time History.

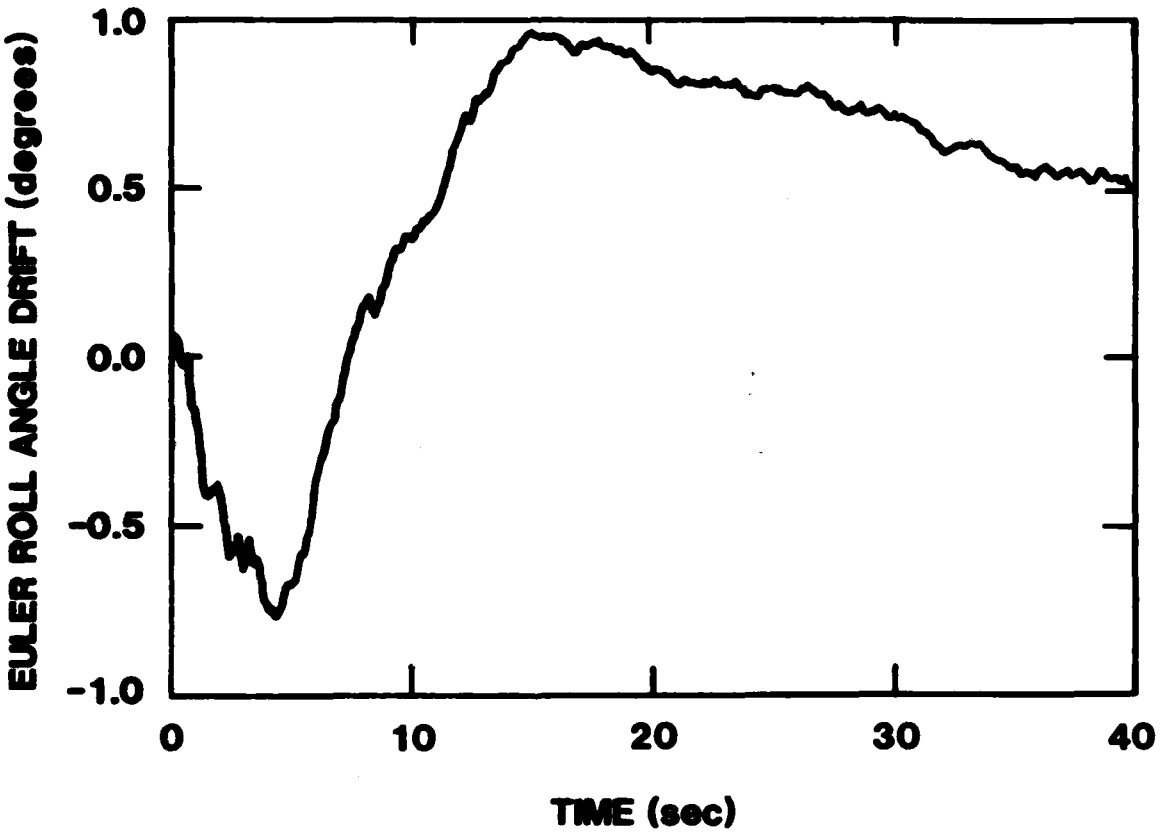

Figure 8. Euler Roll Angle Drift for a Typical Bomb Trajectory with 50 arc-sec/pulse Quantization.

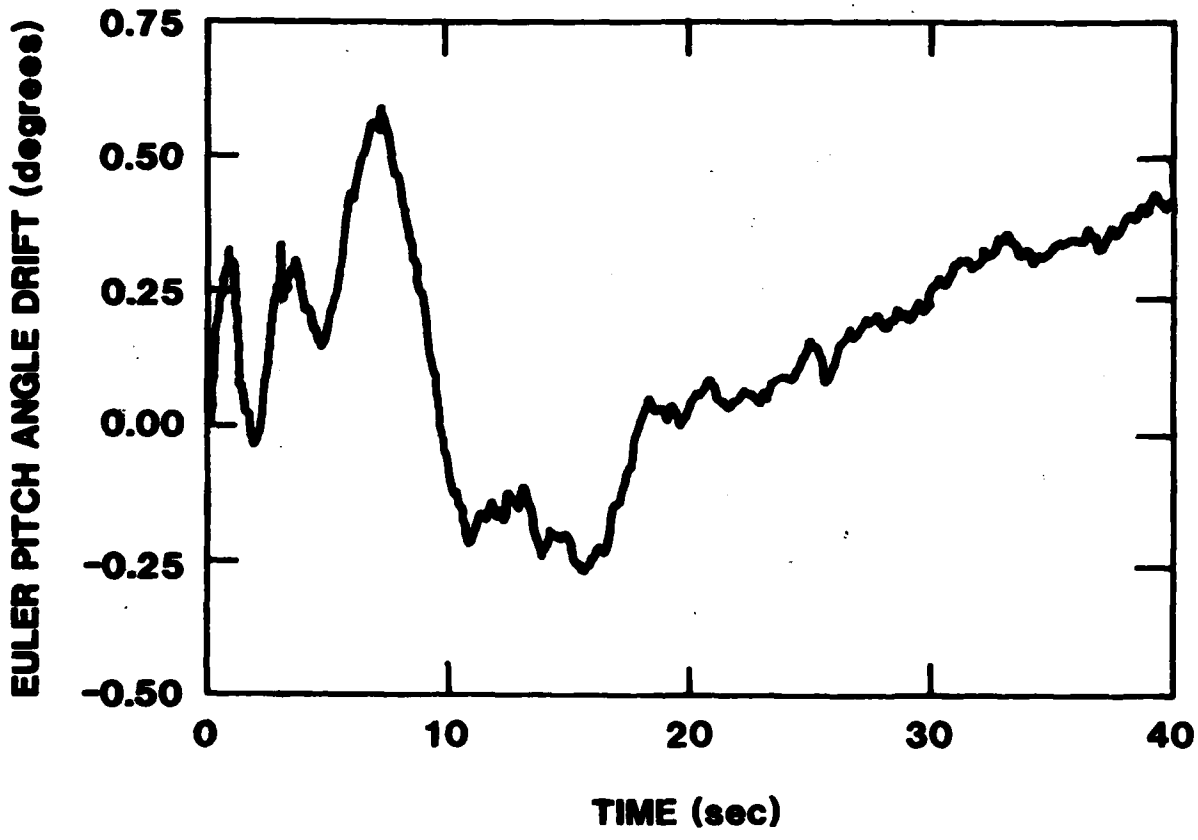

Figure 9. Euler Pitch Angle Drift for a Typical Bomb Trajectory with 50 arc-sec/pulse Quantization.

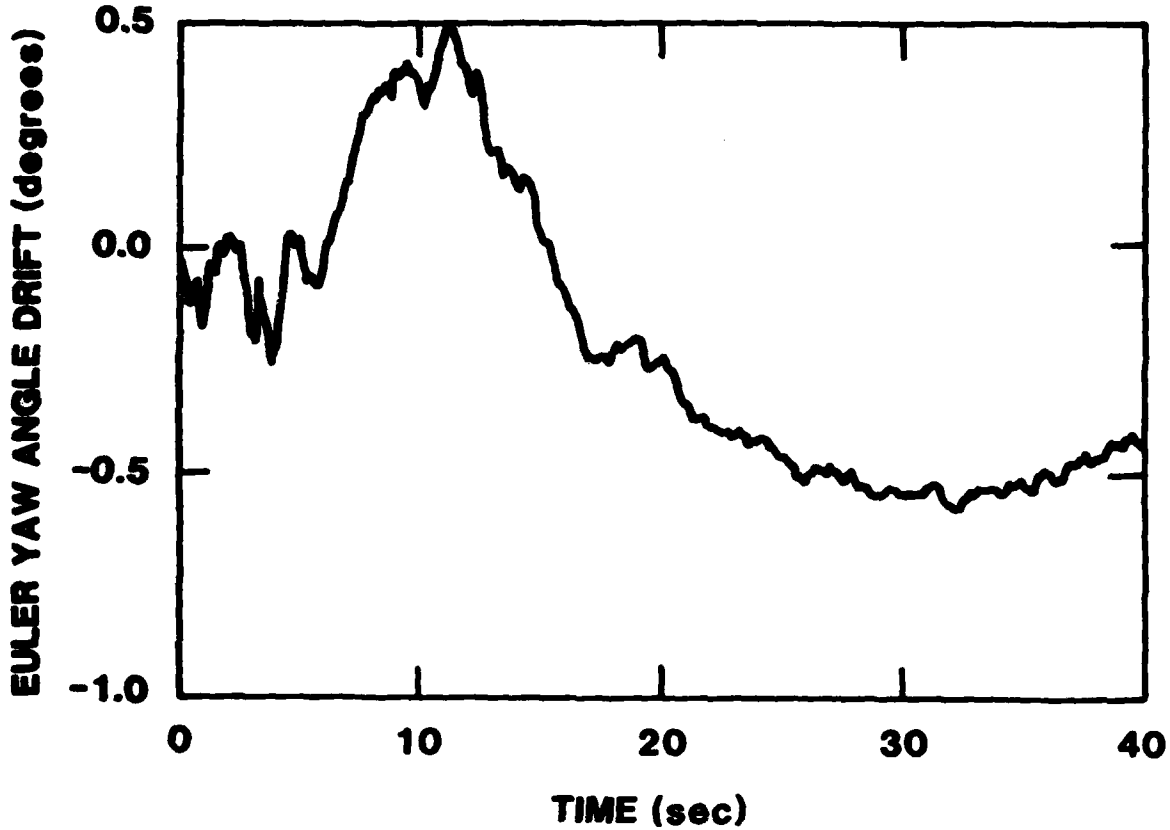

Figure 10. Euler Yaw Angle Drift for a Typical Bomb Trajectory with 50 arc-sec/pulse Quantization.

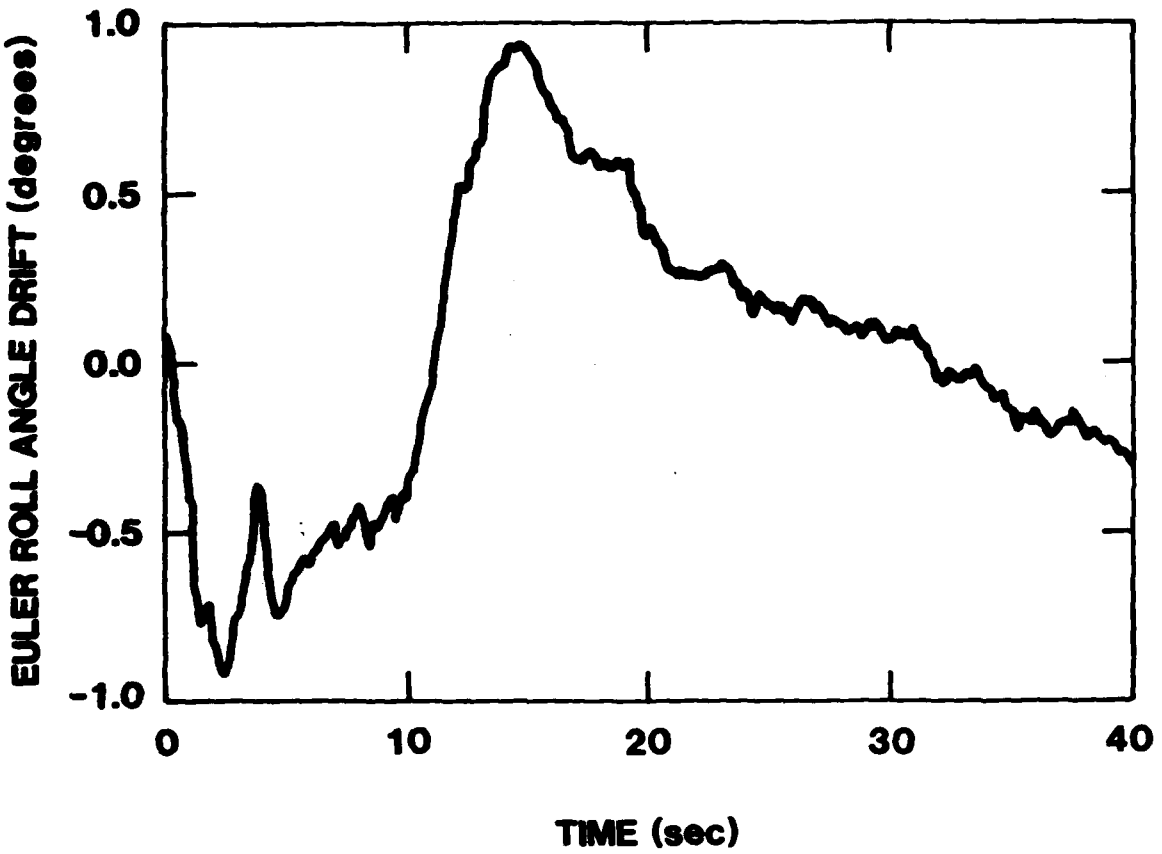

Figure 11. Euler Roll Angle Drift for a Typical Bomb Trajectory with 100 arc-sec/pulse Quantization.

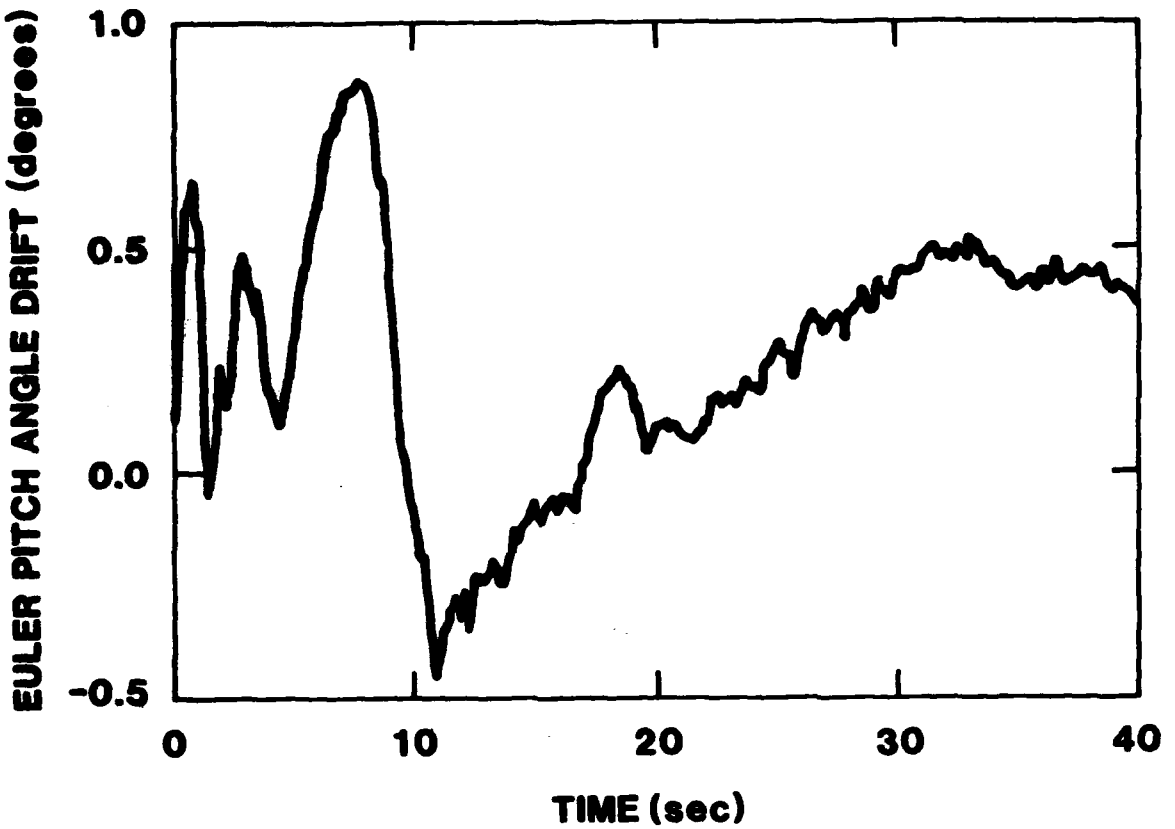

Figure 12. Euler Pitch Angle Drift for a Typical Bomb Trajectory with 100 arc-sec/pulse Quantization.

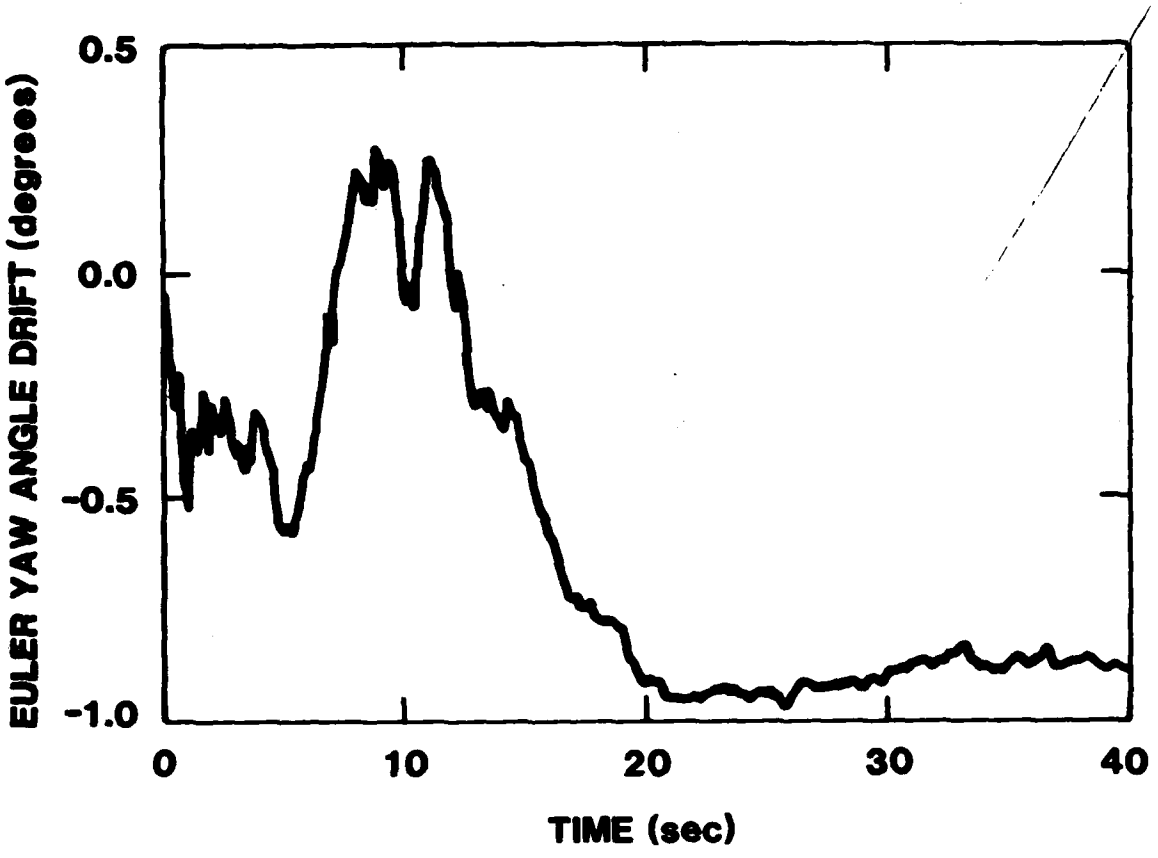

Figure 13. Euler Yaw Angle Drift for a Typical Bomb Trajectory with 100 arc-sec/pulse Quantization.

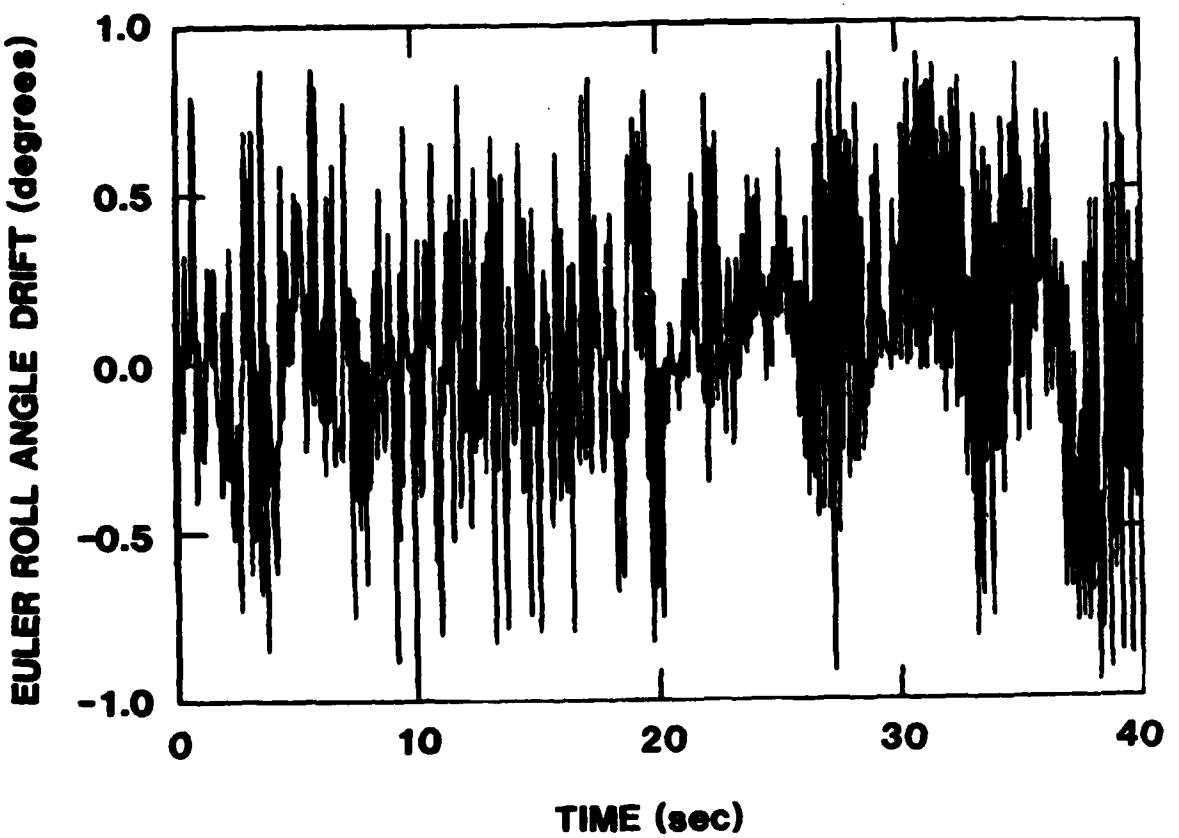

Figure 14. Euler Roll Angle Drift for a Typical Bomb Trajectory with 1 deg/hr. Random Gyro Drift and 50 arc-sec/pulse Quantization.

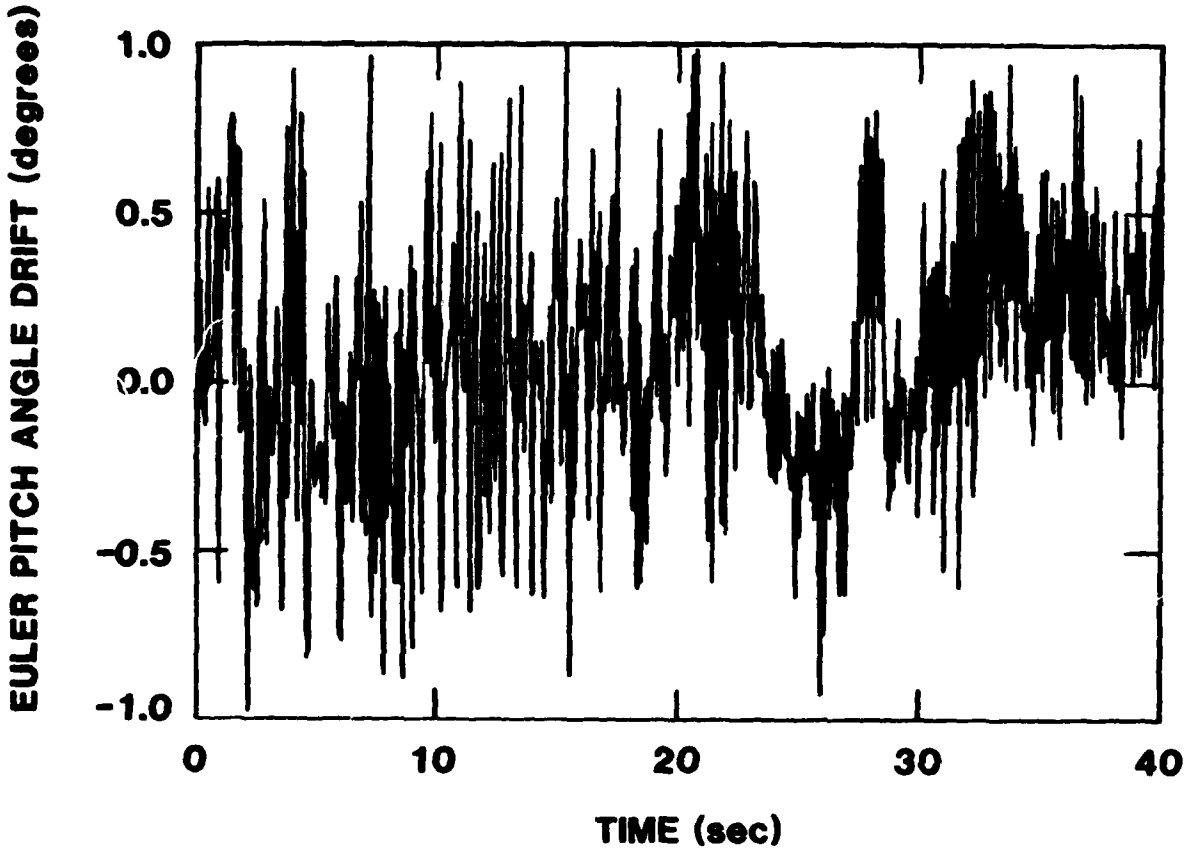

Figure 15. Euler Pitch Angle Drift for a Typical Bomb Trajectory with 1 deg/hr. Random Gyro Drift and 50 arc-sec/pulse Quantization.

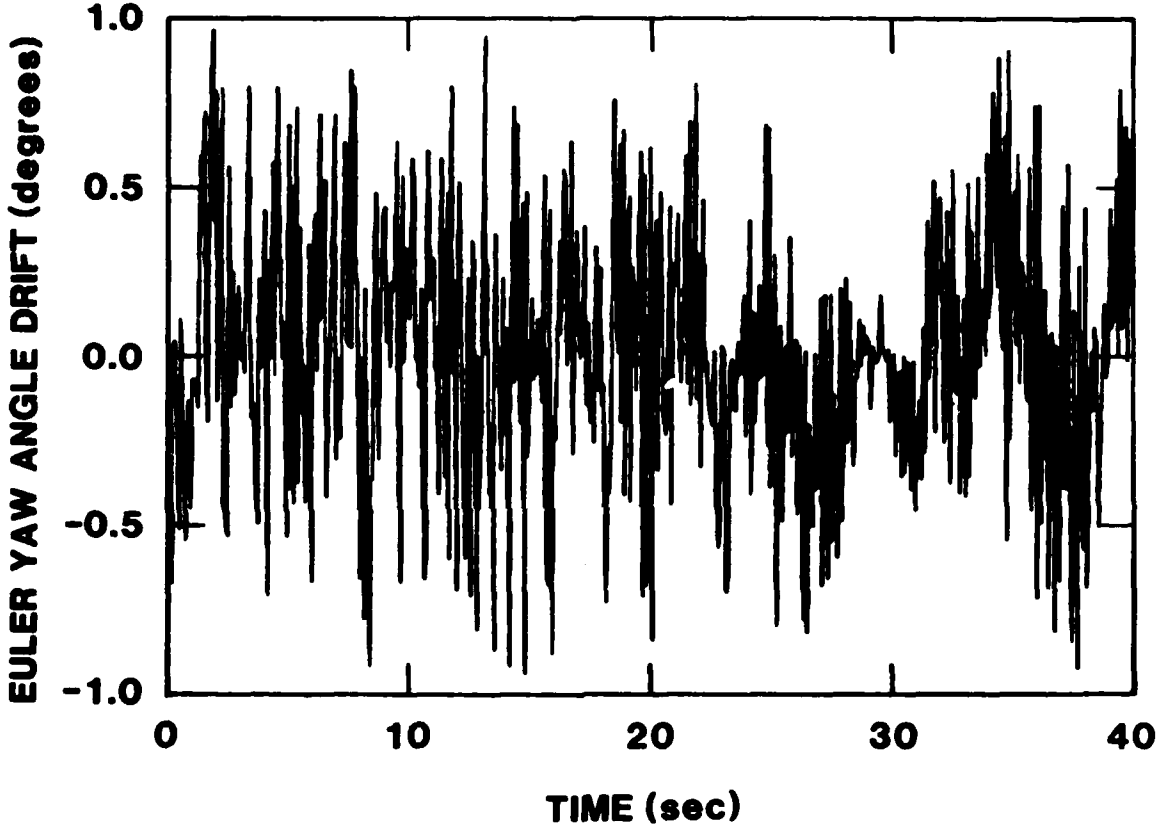

Figure 16. Euler Yaw Angle Drift for a Typical Bomb Trajectory with 1 deg/hr. Random Gyro Drift and 50 arc-sec./pulse Quantization.

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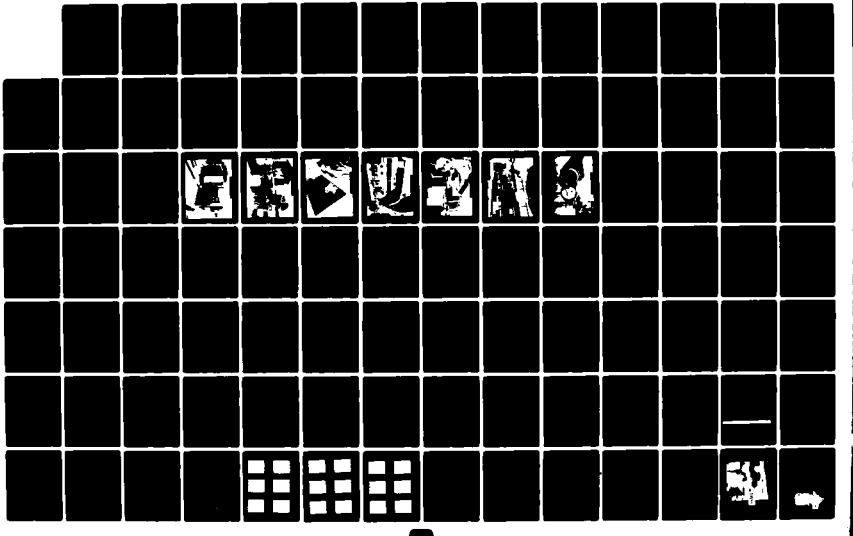

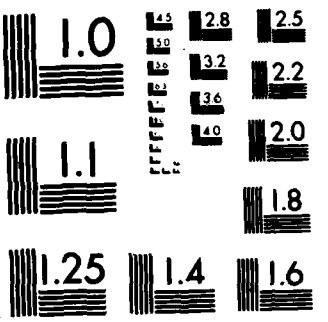

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Twelfth Transducer Workshop
June 1983, Melbourne, Florida

PERFORMANCE EVALUATION OF SENSORS

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ABSTRACT

This paper discusses the basic principles of sensor performance evaluation necessary to assure meaningful measurements with the sensor. The subject is divided into the four major areas of: static calibration, dynamic calibration, investigation of environmental effects, and investigation of durability. Each of the areas is discussed in sufficient detail to be of benefit to the measurement engineer. A selected bibliography is included.

INTRODUCTION

There are ever-increasing demands for all types of sensors, and more is being demanded of sensors, as a result of the rapid spread of microelectronics into new products and industries. At the same time advances in technology are making new types of sensors available.

There is ample evidence ("horror stories") that the sensor may be the weakest link of the chain which makes up the industrial or military measurement or control system. This weakness is due to limited sensor performance or limited knowledge of that performance.

The increasing dependence on sensors as part of complex electronic systems can have a serious impact on those decisions which are based on the data obtained from such sensors. Ranging from automatic test systems for military aircraft and ships, to patient-monitoring in hospitals,to process control in industry, vitally important decisions may hinge on the outputs from these deceptively simple and inexpensive components: the sensors.

Clearly, sensors deserve more attention than they have been getting and these workshops represent a timely effort to achieve this. It has been the author's experience during his three decades of work with sensors that sensor performance evaluation is a neglected field. In view of the great impact which sensor performance has on system performance, it seems appropriate to discuss the subject in more detail.

SENSOR PERFORMANCE CONSIDERATIONS

To put it simply: sensor performance is the measure of the sensor's ability to carry out its measurement functions within specified limits of error over a specified period of time. This concept involves prediction of the future performance of the sensor. Absolute knowledge of the future cannot exist, of course, except in the minds of upper management. However, it is often possible to infer likely performance (within certain bounds) from past and current sensor evaluation tests.

Sensor performance evaluation can be complex and time-consuming. It requires sophisticated calibration and test equipment, and skilled personnel: it can be expensive and therefore requires a strong commitment by management. Justification for the expense involved must be related to the cost of the entire process or system whose operation depends on the proper performance of the particular sensor. As an example, the operational capability of the space shuttle depends critically on the fuel-oxidizer mixture ratio in its main propulsion system. If the correct value of this ratio depends on measurements performed by two pressure sensors, then clearly the cost of the evaluation of the sensors to assure proper performance cannot (and should not) be compared only to the original purchase price of the sensors.

Performance evaluation for sensors can be classified into four major areas:

1. Static calibration: this is the measurement base - the foundation which is used to establish the laboratory performance characteristics of the device and to which all other evaluations are referred. These characteristics include such parameters as sensitivity, zero output, linearity, hysteresis, repeatability, resolution, creep, and dead band. Static calibration procedures for many sensors have been published and incorporated

in standards documents, and, although gaps exist in some areas, the general field of static calibration for sensors is covered reasonably well.

2. Dynamic calibration: a frequently neglected area, but necessary because no sensor is exposed to totally steady-state inputs. All physical quantities are dynamic (although certain phenomena can be considered "quasi-static"). It is necessary not only to know the amplitude of the measurand (the physical quantity to be measured) at a given time, but how it is changing at that time, since such changes may require rapid corrective action.

If the sensor is to be used to measure (or follow) such dynamic changes, the dynamic characteristics of the device must be known. Calibrations to establish the dynamic characteristics such as amplitude response, phase response, resonant frequency, and damping are less well developed than static calibrations. Those dynamic calibrations that are available tend to cover relatively narrow amplitude- and frequency-ranges and may have other restrictions.

3. Investigation of environmental effects. The environment in which the sensor operates may have significant effects on its measurement performance. Tests are needed to determine such effects since the majority of sensors do not operate in a benign environment. They are subjected to a variety of harsh environmental conditions which can greatly influence their performance.

Such environments affect sensors in two major ways. Measurement performance is adversely affected while the sensor is subjected to the specific environment. Such changes in performance are usually reversible and disappear when the particular environment no longer acts on the sensor. An example is extremes in temperature which can change sensitivity. However, the action of the environment of the sensor may also result in an irreversible, and thus permanent, change in performance such as a zero shift. It is essential to be aware of both types of effects to adequately assess sensor performance.

4. Investigation of durability. This represents attempts to predict future performance: how long will the sensor perform in the way it is supposed to perform? Tests are needed to assess sensor durability.

In some aerospace and defense applications, sensors are expected to perform properly and reliably over short periods of time, from minutes to hours. In industrial applications and defense ATE applications, on the other hand, the periods of time over which these devices are expected to operate may range from days to years.

When extended-time operation is considered, durability (stability) and reliability are particularly important factors. The reliability of many devices can be computed from knowledge of component failure rates. This information has been applied to critical aerospace applications and expressed as mean-time-between-failures. This concept of reliability, however, is usually concerned with the total failure of the device, but does not address the deterioration of the sensor performance. The sensor's lack of stability or durability has received relatively little attention, but is of vital importance in the case of military and industrial measurement and control systems.

QUALIFICATION TESTING AND ACCEPTANCE TESTING

A practical approach to performance evaluation of sensors divides the testing into two major classes: Qualification Testing and Acceptance Testing. This is a logical arrangement to reduce the testing effort required.

(A) Qualification Testing

The purpose of qualification tests is to establish the suitability of a type or class of sensor for a particular application. Sensors for use in military applications are almost always required to be qualified according to prescribed military standards.

Qualification tests are intended to thoroughly explore all those characteristics of the sensor which might have a bearing on the sensor's proper performance of its measurement function. Qualification tests are usually performed on a selected sampling of the type or group which they are intended to represent. Once such type or group of sensors has been "qualified"; individual devices must still undergo acceptance tests, which are discussed below. In addition, depending on the number of sensors being procured, it may still be desirable to subject new samples periodically to complete qualification tests to assure that quality has not deteriorated since the first samples were qualified.

Qualification testing is exhaustive, complicated, extensive, and expensive. Not all laboratories are equipped to carry out such a qualification test program. Sophisticated test methods are used (and sometimes new ones must be developed if existing ones are inadequate). Qualification testing by its nature requires expertise, since it involves not only static and dynamic calibrations, environmental tests, durability and reliability investigations, but also proper interpretation of test results.

Qualification testing includes procedures which are covered under Static Calibration, Dynamic Calibration, Operating Environment, and Durability and Reliability. However, there are some test procedures which do not really fall within any of these sections and these are briefly discussed.

(1) Visual examination

The first step of any qualification test procedure is a thorough visual examination of the sensor. Check for defects in workmanship: loose parts and connections missing screws, damaged surfaces, improper fit with mating connectors, missing labels, etc. If sensor dimensions are critical, such as for proper fit into a tight location, they must be verified.

(2) Mechanical inspection

The next step is a check of the mechanical aspects of the sensor. For example, in the case of a pressure sensor, check for absence of leaks or, in the case of a turbine flowmeter, verify the freeness of rotation of the wheel. Other checks include flatness of mounting surfaces for accelerometers, and fit of screws for mounting.

(3) Tests for effects of excitation variations

Most sensors exhibit changes in sensitivity and zero-measurand output when operated at excitation values other than the nominal values recommended by the manufacturer.

(4) Tests to establish "warm-up" effects

Sensitivity and zero-output of a sensor may change somewhat from the time the sensor is connected to the excitation source until complete internal thermal equilibrium is reached. For this reason, a stabilization period of about 45 minutes is considered good practice before static calibrations and other tests. Under certain conditions of use, however, a sensor may be expected to perform measurements shortly after being energized, and it is necessary to evaluate the performance under such conditions.

(5) Test for contact noise for potentiometer sensors

Contact noise is the result of the variations of contact resistance at the sliding contact of the potentiometer element. The importance of this characteristics depends on the current level, the magnitude of the change in contact resistance, the nominal resistance of the winding, and the resistance of the load circuit. The higher the load impedance, the less will be the effect of a given contact resistance change.

(6) Tests for effects of mounting force or torque

Devices such as pressure sensors, particularly flush-diaphragm instruments, may exhibit changes in sensitivity and zero-pressure output as a result of case deformation in mounting when they are mounted in fixtures. Sensors with integral pressure fittings for tubing are not normally subject to this effect.

(7) Proof or overload tests

Proof or overload tests are part of the qualification procedures. They are used to verify the integrity of the sensing element (or sensor case, depending on the device) to measurand amplitudes well above the rated range. In the case of pressure sensors, such a test is designed to assure that no safety hazard exists when the pressure exceeds the rated value. This test is usually referred to as a proof test, a term used for such tests of ordnance items.

(8) Tests for effects of position

Some sensors may be position sensitive, that is, their output may be influenced by gravity acting along a particular axis of the device. An example is the turbine flowmeter which can show different amounts of bearing friction depending on its orientation. Low range acceleration sensors and low range pressure sensors may be position sensitive.

(B) Acceptance Testing

Even when a sensor type has been "qualified," it is still necessary to assure the proper performance of each individual sensor. This is done with an acceptance test, sometimes referred to as "Individual Acceptance Test" (IAT).

Acceptance tests, in contrast to the qualification tests discussed above, are kept as brief as practicable, since often large numbers of sensors must undergo these tests. The tests are used to establish function (i.e., proper signal output, no internal shorts), and static calibration parameters like sensitivity, linearity, hysteresis, and repeatability. If the application is a critical one, additional tests from the qualification sequence may also be

performed. Subjecting specified samples to additional tests is another option.

Generally speaking, the acceptance test is also an integral part of any qualification test program. The main component of the acceptance tests is the static (base or reference) calibration.

While it is quite beyond the scope of this paper to present a detailed discussion of sensor performance evaluation and apparatus, some of the more important considerations are discussed below. Additional details can be found in the publications listed in the bibliography.

Static calibration considerations

Static calibrations of sensors at laboratory ambient conditions constitute the fundamental calibrations to which all further tests are referenced. The static performance characteristics are established from the results of these static calibrations. This approach is used for all types of sensors, except those which inherently cannot respond to zero frequency (steady-state) stimuli. Piezoelectric sensors fall into this category and their characteristics must be evaluated with the aid of dynamic calibrations, which will be discussed later.

The high cost of acquiring calibration equipment, and the high labor cost for the skilled personnel necessary to operate it, make it imperative that the static calibration procedure adopted is the most efficient and practicable one. The procedure must be one which produces the greatest amount of useful information about the sensor with a minimum expenditure of calibration-and data analysis-time.

Among the important factors to consider are the number of calibration points and the number of calibration cycles to be performed. More of each will yield more information, but will increase time and cost of calibrations. Experience has shown that it is reasonable to assume that the overwhelming majority of sensors are designed to be inherently linear devices, i.e., the electrical output-measurant input relation is essentially linear over the entire operation (calibration) range of the sensor.

A calibration sequence commonly used involves eleven points with equal intervals between them. Each interval corresponds to 20 percent of the full-scale range for a unidirectional sensor (0% to +100% FSR). The eleven calibration points of a single calibration for this sensor are attained by a sequence which starts with zero measurand, then increases input in steps of 20 percent of full scale to 100 percent FS (full scale) and retraces the points until zero measurand is reached. For bidirectional sensors (-100% FSR to 0% to +100% FSR), and some full-scale ranges of unidirectional sensors, it may not be feasible to calibrate at cardinal 20 percent FS points or to manage an eleven-point calibration; it may be necessary to use additional points. Nevertheless, the eleven-point static calibration of a unidirectional sensor will probably be the most commonly encountered basic calibration situation.

It is necessary to perform more than one static calibration on a sensor in order to be able to predict anything about the future performance characteristics of the device. "Repeatability" is the term used to describe the short-term variations in parameters with time; "stability" refers generally to long-term changes over periods of months or years. The basic parameters of interest are the slope of the best straight line through the calibration points: the sensitivity; the intercept of this line on the output axis, the linearity

(frequently given as the largest deviation from the best straight line), and the hysteresis: the maximum deviation in output readings at the same value of measurand.

The basic equipment necessary for the static calibration of a sensor consists of the measurand, a source of electrical excitation for passive sensors, and the device which measures the electrical output of the sensor. The combined errors or uncertainties of the entire calibration system should be sufficiently smaller than the anticipated tolerance of the performance parameter under investigation to result in meaningful values. Conservative practice in a calibration hierarchy specifies a tenfold quality ratio, i.e., use of a "0.1 percent" pressure gage to calibrate a "1.0 percent" pressure sensor. This approach may be unrealistic in the case of the better and more "accurate" sensors coming into the market. A three-to-one ratio represents a reasonable approach in view of the customary root-sum-square combination of uncertainties.

Measuring instruments should be checked against standards periodically, and traceability to the National Standards must be provided for. Environmental conditions during the static calibration must be constant (laboratory ambient for baseline calibrations), and specified, to permit possible corrections to the data from the calibrations.

The source of the measurand should be continuously variable over at least the full-scale range of the sensor. Alternately, the measurand may be provided in discrete levels as long as the transition from one level to the next during calibration is accomplished without creating a hysteresis error due to measurand overshoot.

Dynamic calibration considerations

Sensors are almost always required to measure physical quantities which vary with time. A purely static measurement is a rarity; furthermore, certain types of sensors, such as piezoelectric devices, have no static (zero frequency) response at all. For these devices, and to correctly evaluate the performance of sensors which measure time-varying measurands, dynamic calibrations are required.

As in the case of static calibrations, one must apply a measurand with accurately known characteristics and measure the resulting sensor output with comparable accuracy. It is generally difficult to generate measurands with accurately known (or well controlled) dynamic characteristics. Consequently, dynamic calibration procedures are less well developed than static calibrations. Also dynamic calibration procedures are not available for certain amplitude and frequency ranges of some measurands.

One approach to dynamic calibration (and sometimes to static calibration) of sensors is the use of a "reference" sensor mounted close to the sensor to be calibrated and subjected to the same measurand. This procedure has merit only if one has a stable, dependable reference sensor with well-known characteristics. Even under such circumstances, it is highly desirable to be able to verify the dynamic performance of this sensor periodically. Also, the concept of both sensors being subjected to exactly the same measurand becomes less tenable when measurands have high amplitudes or high frequencies. Ultimately then, to assure adequate knowledge of the dynamic characteristics of any sensor, it is necessary to subject it to some form of dynamic calibration.

The sensor's dynamic properties or characteristics of interest to a user will depend to a large extent on the application involved. This section defines and discusses some of the properties most often required. These properties sometimes can be described in terms of the "transient" response of the device to a step input, or in terms of its "steady-state" response to sine wave excitation, or both.

In defining sensor properties related to dynamic response, the transfer function of the sensor provides valuable information. The transfer function is the ratio of output to input (expressed in the frequency domain), and forms the basis for the frequency response parameters. Once the transfer function is known, the input vs time for any output can also be calculated. These topics have been treated by those working in the fields of servo mechanisms and network theory, where it is often necessary to describe system behavior in both transient and steady-state terms. This approach, using the transfer function concept, has much to offer in the consideration of dynamic calibration of sensors.

Because of the limitations of periodic generators, responses to aperiodic generators must be depended upon to provide much of the needed information on sensors. Measurements of frequency response using sine wave inputs are easily defined and understood, whereas the necessity to convert from the time-to the frequency-domain makes analysis with aperiodic inputs more difficult.

The major disadvantage of the use of transient (aperiodic) stimuli is the fact that they are less well controlled or known and that certain modifying assumptions must be made for data reduction.

In the case of the most commonly used transient stimulus, the step function, the inherent assumption in data reduction is that it is indeed a mathematically precise step. Actual measurand stimuli produced by dynamic calibrators cannot be true step functions with infinitely fast rise times. In actuality, the input is a form of ramp-function with a finite rise time and frequently a slightly time-varying amplitude as well.

The advent of Fast Fourier Transform analysis capability in dedicated analyzers or the use of FFT-programmed computers has greatly reduced the efforts of deriving frequency response curves from transient calibrations. The resultant increasing use of non-sinusoidal dynamic calibration techniques requires increased care in data reduction and interpretation, however, because the underlying assumptions and limitations are not always understood or clearly stated.

The use of random input signals for dynamic calibrations of sensors is a more recent development. It became practical with the advent of sophisticated spectrum analyzers and computer-based data reduction equipment. Random stimuli ideally contain signals with all frequency and phase components, thus the power spectral density of a white noise source is constant throughout its bandwidth. The term "white noise" is used in analogy to white light which also contains frequency components throughout the optical spectrum. The usefulness of random stimuli is primarily due to the fact that if they are applied to a lightly damped resonant system, that system acts as a narrow band-pass filter near the resonance. Thus the resonance (or resonances) of a physical system can be excited by random inputs and therefore identified. Random stimuli sources can often excite resonances far beyond those excitable from other dynamic calibration sources.

ENVIRONMENTAL TEST CONSIDERATIONS

Peter Stein stated a universal truth when he pointed out "...the unfortunate fact that every transducer will respond in every way in which it can, to every factor in the environment." He continues "It is the measurement engineer's mission to assure that only the desired response to the desired environmental factor emerges at the measuring system output, and that all other environment-response syndromes have been suppressed." Environmental testing should verify that this mission has been accomplished.

Environmental testing consists of subjecting equipment to various conditions such as temperature, vibration, radiation, and humidity, in order to determine or verify its capability to operate satisfactorily when subjected to such stresses. Strength , life, and performance tests, as well as other basic test types, may all involve environmental testing.

The appropriate test conditions must be carefully selected. Basic factors to consider are:

- The possible environmental conditions during intended use of the equipment.
- The subset of these that must be used in testing.
- The capability for generating and controlling these test conditions.

The environmental factors that can affect the behavior of the sensor during actual operations must be determined and simulated to the extent feasible within the constraints of cost, schedule, and testing capability. Not all environmental conditions that affect behavior can be readily simulated, and very rarely can all be generated simultaneously tc account for interaction effects. Trade-offs therefore must be made when selecting the test conditions.

It should be noted that environmental testing must consider all the environments encountered in manufacturing, storage, transportation, and handling, as well as those experienced during operational use.

The environmental conditions to be encountered by equipment are not always known in exact form. It is only possible to select representative characteristics, such as averages or maximum levels, or major factors which adequately describe conditions for a test.

Environmental conditions of greatest interest from the reliability viewpoint are those that have detrimental effects on equipment operation. In many cases, effects not detectable when the factors are encountered singly, appear when two or more are present simultaneously. For example, some electronic components function properly in either a low temperature or a vibrational environmental environment, but when the environments are combined, component leads break.

Some conditions cause cumulative, nonreversible changes in the equipment; therefore, when considering equipment behavior the history of environmental exposures must be considered. Knowing the environmental history is less important when the effects are reversible, but the reversibility of all important responses can be determined only through careful analysis. Ignoring the nonreversible effects that have occurred in previous tests and operations can result in misleading environmental test results.

Experience is frequently the most useful guide for selecting the environmental factors and the severity levels and combinations of them to be used in

a test. This prior knowledge based on experience can help reduce the number of environmental tests to those needed to ensure the successful operation of the item. This is an extremely important point: testing is very expensive, both in terms of equipment cost and personnel time and cost.

The following table of environments and their possible effects on components and devices is extracted from "Engineering Design Handbook, Development Guide for Reliability, Part 4, Reliability Measurement" AMCP 706-198. U.S. Army Material Command, June 1976.

Environments and Typical Effects

Environment	Effects
High Temperature	Parameters of resistance, inductance, capacitance, power factor, dielectric constant, etc., will vary; insulation may soften; moving parts may jam due to expansion, finishes may blister; devices suffer thermal aging; oxidation and other chemical reactions are accelerated; viscosity reduction and evaporation of lubricants are problems; structural overloads may occur due to physical expansion.
Low temperature	Plastics and rubber lose flexibility and become brittle; electrical constants vary; ice formation occurs when moisture is present; lubrications gel and increase viscosity; high heat losses; finishes may crack; structures may be overloaded due to physical contraction.
Thermal shock	Materials may be overstressed instantaneously causing cracks and mechanical failure; electrical properties may be altered permanently.
Thermal radiation	Causes heating and possible thermal aging; surface deterioration; structural weakening; oxidation; acceleration of chemical reactions; and alteration of physical and electrical properties.
Acceleration	Mechanical overloading of structures; items may be deformed or displaced; mechanical functions may be impaired.

Environment	Effects
Vibration	Mechanical strength may deteriorate due to fatigue or overstress; electrical signals may be mechanically and erroneously modulated; materials and structures may be cracked, displaced, or shaken loose from mounts; mechanical functions may be impaired; finishes may be scoured by other surfaces; wear may be increased.
Shock	Mechanical structures may be overloaded causing weakening or collapse; items may be ripped from their mounts; mechanical functions may be impaired.
Acoustic noise	Vibration applied with sound waves rather than with a mechanical couple can cause the same damage and results as vibrational environment, i.e., the sound energy excites structures to vibrate.
Humidity	Penetrates porous substances and causes leakage paths between electrical conductors; causes oxidation that leads to corrosion; moisture causes swelling in materials such as gaskets, excessive loss of humidity causes embrittlement and granulation.
Salt atmosphere and spray	Salt combined with water is a good conductor which can lower insulation resistance; cause galvanic corrosion of metals; chemical corrosion of metals is accelerated.
High pressure	Structures such as containers, tanks, etc., may be overstressed and fractured; seals may leak; mechanical functions may be impaired.
Low pressure	Structures such as containers, tanks etc., are overstressed and can be exploded or fractured; seals may leak; air bubbles in materials may explode causing damage; internal heating may increase due to lack of cooling medium; insulation may suffer arcing and breakdown, ozone may be formed; outgassing is more likely.
Zero gravity	Disrupt gravity-dependent functions; aggravates high-temperature effects as convection heat removal ceases.

Environment	Effects
Magnetic fields	False signals induced in electrical and electronic equipment; interference with certain functions; can induce heating; can alter electrical properties.
Electromagnetic Interference	Causes spurious and erroneous signals from electrical equipment and components; may cause complete disruption of normal electrical and electronic equipment such as communication and measuring systems.
Sand and dust	Finely finished surfaces are scratched and abraded; friction between surfaces may be increased; lubricants can be contaminated; clogging of orifices, etc.; materials may be worn, cracked or chipped.
Nuclear/cosmic radiation	Causes heating and thermal aging, can alter chemical, physical, and electrical properties of materials; can produce gases and secondary radiation; can cause oxidation and discoloration of surfaces, damages electrical and electronic components, especially semiconductors.
Solar radiation	Effects similar to those for sunshine, nuclear/cosmic radiation; and thermal radiation.
Albedo radiation	Albedo radiation is reflected electromagnetic (EM) radiation; amounts depend on the reflection capabilities of illuminated object such as a planet or the moon; effects are the same as for other EM radiation.
Winds, gust and turbulence	Applies overloads to structures causing weakening or collapse; interferes with function such as aircraft control; convectively cooks surfaces and components at low velocities and generates heat through friction at high velocities; delivers and deposits foreign materials that interfere with functions.

Environment	Effects
Precipitation: sleet, snow, rain, hail, dew, frost	Applies overloads to structures causing weakening or collapse, removes heat from structures and items; aids corrosion, causes electrical failures; causes surface deterioration; and damages protective coating.
Clouds, fog, smog, smoke, haze, etc.	Can interfere with optical and visual measurements; deposition of moisture, precipitation, etc.; enhances contamination; can act as an insulator or attenuator or radiated energy.
Sunshine (ultraviolet radiation)	Causes colors to fade; affects elasticity of certain rubber compounds and plastics; increases temperatures within enclosures; can cause thermal aging; can cause ozone formation.
Chemical contaminants	Corrosion of metals may be accelerated; dielectric strength may be reduced; an explosive environment can be created; heat transfer properties may be altered; oxidation may be accelerated.
Insects, fungi	Can cause surface damage and chemical reactions; can cause clogging and interference with function; can cause contamination of lubricants and other substances.

Test methods for many, but not for all, of the above environmental conditions have been developed and standardized. The bibliography lists some sources for this information.

Durability considerations

The operating conditions in which sensors are used, and which influence their performance characteristics, may be categorized into several major areas. These are: operation at laboratory conditions, operation in harsh environments, operation over extended periods of time, and, finally, operation in harsh environments over extended time. Degradation of sensor performance tends to increase in the order in which these areas are listed.

There is much evidence to show that sensor performance degrades with time, whether in storage only, or while being used. The amount and type of performance degradation also varies with the environment in which the sensor is stored or used.

The concepts of durability, stability, and reliability, as applied to sensors, are similar in that all indicate quantitatively "how long it will work." There is a distinction between the terms which is tacitly accepted by most measurement engineers. "Reliability" is used to show the time to failure of the device (expressed in a variety of ways). "Stability" and "durability" are more concerned with the manner in which the performance of the device deteriorates prior to total failure. Of course, failure itself can also be defined as the point at which performance deteriorates beyond all specified boundaries.

While four operating regimes are listed above, actually there is also a fifth one: non-use storage with zero measurand input. In this case there are two possible situations: storage at "room conditions" (laboratory environment) or at some other conditions, perhaps simulating spare parts storage at an equatorial island base (high temperatures, high humidity, fungus) or in the artic (very low temperatures, low humidity).

It should be emphasized that the performance characteristics of the sensor, as determined through careful calibrations, indicate the "health" of the sensor, i.e., its ability to properly perform its specified measurement function. Knowledge of the continuing health of the sensor is derived from re-calibrations which are compared to the initial acceptance tests, as well as subsequent ones. Static calibrations are usually sufficient (except in the case of sensors with no response at zero frequency, such as piezoelectric devices). It is also reasonable to perform abbreviated calibrations in many cases i.e., five point, instead of eleven- or twenty-one point. Engineering judgment will dictate the choice.

For sensors stored at room conditions and zero measurant, calibrations at yearly intervals are probably adequate. This assumes that sensor characteristics have previously been established through extensive qualification tests and thorough acceptance tests. If the temperature and/or humidity environments are significantly different from room conditions, check calibrations should be performed at more frequent intervals, perhaps even monthly when stored at environmental extremes. The check calibrations themselves should be performed at room conditions to provide a proper base of comparison with the initial calibrations.

A more severe regime is sensor operation at room (laboratory ambient) conditions. It is not possible to generalize the effects of operational life on the stability of any sensor. The effects depend on factors like type of measurand, its amplitude and rate of application, the type, operating principle, and construction of the sensor and the amount of time it is energized. Very little work has been done (or at least published in readily accessible form) on what is often called "life-cycling" (operating life) effects on sensor performance.

Rest periods during which no cycling occurs, followed by static calibrations, will give indications of permanent, versus temporary, changes in performance characteristics. In all cases, control sensors should be used which are not cycled, but only calibrated statically whenever the test sensors are calibrated. This should permit correct assignment of performance changes to the cycling tests itself.

Life cycling under specified environmental conditions: temperature, humidity, vibration, etc., singly or in combination, may furnish additional information on the stability and durability of the sensors in the actual operational conditions. Clearly, all tests of this nature are qualification tests and are not to be performed on each individual specimen, since such tests are ultimately destructive in nature.

Re-calibration considerations

It should be clear at this point that the continuing ability of the sensor to make measurements within acceptable limits of error must be checked throughout the operational life of the measurement system. Qualities such as stability, durability, and to some extent, reliability, are established with the aid of re-calibrations of the sensing system. Unfortunately, it is very difficult to specify the intervals at which such re-calibrations are to be performed since a variety of factors need to be considered.

The real problem, with major significance to the overall performance of the measurement system, is that knowledge of the sensor's performance alone is insufficient. It is necessary to assess repeatedly the performance of the entire measurement system in order to be continuously assured of obtaining meaningful data.

The two major considerations are: How realistically can one re-calibrate the entire measurement system, and how frequently should this be done? The major trade-offs for the latter are availability for service and cost effectiveness.

There are other considerations for meaningful calibrations of sensors. The most realistic approach is to apply one or more known values of measurands to the sensing end of the sensor and record the corresponding output at the end of the entire system. This presents several difficulties, including problems of generating measurands with the proper characteristics and injecting them at the right point of the sensing chain. Of necessity, the sensor and system (or channel) must be taken out of service during calibration.

"Self-calibrating" sensors with a built-in mechanism to apply the measurand to the sensing element have been developed. The fact that no such sensors are commercially available now suggests that they were not satisfactory. However, the tremendous demand for long-term reliable measurements in complex systems such as ATE did not exist when those self-calibrating sensors were first developed. Perhaps interest in self-calibrating sensors will be renewed for specialized applications. It appears that this field deserves serious attention.

Present approaches to quantitative performance checks of the total measurement system (including the sensor) appear inadequate. This calls for generic investigations of a thorough nature. Past experience shows that it is difficult to find adequate support and resources for this type of research activity. Yet without it, knowledge of measurement system performance, particularly in critical applications such as ATE, can never be adequate to the needs.

In Conclusion

If the presentation above has created an overwhelming and pessimistic picture of the pitfalls besetting the performance of sensors, my purpose has been achieved. I felt it necessary to show the many factors which bear on the performance of sensor-based measurement systems, factors which are frequently poorly understood or neglected.

Yet they must be considered if we are to achieve meaningful and dependable measurements by the use of sensors.

SELECTED BIBLIOGRAPHY

A large amount of information on sensors is scattered throughout the technical literature. The information varies considerably in its quality and timeliness; much of it is not readily accessible. The following list contains the references which the author has found most useful.

1. Lederer, P.S., Sensor Handbook For Automatic Test, Monitoring, Diagnostic, and Control Systems Applications to Military Vehicles and Machinery, Nat. Bur. Stand. (U.S.) Special Publication 615, October 1981.

2. Harvey, G.F., Editor, ISA Transducer Compendium, Second Edition, IFI/Pioneer Press, 1969.

3. Ferson, L.M., Standards and Practices for Instrumentation, Sixth Edition, Instrument Society of America, 1980.

4. Lederer, P.S., NBS InterAgency Transducer Project, 1951-1979, An Overview, Nat. Bur. Stand. (U.S.), Tech. Note 1110, August 1979.

5. ANSI-MC 6.1-1975, Standard Electrical Transducer Nomenclature and Terminology, Instrument Society of America, 1982. The reader is urged to obtain pertinent transducer standards from the ISA.

6. MIL-STD-810C, Environmental Test Methods, March 10, 1975.

7. MIL-STD-202E, Test Methods for Electronics and Electrical Component Parts, April 16, 1973.

8. Stein, P.K., "Transducers in Temperature Gradient/Transient Environments", LF/MSE Publication #72, 1978, Stein Engineering Services, Phoenix, AZ 85018. This is one of a series of continuing papers by the Laboratory for Measurement Systems Engineering. The reader is urged to obtain a list of their publications.

9. Norton, H.N., Handbook of Transducers for Electronic Systems, Prentice-Hall, 1969.

SELECTED BIBLIOGRAPHY

10. AMCP 706-198, Engineering Design Handbook, Development Guide for Reliability, Part 4, Reliability Measurement, U.S. Army Material Command, January 1976.

11. Meindl, J.D. and Wise, K.O., Editors, IEEE Transactions on Electronic Devices, Vol. ED-12, pp. 1861-1977, December 1977.

12. Middlehoek, S., Angell, J.B. and Noolag, J.W., Microprocessors Get Integrated Sensors, IEEE Spectrum, pp 42-26, February 1980.

13. Anon, Electromagnetic Susceptibility of Process Control Instrumentation, SAMA Standard, PMC 33.1-1978, Scientific Apparatus Makers Association, 1978.

14. Natrella, M.E., Experimental Statistics, Nat. Bur. Stand. (U.S.), Handbook 91, August 1963.

15. ANSI B88.1-1972, A Guide for the Dynamic Calibration of Pressure Transducers, American National Standards Institute, 1972.

16. Harris, C.M. and Crede, C.E., Shock and Vibration Handbook, Second Edition, McGraw-Hill, 1976.

ADP002676

TEST AND EVALUATION OF RADIOACTIVELY CONTAMINATED TRANSDUCERS AND TRANSMITTERS

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ABSTRACT

People in the nuclear industries face some unique problems when handling, testing, or examining transducers and transmitters that have been radioactively contaminated. Although many people and organizations, including EG&G Idaho, have performed such work for many years, there are no set, structured approaches or procedures. This paper discusses a disciplined laboratory approach to contaminated transducer testing and evaluation, utilizing equipment and facilities developed specifically for this type of work.

INTRODUCTION

As a prime contractor, EG&G Idaho operates several experimental nuclear reactors at Idaho National engineering Laboratory (INEL) approximately 50 miles west of Idaho Falls, Idaho. Among the nuclear facilities are Loss of Fluid Test (LOFT), Power Burst Facility (PBF) and Advanced Test Reactor (ATR). EG&G Idaho is also involved in a program to remove certain selected instruments and other electrical devices from the TMI-2 reactor building for testing and examination at INEL.

Many transducers and transmitters are utilized in and around nuclear plants. In addition to the control and process monitoring transducers and transmitters normally used in nuclear plants, many specialized transducers may be found in the experimental reactors at INEL.

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These devices frequently become radioactively contaminated in service. Contamination may be internal, external, or both. This does not alleviate the necessity to periodically retest or calibrate these transducers, or to evaluate and/or examine them for cause of degradation or failure. Most transducer test laboratories are not licensed or equipped to handle radioactive material, and therefore the users must solve the testing problems themselves.

Contamination is removable radioactive dust-like particles, which can be ingested or inhaled. Contamination ranges from that which is easily removable to that which is very tenacious and locked into pores or crevices of a device. Some contamination may be extremely difficult to remove, yet still be capable of contaminating equipment or personnel. The types of radiation typically encountered are alpha, beta, and gamma.

Considerations

Some of the areas that must be considered when testing and handling radioactively contaminated transducers are:

1. Personnel and Public Safety--Radioactively contaminated material is potentially hazardous. Medical and radiological monitoring is necessary to protect personnel and requires specialized instruments, personal dosimetry and documentation. EG&G Idaho subscribes to the ALARA (as low as reasonably achievable) philosophy, so that jobs are planned carefully to reduce personnel exposure to levels below DOE guidelines.

   All personnel who work with radioactive materials at EG&G Idaho must take special training and become qualified Radiation Workers.

   All materials and equipment contaminated during testing and examination must be controlled, cleaned up, or disposed of properly and safely, to protect personnel and preclude the spread of contamination to the general public.

2. Special Handling--All radioactive materials require special controls and must be handled and shipped in accordance with government regulations. Special paper work is required and at EG&G Idaho, only trained and qualified personnel may handle or ship radioactive materials. All actions connected with handling are monitored by personnel trained in health physics. Typically, each job involving any radioactive material requires a "Safe Work Permit" so Safety and/or Health Physics personnel can review the job and assure adequate safeguards to protect personnel and to prevent the spread of contamination.

3. Protection of Test Equipment and Facilities--Unless the test equipment and facilities being utilized to test the contaminated components are dedicated solely to working with such articles, they must be either protected against contamination, cleaned up after this use, or disposed of when the job is complete. Generally, calibration and test equipment is too expensive to dedicate only to testing contaminated components, and attempts are made to use the same equipment on nonradioactive tests as well. This may be risky because once a piece of equipment is contaminated, it may be extremely difficult or impossible to clean and therefore no longer useful on noncontaminated items.

TEST OPTIONS

Several options are available in testing and evaluating radioactive transducers and transmitters:

1. Discard and Replace. The cost of handling and testing the device may be greater than that of simply discarding it and replacing it with another. This is commonly done, especially with highly radioactive devices. However, aside from the fact that it costs even to discard or store radioactive material, there are several reasons for testing a radioactive transducer or transmitter.

- The most obvious is to enable its reuse. While transducers and transmitters normally last years, periodic calibration tests are necessary to assure continued accuracy of the unit. Radiation contamination, itself, does not constitute failure.

- Validate Data Already Obtained. The device may have provided data during an experiment that subjected it to potentially damaging radiation (or other phenomenon), and requires testing to assure that device still functions properly.

- Determine survivability or cause of failure or degradation. When failure or degradation does occur, it is useful to know the cause in order to improve future designs or applications, as in the case of the TMI-2 transmitters.

- Radiation Effects Testing. Some experiments are designed specifically for testing radiation effects on devices or materials, in which case testing is required to evaluate such effects.

2. Clean Up and Test. Sometimes devices may be cleaned up so they can be handled as nonradioactive items. This approach generally works only on items mildly contaminated with loose particles. It is not uncommon to have to resort to harsh cleaning techniques such as scrubbing, pressurized steam, acid etching, etc., and even these techniques are not always successful.

   Cleaning operations may damage or affect device performance in such a manner as to question its performance in a previous experiment or operation. For example, if water used in a cleaning operation were allowed to enter a sensitive area of a transducer or transmitter, and it subsequently did not work properly, its prior performance would remain in question.

3. Test in Place. Frequently, transducers and transmitters may be tested in place. Process and control pressure transducers and transmitters for example, are often configured so they may be tested with a portable pressure calibrator, but this approach has its limitations. The logistics are sometimes cumbersome, testing may be compromised, and often results are not as good as a laboratory calibration. In the case of failure or degradation, detailed troubleshooting and repairing in the field is generally not practical; it is simpler to physically replace the device and not delay the operation of a costly facility.

4. Test Device in Contaminated State. It is often desirable to test the device in the contaminated state because: 1) The device may not be cleanable, 2) cleaning may damage it or affect the test results as previously indicated, or 3) it may be most efficient and economical if equipment and facilities are readily available. Conversely, it may be very expensive if special facilities and/or equipment must be separately provided for each task.

   Special "Hot Cells" are available at INEL. These are enclosed and sealed areas that have been designed and constructed to handle highly radioactive materials, and are equipped with remote control manipulators. They are generally very expensive and awkward to utilize, and are too restrictive for handling and testing mildly contaminated transducers.

TEST FACILITIES

At the INEL, in spite of the fact that we have been handling radioactive materials for years, it still seemed that when it was required to test or calibrate a radioactively contaminated transducer or transmitter, it was necessary to set aside a special area or facility, and set up calibration and test equipment on a temporary basis. The tests were usually set up in a remote area that was designed to handle radioactive material, but not conducive to good instrumentation practices. With an

expected influx of transducers and transmitters from LOFT and TMI, and recognizing that there must be a better way, a laboratory designated Contaminated Components Test Facility (CCTF) was set up for the primary purpose of testing and evaluating radioactively contaminated instruments. The laboratory is located in an area where nonradioactive transducers have been tested for years. Most of the necessary equipment was on hand and experienced personnel were already available to staff the facility.

The general philosophy was to provide a facility at minimum costs that could utilize as much existing equipment and personnel as possible. Further, it was desired to be able to handle and test devices in a "as received" contaminated state to avoid compromising data by any clean-up operation.

Figure 1 is a layout of the CCTF, which is located in a metal frame building at ARA-III at the INEL. The principle features are the tent, the fume hood, and a glove box, in which contaminated articles are tested and examined. Also in this facility is radiation monitoring equipment consisting of a constant air monitor, radiation area monitor, a smear counter, personnel monitor, and several portable instruments.

The tent was fabricated to our requirements and is made of Herculite, a fiberglass-reinforced plastic. See Figure 2. The material is strong, washable and easily cleaned. Four separate rooms and a "step-off area" are provided, so separate experiments may be set up and left in place. A blower system maintains a negative air pressure on the tent. Blower system air intake and exhaust is forced through high efficiency particulate air (HEPA) filters. It is designed so any airborne contamination is drawn into the filters and trapped. The fume hood, Figure 3, is also exhausted though a HEPA filter.

The glove box, Figure 4, is an option for handling and disassembling devices.

Provisions for collecting liquid, solid, and compactable radioactive waste are incorporated in the facility.

Mildly contaminated articles may be evaluated in either the fume hood or the tent. Articles that have higher levels of loose contamination are evaluated in the tent. Such items may require that personnel be more fully protected, so an air purification system is provided to allow personnel to work in the tent with hood respiratory protection. See Figure 5.

The tent is provided with a zippered door in its ceiling, and a rail-mounted chain hoist is available so that heavy articles, such as instrumented piping, may be lowered into a back room for testing.

Figure 6 shows radiation monitoring equipment, including a "smear" counter. Smear counters are used to measure contamination levels by wiping (smearing) the questionable article with a cotton or a paper swab, and then placing the swab in the lead lined detector housing. The radiation events (disintegrations), are then counted, and the results provide an indication of the level of contamination. The detection systems are capable of discriminating between the types of radiation, i.e., alpha, beta, or gamma.

Figure 7 shows a computer-based control and data acquisition system which is located in a separate building several yards from the CCTF. There are several computer-controlled RUSKA pneumatic pressure calibration instruments mounted in the racks. The control and data acquisition system is used to test pressure transducers and to control and acquire data from a variety of experiments in the area. It was a relatively simple matter to connect the CCTF into this sytem with pressure tubing and cabling. Of great concern is that the pressure test system not be contaminated by the radioactive transducers and transmitters. This concern was resolved by placing filters in pressure lines as shown in Figure 1. A number of tests were performed to assure that contamination did not pass the filters. Two filters are used for redundant protection.

An alternate method of protecting pressure test equipment is to pressurize from the test equipment, but exhaust or bleed-off into the contaminated area. This technique has been used with pneumatic and water test systems. It is still recommended that a filter be placed in the pressurizing line, in case of leakage or errors in operation.

The limits of radiation levels that may be accommodated in the CCTF are based on allowable personnel exposure. Such measures as shielding, maintaining distance, and minimizing time of exposure are taken to reduce personnel exposures to within the EG&G Idaho ALARA guidelines. Contaminated articles must be enclosed in sealed containers for shipping and handling, and may be exposed only in a controlled area such as the tent or fume hood.

Each device to be tested must be evaluated by Health Physics and test personnel to determine the best handling and test techniques to maintain low personnel exposure. In general, articles with up to 2 or 3 roentgens per hr (R/hr), as measured by an ion chamber instrument, or smearable contamination of several hundred thousand disintegrations per minute (dpm) can be readily accommodated. Higher levels may require special controls and procedures, with additional shielding required.

TEST & EVALUATION EXPERIENCE

The CCTF was set up primarily to repair and recalibrate LOFT pressure transducers and to test and examine TMI-2 pressure transmitters. Other devices have also been tested and examined in the facility.

Loss of Fluid Test (LOFT)--The LOFT reactor uses approximately 50 experimental absolute and high-line, low-differential pressure transducers on and around the primary coolant system. These transducers become contaminated internally and externally, and require periodic calibration and repair. In the past, it was very difficult to obtain good "as received" calibrations because of inadequate facilities, and the areas in which it was necessary to repair them was not of instrument handling quality. The transducers are now tested in the CCTF in a "as received" contaminated condition, with the precision pressure test system. This allows validation of prior supplied data. The transducers are then cleaned up and repaired as necessary (new "O" rings, fittings, etc). They are then recalibrated and returned to service with a minimum of turn-around time.

The radiation and contamination levels of these transducers is fairly low, ranging about 0.05 to 0.5 R/hr and smearable contamination of 500 to 5000 dpm.

Three Mile Island (TMI)- A number of TMI transmitters were to have been tested by this time, but removal has been delayed at TMI due to the high priority of the fuel examination program. Two pressure transmitters and one flow indicating transmitter have been tested/examined, along with pressure switches and valve actuator solenoids. A Foxboro E11GM series pressure transmitter was tested and appeared to have suffered no degradation, while a Bailey Model BY8231 did not function at all due to severe internal corrosion.[1] See Figures 8 and 9. The corrosion in the Bailey unit was caused by leakage of water into it, apparently by way of its cable conduit.

A Brooks flowmeter indicator also did not function at all. The failure was found to be severe corrosion at solder terminals in the transformer sensing coils. The corrosion is not attributed to leakage, as with the Bailey unit. A report will be issued on the Brooks unit at the end of the fiscal year.

These TMI transmitters exhibit radiation levels of up to 1.5 R/hr, with smearable contamination levels of up to 100,000 dpm. The Bailey unit was also heavily contaminated internally.

When actually working on a unit, as in a disassembly or troubleshooting operation, it has generally been found most convenient to work in the fume hood, as shown in Figure 3. One technician, dressed in anti-contamination clothing, actually handles the test articles in the controlled area while the other operates meters and test equipment and maintains a log, and transcribes data.

For long term tests, or calibration tests where the transducers are to be left unattended, it has been found most convenient to set up the experiment in the tent, and test the articles remotely.

Other Examples

Flow--Flow testing of contaminated turbine and similar flow transducers and transmitters is limited because of the problems in contaminating expensive flow loops and the large number of flow ranges required. Dedicating a flow calibrator to testing contaminated devices has been cost prohibitive to date. EG&G Idaho has a Ballistic Flow Calibrator which is in full time use in calibrating nonradioactive flow transducers. Therefore, the approach in testing turbine type transducers has been to completely clean up the turbine. Internal parts such as bearings and turbine blades are replaced and the body is acid etched, if necessary, to completely remove surface and loose contamination. The device is then tested as a nonradioactive unit.

Temperature--There has been little demand to test contaminated temperature devices such as thermocouples and resistance temperature detectors (RTDs). Testing of these devices would be fairly straight forward in this facility for mid-range devices. Present plans are to commit a fluidized bed and appropriate reference RTDs to the facility. The control and data acquisition system will be used to control the fluidized bed temperature and acquire data.

CONCLUSIONS

The CCTF has proven to be a cost effective facility in which to test radioactively contaminated transducers and transmitters. Its location near an existing transducer test laboratory is an efficient utilization of equipment and personnel. Although the emphasis to date has been the testing of pressure transducers and transmitters, the facility lends itself to a variety of instrumentation tasks and devices, and it is expected that its role will be expanded in the future.

Testing of devices in their "as received" contaminated state has proven practical, and removes an element of uncertainty that may be caused by a cleaning operation.

Testing of LOFT and TMI-2 transducers and transmitters will continue. Removal and testing of several more TMI-2 pressure transmitters is expected to be completed in the next few months.

REFERENCES

1. Rolf C. Strahm, Merlin E. Yancey, TMI-2 Pressure Transmitter Examination Program Year-End Report: Examination and Evaluation of Pressure Transmitters CF-1-PT3 and CF-2-LT3, GEND-INF-029, February 1983.

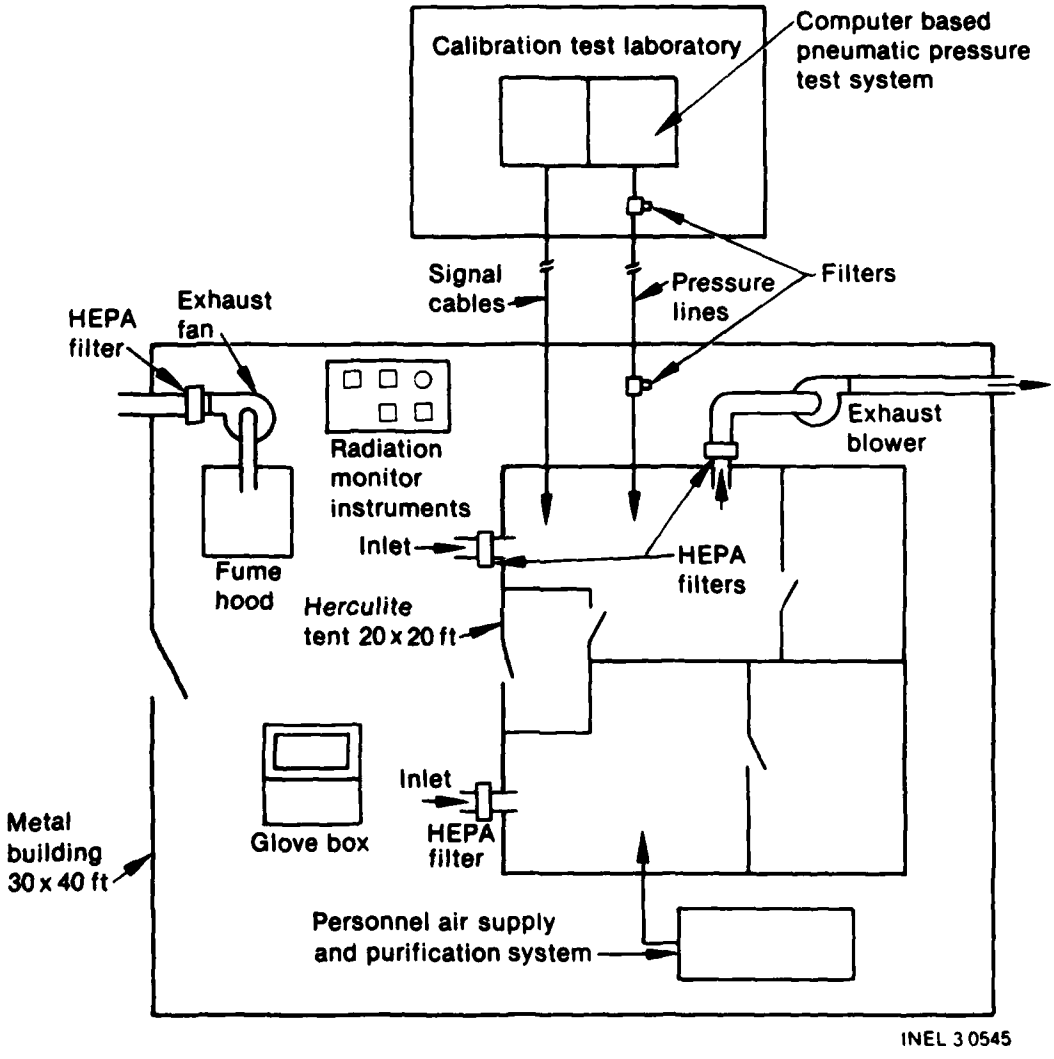

Figure 1. Layout of Contaminated Components Test Facility (CCTF)

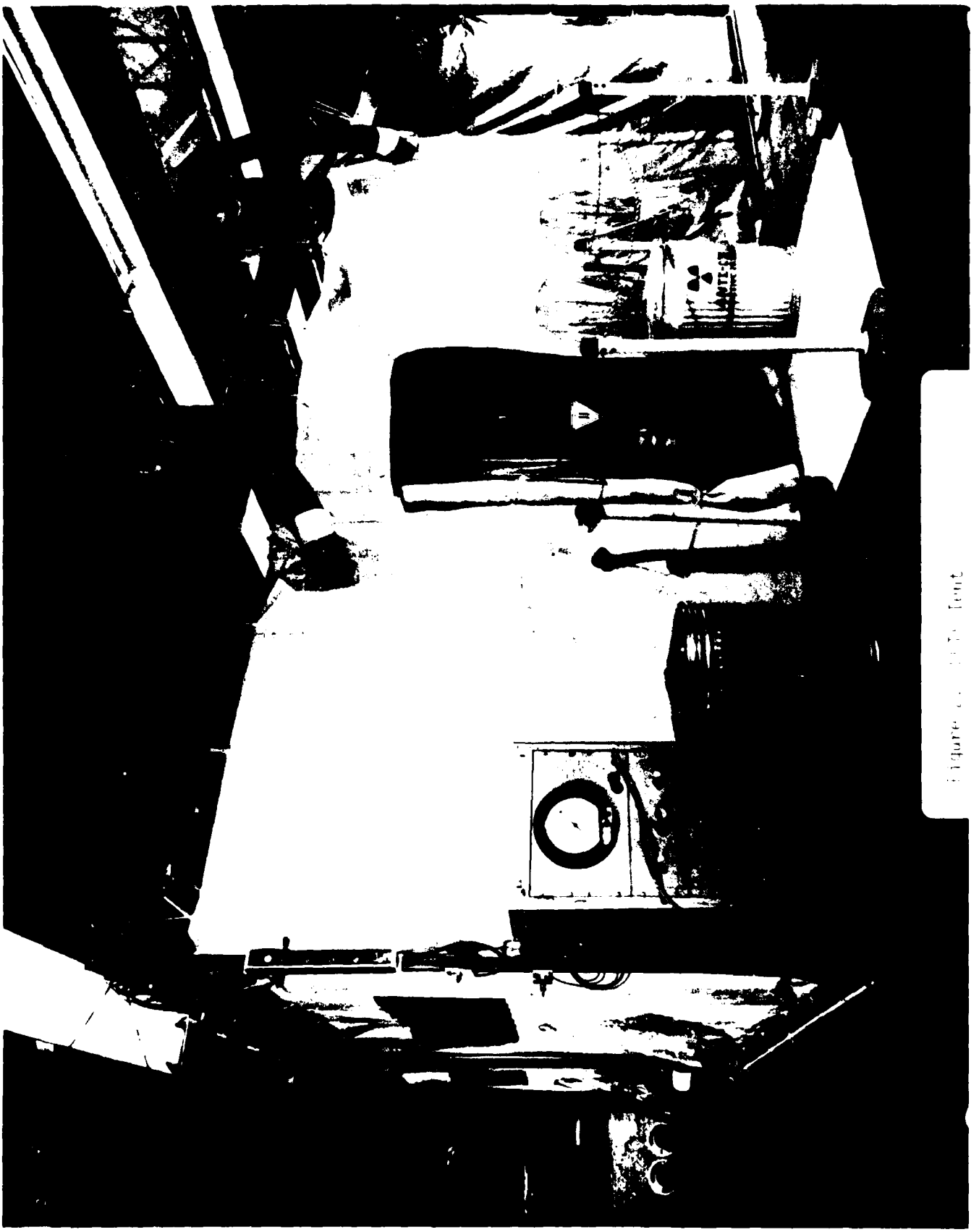

Figure 3. Fume Hood Area

Figure 4. Glove Box

Figure 6. Radiation Monitor Equipment

ADP002677

Non-Self Generating Transducer Signal Conditioning Technique

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ABSTRACT

The Structural Vibration Branch (FIBG) of the Air Force Wright Aeronautical Laboratories (AFWAL) is responsible for acquiring large quantities of data from tests conducted in laboratory, field, and airborne environments. These data consist of signals from accelerometers, microphones, strain gages, thermocouples, resistance-temperature-devices (RTDs), flow meters, hygrometers, etc. For many years this organization has been plagued with the problems associated with acquiring data from resistance type transducers especially in the airborne and field environment. The primary areas of concern are those of lead wire resistance, effects of temperature changes, and vibration induced signals in these wires.

This paper presents an approach to signal conditioning of resistance type transducers that provides improved accuracy under the adverse conditions encountered in airborne and field testing as well as simplified calibration requirements.

The technique involves using a dual tracking constant current circuit to supply the "bridge" power and measuring the differential IR drops across the elements. The "bridge" in this case, is really a "Y" circuit composed of two series branches with a common node. In this configuration the two current sources are connected to the tips of the "Y" and the IR drops between the supplies and the supply common are measured. The common node is connected to the power supply common. The change in IR drop (Δ R) is a linear representation of the physical phenomenon at the transducer plus the lead wire effects, and since the circuit is symmetrical in every respect it requires only three wires to implement any conventional "bridge" circuit with complete lead wire effect cancellation.

BACKGROUND

The Structural Vibration Branch (FIBG) of the Wright Aeronautical Laboratories (AFWAL) is responsible for acquiring and processing data from field, airborne, and laboratory tests. These measurements are primarily aircraft structural in nature such as, modal parameter estimation, flight environment definition and structural failure problem solving. These data are acquired from microphones, pressure transducers, accelerometers, strain gages, resistance temperature detectors (RTDs) and thermocouples.

Over the years we have steadily improved our measurement accuracy and capabilities. Some of the milestones are:

1967	Design and Development of Automatic Gain Ranging Amplifier (AGRA)
1971	Design and Development of Airborne Electronic Temperature Reference Module

1974	Design and Development of High Temperature Microphone
1978	Development of Miniature Line Driver for High Impedence Transducer.
1979	Design and Development of Bridge Conditioning Module
1982	Redesign & Repackaging of AGRA
1983	Design of Optical Isolators

All these efforts plus a large amount of in-house work in the area of packaging and system design has improved the instrumentation accuracy. The predominant source of error has now moved to the bridge conditioning module.

INTRODUCTION

The task of acquiring more and more data from non-self generating transducers such as strain gages, resistance-temperature detectors (RTD), pressure transducers (strain gage type) and potentiometers (such as extensometers) has created many problems. Some of these problem areas are:

1. Large Changes in Resistance (RTDs, potentiometers)
2. Long leads between transducer & signal conditioner
3. Restriction in number of wires available
4. Airborne environment (Large temp changes)

The goal of the recent in-house work was to find a method of dealing with this class of transducer that would satisfy as many of these problem areas as possible.

It was to this end that a program was started to reanalyze the problems associated with resistance type measurements and determine if there were any better approaches. Our main concern at the onset was the number of wires and sizes that are available, especially in airborne applications, to achieve the required accuracies. When considering the problem of taking data in an airborne environment, errors can build rapidly and, in general, the total space available for everything from wire runs to instrumentation is very limited.

DISCUSSION

The accepted method for acquiring these types of measurements is to form the resistor elements (i.e. strain gages) into a Wheatstone bridge configuration. Seismic accelerometers, pressure transducers and microphones have used this technique, with either a diaphram or beam gages, to convert mechanical motion to strain with the output calibrated in G's, PSI, dP, etc., strain measurements being calibrated in units of strain.

The Wheatstone bridge signal conditioner with a simple constant voltage source (A/C or D/C) can turn into a very complex circuit when one wants to

minimize the errors in a measurement. A typical circuit for a full bridge transducer is shown in Figure 1. In this configuration the excitation voltage (E) is applied across Nodes 1 & 3 and the output voltage (e_o) is across Nodes 2 & 4. The readers attention is drawn to the lead wire (R_L) terms in this figure. Since todays instrumentation amplifiers have input impedences of 10^7 ohms and greater there is essentially no current drawn in the output wires so the resistance terms drop. If this were not the case, if the instrumentation amplifier has true differential inputs then the terms would cancel from a noise stand point, however, the lead wire resistance would reduce the sensistivity of the bridge. The resistance terms in the input power leads have to be accounted for since they reduce the voltage across the transducer, thus reducing the sensitivity. The second problem that occurs is that the power supply lead wire acts like a transducer itself and responds to vibration, temperature, etc. One method of eliminating this would be to add another pair of wires, one from Node 1 and one from Node 3, to sense and correct the bridge voltage at the transducer. The bridge circuit now requires 6 wires. If calibration is required, more wires must be added. Depending on whether single point calibration or deviation in both directions is required, the bridge can grow to nine wires and we also require a shield for these wires. It should be noted that any time current flows through a bridge element in a constant voltage circuit there will be some alteration of the expected result if parasitic resistance is present. When all is said and done we must not forget that we are dealing with a circuit that is inherently non-linear. The assumption of linearity is only reasonable for very small deviations (ΔR) from a balance condition and since non-linearity is a second order effect the result is harmonic distortion for the dynamic measurement.

Figure 2 presents a typical single arm bridge circuit that uses three wires to connect a single active gage. Although this circuit will maintain static balance due to changes in the lead wires, there is a change in sensitivity of the gage. No gage temperature compensation is provided with this circuit unless the gage itself is compensated. The output equation for this circuit is as follows:

$$e_o = e_2 - e_1$$

and

$$e_1 = E\,(R_s + \Delta R_s + R_L)/(R_c + R_s + \Delta R_s + 2R_L)$$

$$e_2 = E\quad R_d/2R_d$$

where

R_d = dummy resistors

R_L = lead wire resistance

R_s = strain gage

then

$$e_o = E\,(R_d/2R_d) - E\,(R_s + \Delta R_s + R_L)/(R_d + R_s + \Delta R_s + 2R_L)$$

Assume

$R_d = R_s = R$ Balance condition

then

$$e_o = E/4\ (\Delta R_s)/(R + \Delta R/2 + R_L)$$

$\Delta R/2$ is the nonlinearity term for the bridge

if

ΔR small such that $R + \Delta R \doteq R$

then

$$e_o = E/4\ (\Delta R)/(R + R_L)$$

The error due to the lead resistance can be expressed in the following manner:

$$\% \text{ error} = (\Delta R/R - \Delta R/(R + R_L))/(\Delta R/R) \times 100$$

$$= (1-R/(R + R_L)) \times 100$$

$$= R_L/(R + R_L) \times 100$$

This error term can rise quite rapidly and must be accounted for if accuracy is the goal. With gage resistances in the range of 120-350 ohms errors of 5 to 10 percent are not uncommon.

For the bridge with two active arms (Figure 3) a similar derivation can be made such that the output equation is

$$e_o = E/2\ (\Delta R_2 - \Delta R_1)/(R + (\Delta R_2 + \Delta R_1)/2 + R_L)$$

where $(\Delta R_2 + \Delta R_1)/2$ is the bridge nonlinearity

Depending on what sign you assign to the ΔRs they will either add or subtract. If the measurements were pure bending with one gage in compression and the other in tension it can be seen that the non-linearity term cancels and the numerator becomes $2\Delta R$. This is also known as the constant current condition. However, the R_L term is still present and reduces the sensitivity. A balance pot across an active element would act the same as lead resistance causing a loss of sensitivity. It became apparent that no matter how one manipulated the Wheatstone bridge circuit, at best it was a compromise. So, an alternate approach was pursued.

Since constant current has been used for many years for single active gage dynamic work we decided to take a second look. The method most commonly used was the "brute force" approach (Figure 4). A resistor is installed in series with the gage and the signal is taken out between the gage and resistor through a capacitor. Depending on how large the series resistor is, this circuit will approach constant current. This circuit looked promising since it produced a voltage that was directly proportional to the change in resistance, not the ratio of resistances. Instead of using a "brute force" regulator, a true constant current source (Figure 5) was devised. This provides dual tracking current outputs for the circuit ("bridge"). This regulator would use a common voltage reference such as a bandgap diode (which is highly stable, but tends to have considerable noise) and a dual op-amp IC.

This combination would provide the best temperature stability and the circuit accuracy is a function of the components only. The noise from the diode would appear in both outputs equally and would subtract at the amplifier. If a programmable current source is desired, there are several methods of accomplishing this. There are several current mode digital to analog converters on the market that use bandgap regulators that should work nicely. Another approach would be to use a regulator with a voltage divider and an analog multiplexer/switch to select the current output.

Figure 6 illustrates the configuration for a single active gage with DC (static) measurement capability. In this configuration lead wire characteristics are cancelled, however, no temperature compensation for the gage is provided. Balance is accomplished by either a series resistance in one leg of the circuit or by summing a voltage with one of the outputs (e_1 or e_2).

The output equation for this circuit is as follows:

$$e_o = e_2 - e_1$$

and

$$e_1 = i_1 (R_s + \Delta R + R_L) + (i_1 + i_2)R_L$$

$$e_2 = i_2 (R_d + R_L) + (i_1 + i_2)R_L$$

then

$$e_o = i_2 (R_d + R_L) - i_1 (R_s + \Delta R + R_L)$$

assume

$$i_1 = i_2 \text{ and } R_d = R_s = R \text{ (Balance condition)}$$

then

$$e_o = i (R + R_L - R - \Delta R - R_L)$$

and

$$e_o = i \Delta R$$

Strain $= e_o/(iRK)$ where R = gage resistance at which the K was obtained

For 2 active arm (Figure 7) the output is

$$e_2 = i_2 (R_{s2} + \Delta R_{s2} + R_L)$$

$$e_1 = i_1 (R_{s1} + \Delta R_{s1} + R_L)$$

$$e_o = i_2(R_{s2} + \Delta R_{s2} + R_L) - i_1(R_{s1} + \Delta R_{s1} + R_L)$$

assume

$$i_1 = i_2 \text{ and } R_{s1} = R_{s2} = R \text{ (balance condition)}$$

then

$$e_o = i(\Delta R_2 - \Delta R_1)$$

Strain $= i(\Delta R_2 - \Delta R_1)/(iRK)$

There are many advantages to this circuit. First, when an even number of

gages are used and the ΔR_s have opposite signs, only active elements are involved (assuming the unbalance is small). When the gage circuit has an odd number of elements or the requirement is for addition of the outputs, only one dummy element is required and this could very well be the balance control. It should be noted that gage temperature compensation is only accomplished when the gages are in opposite legs (unless the gages are self-compensated). The only limitation in total resistance is the compliance of the supply (maximum voltage available) and/or the common mode voltage range of the instrumentation amplifier. Secondly, but no less important, is the fact that no more than three wires are required to implement any type of gage circuit. Further, the circuit is Linear since it is responding to a change in resistance not a change in ratio of resistances. Next the lead wire effects are completely cancelled. Since the circuit is described as being 100% efficient instead of 50% as in the conventional Wheatstone bridge the output per unit strain would double. This says that only half the power would be required from the supply for the same output, thus reducing the gage self heating.

With a slight modification to the standard bridge transducer (Figure 1) the constant current supply can be used. This modification consists of opening Node 1 and rewiring the transducer as shown in Figure 8. Since most manufacturers offer repair facilities this should present no problem. It is possible to build new transducers in this configuration and change to smaller connectors since only three wires would be required. This configuration also would greatly enhance the measurement accuracy while simplifing the installation.

Calibration of this measurement is a function only of the current through the gage. If one knows the current, the calibration can be calculated. Since the current remains constant regardless of the total resistance, it could be measured in the laboratory prior to installation. If in-circuit calibration is a must a small series resistor can be switched into the circuit.

There is only one miror disadvantage of this measurement circuit. The gage factor is not directly applicable to the calculation of strain. The calculation of strain now requires not only the gage factor but gage resistance.

It should be pointed out that throughout this discussion the assumption has been that the model for the lead wire (R_l) is consistent from wire to wire (essentially equal). This is true for almost all cases except the one of slip-rings. The resistance is partially a function of contact pressure and the contacts slide across a surface that has minute random variations in height and spacing. Therefore, it is safe to assume that the contact pressure, thus the resistance, will be a random phenomenon. So one has to assume an uncorrelated random model for that portion. For this reason the lead wire effects would not completely cancel.

Since the circuit described above is limited only by the power supply range, it can handle very large resistance changes linearly. This fact makes it very useful for conditioning such measurands as RTDs, extensometers, potentiometers, etc.

CONCLUSION

It is the conclusion of the author that this circuit meets all of the initial objectives and more. It simplifies the installation both in the number of wires required and the size of the instrumentation. The circuit is insensitive to lead wire length and is capable of handling very large ΔRs. At the same time it is a circuit that can be calibrated prior to installation and has greatly enhanced measurement accuracy.

REFERENCES

Experimental Stress Analysis and Motion Measurement: Dove, Richard C., C. E. Merrill Books, Columbus, Ohio, 1964.

Measurement System Engineering Short Course Notes: Stein, Peter K., et al., Stein Engineering Services, Phoenix, Arizona, 1976.

Semiconductor and Conventional Strain Gages: Mills, Dean, III, Douglas P. D., Academic Press, New York, 1962.

Strain Gage Techniques, Murray, William MacGregor, Stein, Peter K., Cambridge, Massachusetts Institue of Technology 1962.

Measurement Engineering, Stein, Peter K., et al., Phoenix, Arizona, Stein Engineering Services 1964.

Application of B&K Equipment to Strain Measurements: Vaughn, John 1975.

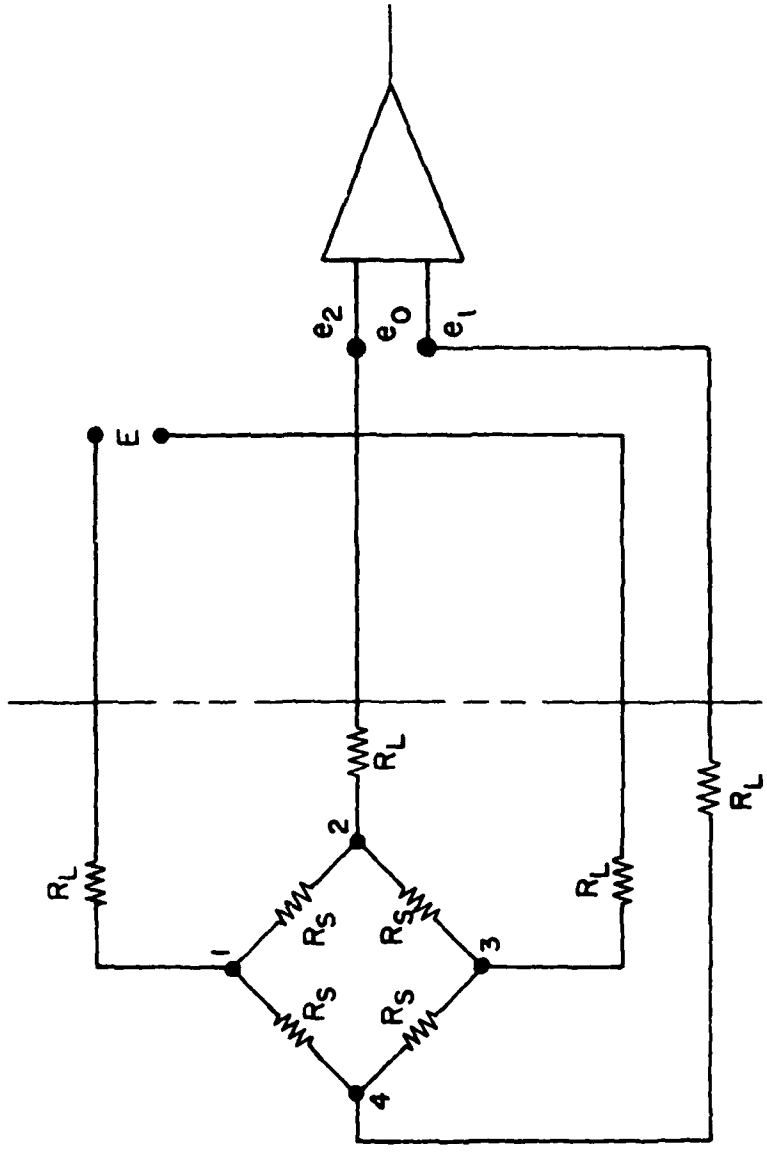

Figure 1. Full Bridge Transducer

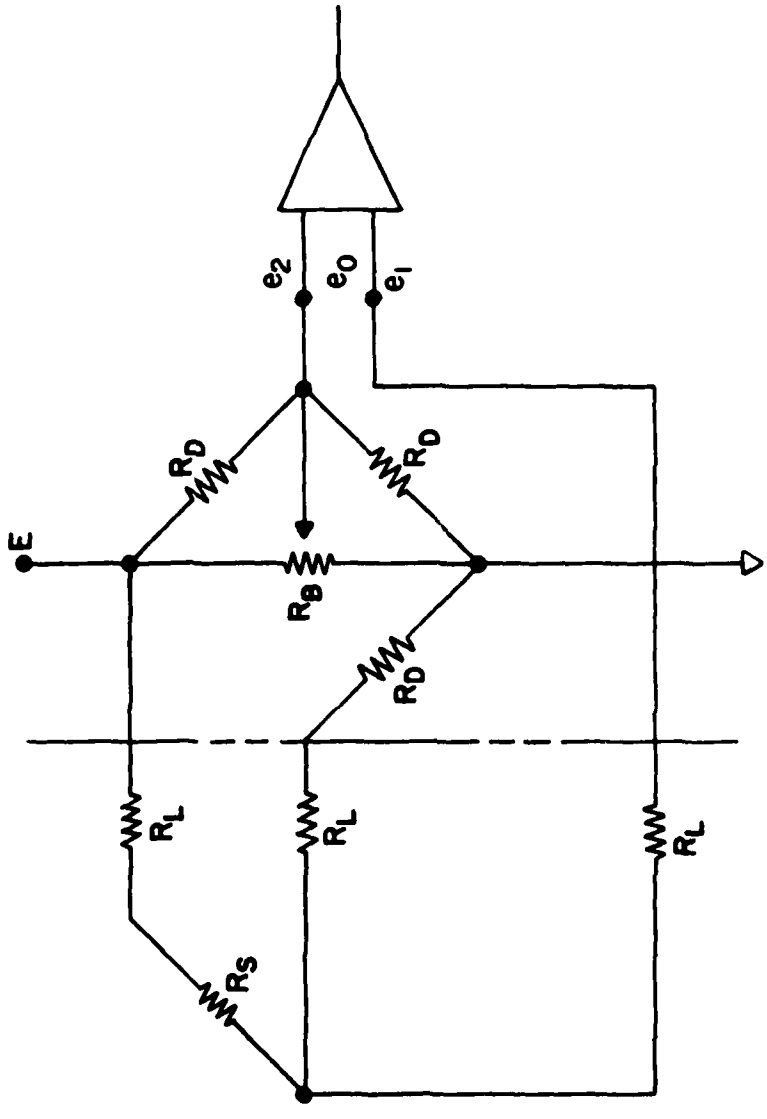

Figure 2. Single Active Arm Bridge Circuit

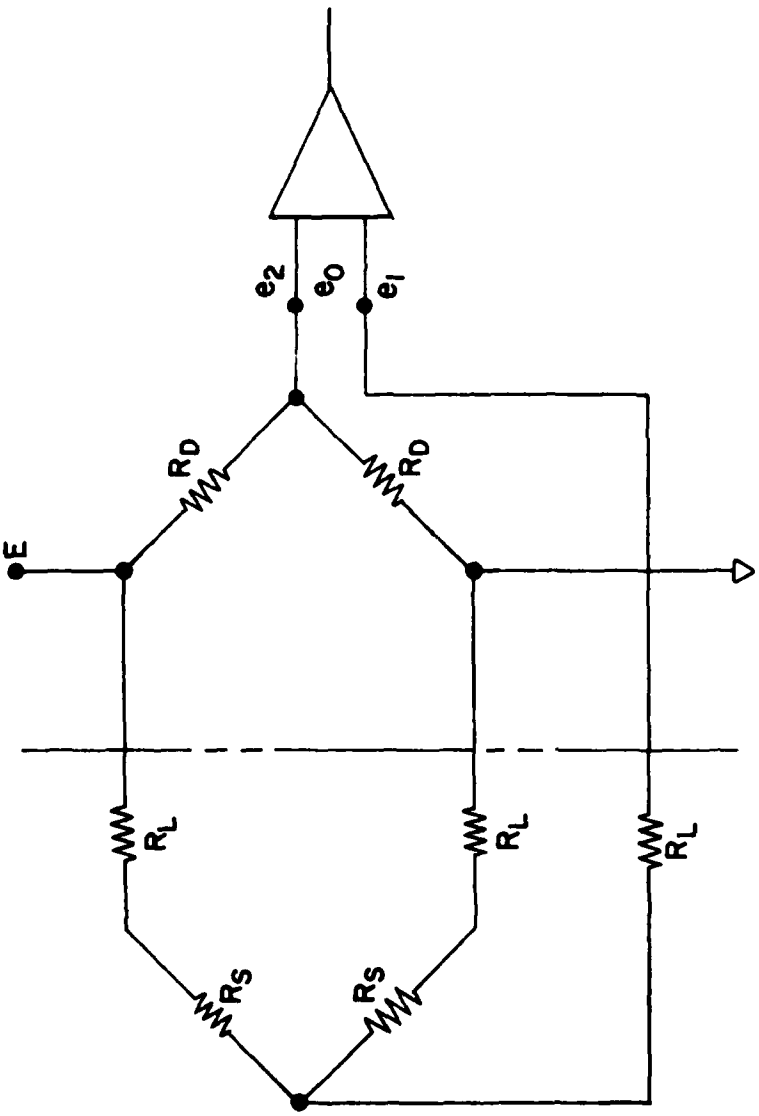

Figure 3. Two Active Arm Bridge Circuit

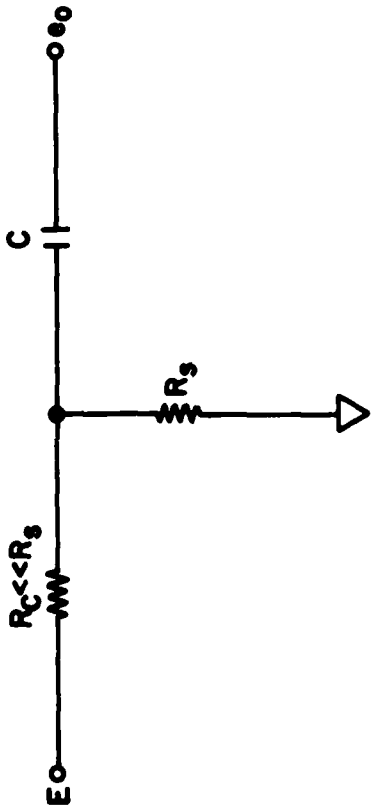

Figure 4. Brute Force Constant Current Circuit

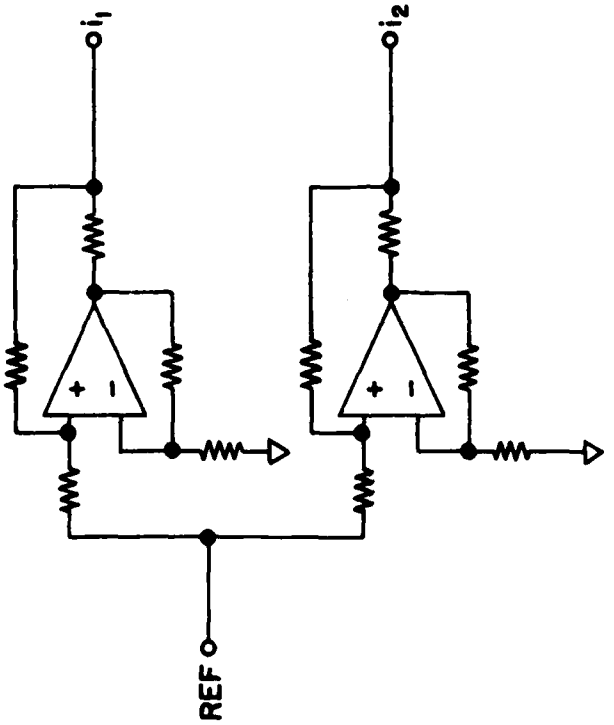

Figure 5. Dual Tracking Constant Current Supply

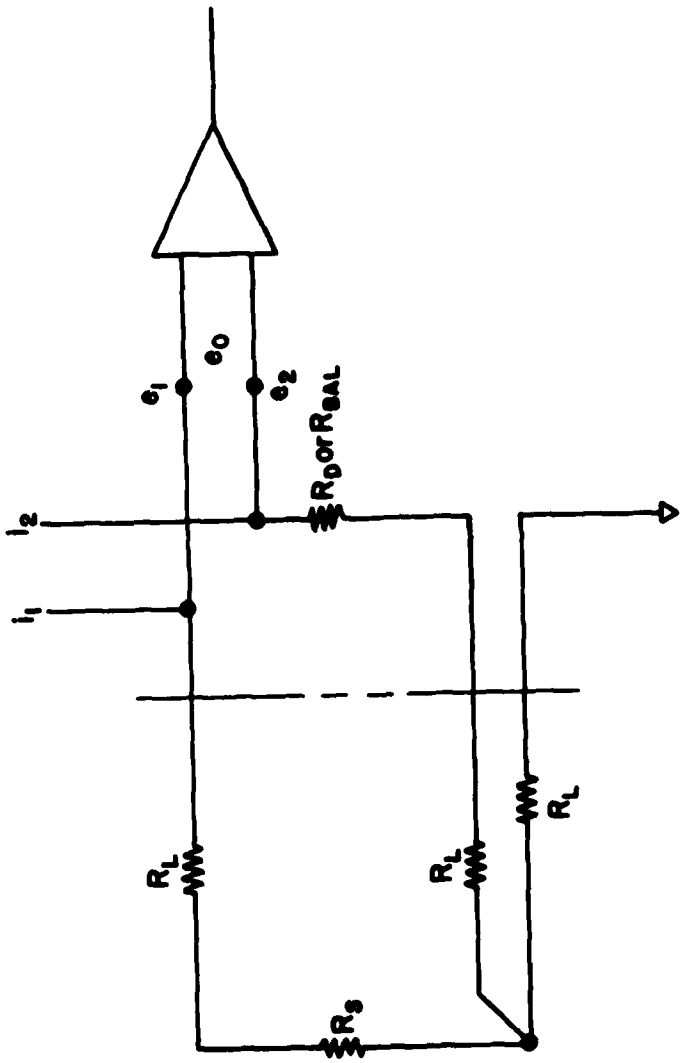

Figure 6. Single Active Gage Circuit With Constant Current Supply

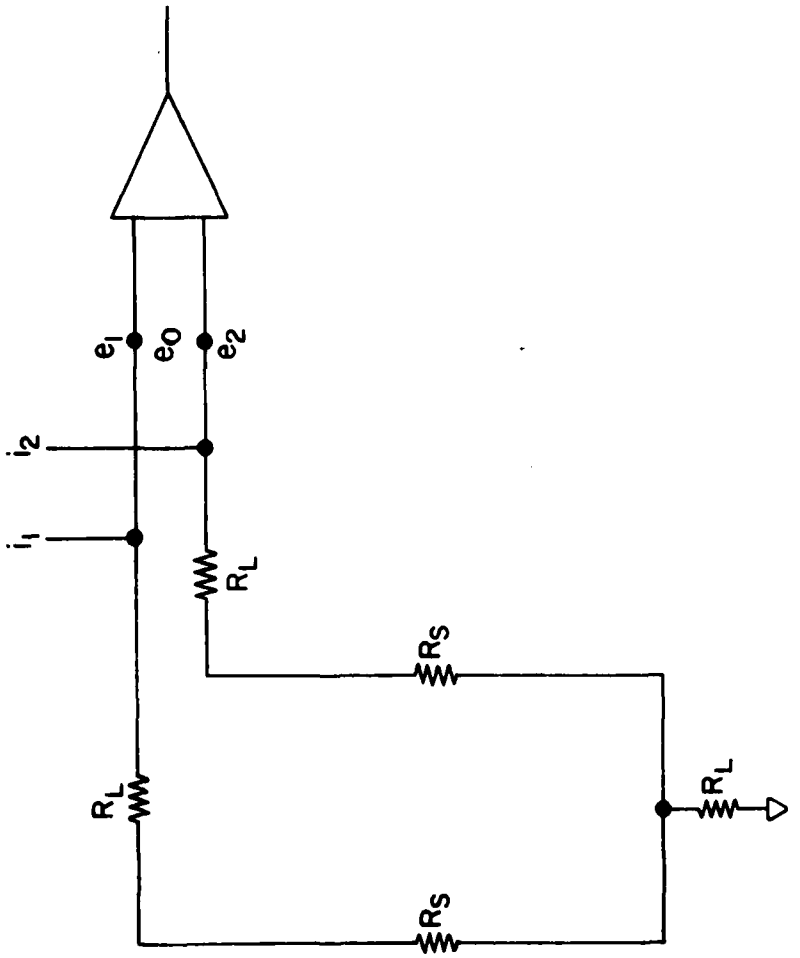

Figure 7. Dual Active Gage Circuit with Constant Current Supply

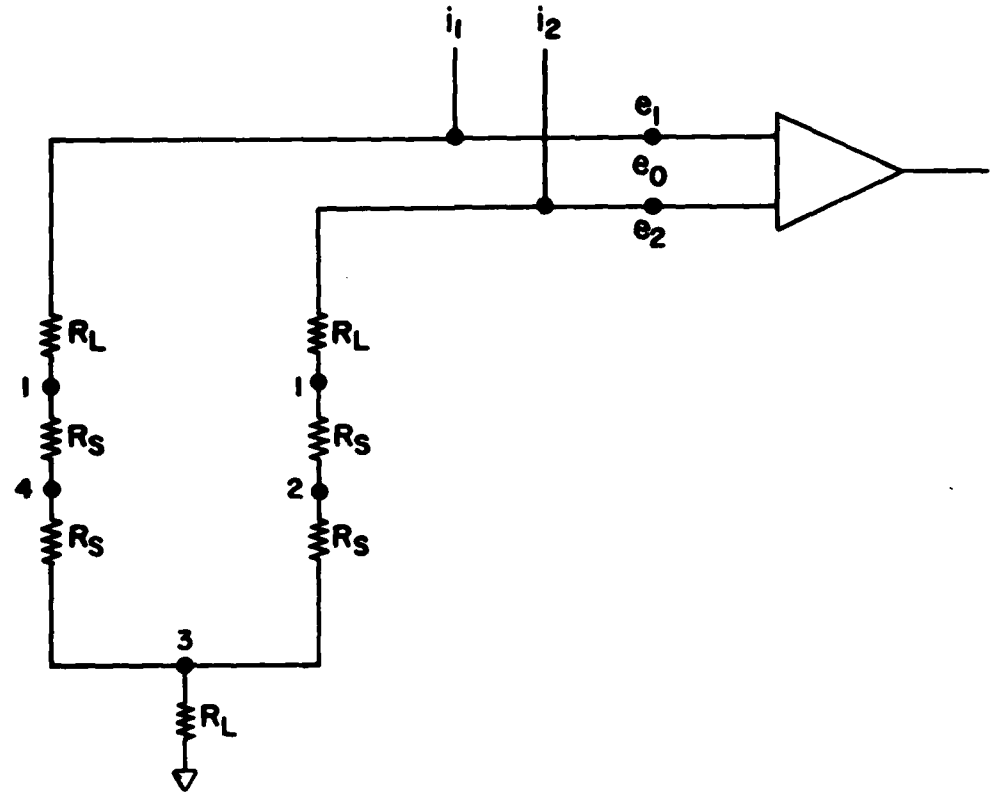

Figure 8. Modified Bridge Transducer Internal Wiring For Use With Constant Current Supply

TUESDAY MORNING Q&A SESSION

Q: SCOTT WALTON, ABERDEEN PROVING GROUND, TO RICHARD TALMADGE, AFWAL

You're tracking circuit for constant current, I think you mentioned at one point a frequency response of 20 KHz, is that appropriate for that circuit and could it possibly go higher than that? What's the limitation for frequency response in that circuit?

A: RICHARD TALMADGE

Our data bandwidth is basically 20 KHz, the data bandwidth we require. That circuit is basically a DC type of circuit. It generates a constant current, stable and the circuit rejection would handle the 20 KHz bandwidth.

Q: SCOTT WALTON

O.K., but as your signal oscillates up and down wouldn't your constant current source have to respond to that even though it would be a small change it would have to move that? You're saying that will definitely handle 20 KHz. Is it an audio offamp that you prefer to use? Do you think it would go to 80 KHz, which is what I would like?

A: RICHARD TALMADGE

I see what you're saying; yes, we have not checked it out that high but I don't see any reason why with the proper design on the amplifier, it is an operational

amplifier with gain bandwidth extremely wide, so I don't see any reason why it wouldn't work to 80 KHz.

Q: BOB SILL, ENDEVCO CORPORATION, TO VESTA BATEMAN, SANDIA

You described improvement in the apparent drift using the 8-KHz sampling as opposed to 4-KHz sampling. Do you attribute that improvement to improvement because of aliasing, or because of aperture uncertainty? What kink of parameters do you attribute that improvement to?

A: VESTA BATEMAN

The 8-KHz and 4-KHz numbers are not sampling rates. They are maximum frequency outputs from the analog to frequency converters. So that just tells you the different number of pulses you might see in a sampling period. In other words, if you operate at a higher frequency, you get twice the number of pulses and each pulse represents a smaller angle increment so you have a finer resolution in the data. So I can't answer your question with respect to sampling rate.

Q: LARRY SIRES, NAVAL WEAPON CENTER, CHINA LAKE

Rather than a question, I would like to address a few comments in regard to what Paul Lederer said as to his philosophy. In one of them he was talking about essentially what I would call combined environment testing of transducers. Because evidently what he was trying to say was the effects can be different when more than one of these environments are tested at the same time. This is hard enough to do when you are talking about static environments, but when you

start talking about dynamic environments, where not only do you have to worry about the combination of effects but the combination of what phase they occur in with each other, it becomes extremely difficult and in some cases almost impossible. I might be interested in a few comments and philosophy in that direction.

A: PAUL LEDERER, WILCOXON RESEARCH

Ideally you would like to simulate the environment exactly as it's going to occur when the transducer is in its measurement mode. Practically you can't always do this so you can only approach it, and you can try to predict what the effect is likely to be if you can't simulate the environment. This whole business is one of never having any certainty, but you can approach within reasonable bounds depending upon how much money, time, and effort you want to put into it, what kind of equipment you have, but you will never have certainty. There will always be an element of uncertainty and that has to reflect itself in the error bandwidth you give for your measurements. I think the important thing about the approach you take looking at your system is that you don't kid yourself.

C: PETER STEIN, STEIN ENGINEERING

One of the things that Paul emphasized is that if you check your transducer under individual checks like temperature, acceleration and pressure, then when you try to interpret your data it may not make sense because there are interactions. The whole is not bigger than the sum of the parts, it's only that you forgot to add in some of the parts. One of the philosophies that I have tried

to transmit, 33rd year now, is that during the test you've got to have check channels or check the working channels so that in fact you are recording what happens in the test environment with all the interacting phenomena together. That's the only way you can get any degree of confidence in your data because in the calibration lab you just cannot produce the test conditions. That's a very important point you made Larry.

C: LARRY SIRES

That's the kind of the philosophy I think that we maintain as we try in our transducer evaluation to separate out the elements, see what their effect is separately in the laboratory and then, like you said, either using check channels or try to predict what the effect will be in a combined dynamic environment, and try to separate that out of the data. Then if we can't, then we go back and redo the test. But this has the other part of the philosophy that I wanted to comment on, was the terms of cost. Paul mentioned that he thought the transducer cost was irrelevant compared to the cost of getting the information, and what the information is worth. Unfortunately in the world I live in that is not always the case. What I end up getting is a lot of requests for data, one which is usually the day before or if we're lucky the week before the test is supposed to be conducted, and the people wishing the data have no idea why they want the data. This is the first question I always try to ask. If I know why or what purpose the data is going to be put to, often the cost can be drastically limited. If I can't get an answer as to why you want the data and typically the answer I get is: "Well, we're gonna run the test anyway and I thought it might be nice to have a little data along with it". If I don't try

to outright discourage collecting data under those circumstances, then I end up discouraging it because I end up having to put the cost at such a high rate because now we have to cover everything. If you don't know what the data is going to be used for then you have to make sure the measurement system is capable of responding accurately, regardless of what the actual purpose of the data is going to be put to. That really drives up cost.

Q: PAT WALTER, SANDIA LABS

I have two questions; one to Mr. Talmadge, which I ask first, the other for Mr. Strahm is shorter and easier to remember.

On the auto ranging flight amplifier that you eluded to in the beginning - that's something that I've heard Charles Thomas remain excited about over the last 3 or 4 years, kind of like a birth that everyone expects to happen that hasn't quite gotten here yet. So the type of questions I wanted to ask are the first if you feel comfortable answering and the last really reflects more of my interest. The first question is around the supplier and what kind of development costs you are encountering, and then in regard to some technical questions what kind of dynamic range are you trying to cover, during gain changes what kind of time interval do you have that you actually lose data, and what are the frequency response characteristics of the overall system? So I would like some information about that.

A: RICHARD TALMADGE

The AGRA is being developed by Adyin Vector and the development cost that we put in is in the order of 160K for that we get the design and essentially 25 prototypes which are full mil spec tested. It's basically designed as a DC to 20KHz amplifier. It's got four six-pole butterworth filter selections built-in. It will go DC to 500, DC to 2K, DC to 5K, or DC to 20K. It's also got an AC coupled front end switch selectable digital control externally. So we've moved the capacitors inside the device, which was the predominate problem basically in the previous designs. In the dynamic range, minimum gain is .25 and has maximum gain of 10.24 and powers of 4. Drift, we are down to about half a microvolt per degree C. I'm trying to remember off the top of my head some of the other specs. We're right now in the finalization of specs from breadboard. We have not tested any units in the hybrid version yet. They're in the build-one mode right now. The contract is supposed to deliver the 25 on the 30th of September, or there abouts, of this year. Did I forget anything?

Q: PAT WALTER

Yes, one of the key points was during gain changes, what kind of a blank out window do you have that you just lose information?

A: R. C. STRAHM, EG&C IDAHO

It's spec'd at recovery time of less than 100 microseconds. So, we don't know exactly where that is until we got into full scale testing of the hybrids, but from what I've seen on the breadboard it looks excellent.

Q: PAT WALTER TO R. C. STRAHM

You talked about the radioactive contaminated transducers and I noticed that most of your measurements were pressure and in fact I saw some variable reluctance transducers, some Validynes or something, and apparently you are using different types of transducers. You eluded to the fact that some have been corroded due to long term exposure to water. I wondered if you had any type of qualitative information you'd be willing to share in terms of degradation of transducer performance due to the radioactive type of environment, and if you had noticed anymore susceptibility between one type of transduction mechanism or another?

A: R. C. STRAHM

I'm not quite sure where to start, but to begin with there were no Validynes in there and we have not evaluated any Validynes recently that have been exposed to radiation. We're not engaged in a radiation effects program per-se. I have some general observations, but there are other people that have tested a number of transducers and of course it's generally materials oriented as to radiation effects. My observations from the TMI instrumentation that we've tested is that the damage or the failures that we have observed ourselves are not based upon radiation effects per-se either. They are more directed toward the corrosion aspects or installation aspects and that kind of thing. However, I do know of another, a charge amplifier for example that was removed that had an FET in it and they attributed the failure to damage to the FET caused by radiation. But the program is really not all that far along in terms of the

transmitters themselves. But we have also tested a flowmeter transmitter that had failed and there again there was some corrosion in the unit. This particular unit did not leak, that we know of, and yet there was corrosion that caused a pair of coils to open up in that unit. The loft transducers that we tested, the radiation exposure limits have been fairly low and those are all strain gage type transducers. So there again we don't see any effects of radiation damage in those devices. But there has been some damage because the loft uses aberated water which tends to leak somewhat and will corrode anything that comes in contact with it. I'm not sure whether I answered your question or not.

Q: PAUL LEDERER TO R. C. STRAHM

The slide of your calibration facility indicated you have a Ruska pressure generating system and then you feed the pressure through two filters to the transducer that you are evaluating. It occurs to me that if you have this kind of a service system that generates known pressure and holds it, and if you have the slightest amount of leakage near the transducer, through those long lines plus the two filters you're putting in, you're going to have a different pressure at the transducer then what you think you have in the calibration facility. Would you comment?

A: R. C. STRAHM

That's true, we have that problem even without the long lines to the CCTF and we just do the best we can. We allow the pressure to stabilize for a long enough period, that we think we can see a leak. We have had a couple of problems in that area. It's not an entirely fool-proof system. We recognize that though.

Q: LARRY SIRES TO RICHARD TALMADGE

On the amplifiers you were talking about previously, did they have the built-in optical isolators that you were also talking about or is that something separate yet?

A: RICHARD TALMADGE

That's something separate.

Q: LARRY SIRES

Are there gory details in your paper since all we got before us is the abstract? I don't know how to ask any question, intelligently, until I can see what kind of details.

A: RICHARD TALMADGE

On the optical isolators?

Q: LARRY SIRES

Yes.

A: RICHARD TALMADGE

No, there is nothing in the paper other than a note that we did that development.

Q: BOB WHITTIER, ENDEVCO,TO RICHARD TALMADGE

For the dual constant current approach to work properly requires transducers which are optimized for that circuit configuration. Just wondered if you would comment on what you're doing to obtain the correct kinds of transducers for that?

A: RICHARD TALMADGE

We're not doing anything currently in that area. Although we are going to suggest to some manufacturers here in the near future that we look at that and solve that problem. Currently we are just using it on strain gage applications.

Q: LAWRENCE MERTAUGH, NAVAL AIR TEST CENTER,TO RICHARD TALMADGE

Do you suppress the gain change so you don't get it right when you don't want it on your device?

A: RICHARD TALMADGE

That capability is in the amplifier. There is an inhibit line that can be energized to stop the gain change at any point in time.

Q: LAWRENCE MERTAUGH

But you have to make provisions for that signal?

A: RICHARD TALMADGE

Yes, you have to have computer control or something in the system to suppress it.

Q: LAWRENCE MERTAUGH TO VESTA BATEMAN

You say the advantage of doing your computation onboard was for greater accuracy. If you just digitized onboard and sent that back would there still be an advantage to computing onboard , or do you need it for the rest of your system? Thinking that just digitizing the position and sending it back and doing all the computation on the ground.

A: VESTA BATEMAN

The problem is you can't digitize the position onboard. What you can do is send angle increments from the platform to the ground. If you get what they call "dropouts" then you've lost where you are, because with this new type of Gyro you don't get an absolute angle you get increments and so the advantage of the onboard is your getting a continuous complete angle output.

Q: DON GERIGK, LAWRENCE LIVERMORE LABS, TO RICHARD TALMADGE

How do you indicate the new gain in your recorded information?

A: RICHARD TALMADGE

The amplifier has a binary code coming out which has to be encoded by some method and what we are looking at is basically the next generation PCM type system, digital recording. I don't like the word PCM because there are too many ramifications to it and we're not necessarily talking about true IRIG standard type encoding. There are a lot of advantages to going to different encoding techniques as far as handling the data from a systems standpoint. If you go "PCM", then you have a decom problem at the other end. We are looking at bit rates on our full system of 160 Megabits or better. That imposes a tremendous load on the ground processing end.

Q: DON GERIGK

Is this gain information per channel or is that included in the data?

A: RICHARD TALMADGE

The amplifier has three gain bits in parallel coming out of it that are accessed any time you want them. They can be encoded with a digital word on a sample-by-sample basis or they can be blocked into the data if you didn't have the update requirement, or any way that you wanted to put them in.

Q: DAVE MILLER, SUNDSTRAND AVIATION, TO PETER STEIN

Can you tell me what the best approach is to using transducers which are inherently nonlinear? For example, the thermocouple or a drag-body type flowmeter.

A: PETER STEIN

The ideal approach, which is the least practical, is to linearize the transducer within the transducer itself. The paper discusses that a bit, and thermocouple measuring systems, which you very often do, is have a linearizing amplifier where the amplifier is non-linear inversely to the thermocouple. One of the problems that you get into there is if electro-magnetic interference gets into your thermocouple channels, the non-linearity of the amplifier will in fact take some of that accumulated 60Hz noise and convert it into small amounts of DC bias which then gets into your thermocouple channels. The later in the system you linearize, you've got the transducer, you've got the connecting leads, you've got the signal conditioning, you've got the amplifier. The later you linearize, the more danger there is of getting DC offsets due to sinusoidal pick-up, electromagnetic or electrostatic interference being converted into a DC level. A linearized thermocouple would be the absolute ideal, but is in general not available. So what you might consider for dynamic temperature testing is a resistance thermometer which is linear in and of itself. Those are commercially available. So sometimes the choice in the actual transducer is based on how important it is to maintain frequency content integrity of the signal. If it's not that critical to maintain the frequency content integrity

of your temperature signal, it doesn't that much matter. If it is very important for you to have an exact frequency content of the temperature fluctuations, and your working in high noise level areas, the thermocouple may not be your best choice. So there are a number of different factors that would influence your decision. It's not a simple statement, "here's what you do".

Q: HARVEY WEISS, GRUMMAN AEROSPACE INC., TO VESTA BATEMAN

The angle increments that you were talking about, the gyros, are these single degree of freedom gyros which essentially have some computation which additively obtains a new value for each time increment, or is it something completely different, and if so can you give us a little bit of discussion?

A: VESTA BATEMAN

The gyros are dynamically tuned rotor gyros and they offered a very high spin speed and output two axes of information. They are essentially a rate restrained gyro in that they have two sensors on either side of the rotor for one axis and they sense the movement of the rotor output of the rotor for that axis, and on the opposite axis for that rotor they have torquers that torque the rotor back into place. So what you have is a torquer current that's being fed back through the servoboard to the gyros and thus you see an angle increment at any particular time which is the torquer current to put the gyro back into position.

Q: HARVEY WEISS

Then they are actually rate gyros? They are not free gyros or attitude gyros, they are rate integrating gyros?

A: VESTA BATEMAN

Yes, that would be one way to put it.

SESSION II

TEMPERATURE, DISPLACEMENT AND VELOCITY

Norm Rector, Chairman

AD P002678

A HIGH ACCURACY TEMPERATURE MEASUREMENT ON A DIAGNOSTIC CANISTER FOR THE NEVADA TEST SITE

Donald C. Gerigk
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ABSTRACT

A data system was designed to measure 30 temperatures to an overall accuracy of ± 0.1°C. The temperature measurements were part of a dimensional stability study being done on a diagnostic canister used at the Nevada Test Site by the Lawrence Livermore National Laboratory. The system consisted of thermistors as the temperature-sensing element and a data logger which provided the following functions: current source, scanning system, voltmeter, and clock. A microprocessor, in turn, provided control to the data logger, a storage medium for the data, and the means for on-line conversion and display of the data. The performance of the system was optimized by calibrating each thermistor channel using the data system as readout and creating a unique calibration equation for each thermistor. Thus the system was calibrated as a whole to eliminate as many variables as possible. Four separate calibration runs were made. The data from one of these runs were used to calculate the constants for the temperature versus resistance equation for each thermistor channel. The data from the remaining three runs were then compared to resistance points calculated using this equation. The maximum deviation for any thermistor channel was 0.03°C. The system performed very well, recording data every hour for approximately three weeks.

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

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ABSTRACT

A data system was designed to measure 30 temperatures to an overall accuracy of ± 0.1°C. The temperature measurements were part of a dimensional stability study being done on a diagnostic canister used at the Nevada Test Site by the Lawrence Livermore National Laboratory. The system consisted of thermistors as the temperature-sensing element and a data logger which provided the following functions: current source, scanning system, voltmeter, and clock. A microprocessor, in turn, provided control to the data logger, a storage medium for the data, and the means for on-line conversion and display of the data. The performance of the system was optimized by calibrating each thermistor channel using the data system as readout and creating a unique calibration equation for each thermistor. Thus the system was calibrated as a whole to eliminate as many variables as possible. Four separate calibration runs were made. The data from one of these runs were used to calculate the constants for the temperature versus resistance equation for each thermistor channel. The data from the remaining three runs were then compared to resistance points calculated using this equation. The maximum deviation for any thermistor channel was 0.03°C. The system performed very well, recording data every hour for approximately three weeks.

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INTRODUCTION

The Measurement Systems Engineering Section was asked to measure temperatures on a diagnostic canister at both the EG&G North Las Vegas Atlas facility and at the assembly tower at the Nevada Test Site. In order to determine the nuclear performance of an underground nuclear explosive, a number of high energy physics measurement systems are installed in a structural framework called a diagnostic canister. The diagnostic canister varies from 1.73 to 2.18 meters in diameter and from 13.7 to 30.5 meters in length. The diagnostic canister houses the equipment to measure x-ray, neutron and gamma spectra emanating from the nuclear explosive. To limit the field of view for each detector to a particular area of the nuclear device, two circular apertures are accurately located along the length of the canister. For certain measurements the centerline passing through the center of the two apertures, located 3 to 6 meters apart, must fall within a 20 milli-inch radius of the working point on the nuclear device.

For accurate alignments such as this, it is important to understand misalignment caused by thermal distortion of the steel structure. The temperature at 30 locations was to be measured with an accuracy of $\pm 0.1^{\circ}C$. The measurements would be made over a temperature range from $10^{\circ}C$ to $40^{\circ}C$ for two months. In addition to the rather high accuracy needed, the measurement system for this application would be required to meet other demanding requirements. These include operation in a somewhat hostile environment including temperature variations of up to $\pm 10^{\circ}C$, on-line readout at full accuracy, and ease of operation and transport.

This paper will describe the transducer and data system selection, the error analysis, and the calibration procedure used to achieve the required degree of accuracy.

THE TEMPERATURE SENSORS

The important parameters for the sensor to be chosen for this application include high output, high accuracy, stability, and noise immunity. All of the various kinds of temperature sensors available today have parameters acceptable to some degree.

A summary of the most common types of temperature sensors and their characteristics is shown in Table 1. Thermistors were selected because they best met the measurement requirements. They have high accuracy and good stability. The one drawback is their nonlinear temperature versus resistance curve. However, all other types of sensors have nonlinearity larger than the allowable error band of this experiment. Thus all would require some form of correction. A Yellow Springs Instrument Company (YSI) Model 44030 thermistor was chosen; this unit has a resistance of 3000 ohms at 25°C, a calibration interchangeability of 0.1°C, and a nominal sensitivity at 25°C of 135 ohms per °C. Thus, even though this is one of the most accurate temperature sensors available, its vendor-supplied error band alone is the same as the total allowable measurement system tolerance.

Table 1. A summary of the most common types of temperature sensors and their characteristics

Transducer Type	Sensitivity	Error Band °C
Thermocouple (Type E)	60 μV/°C	± 1.0
RTD		
Platinum	0.39 mV/°C	± 0.45
Nickel	0.33 mV/°C	± 2.0
Thermistor	40 mV/°C	± 0.1
AD 590 (Analog Devices)	1 μA/°C	± 0.5

THE DATA SYSTEM

There are many data systems or combinations of components that could have been used for this project. However, because of availability, compactness, and familiarity with the unit, an HP 3497 was chosen as the data system. It consists of a DVM, a scanner, a power supply, a clock and a means of local control and data display all in a fairly compact case. To provide additional flexibility, on-line hardcopy and magnetic tape storage, an HP 85 computer was also used.

The resistance of the thermistor was read using a two-wire lead configuration and a 10 microamp current level. Although 30 meters of lead were required on the thermistor, it was decided not to use a four-wire configuration. Calculations to support these decision are shown below.

Cable type:	Belden 8451, 22 gage twisted, shielded pair
Length:	30 meters
Temperature Change:	$40^{o}C$
Resistance at $25^{o}C$:	1.65 ohms
Resistance at $65^{o}C$:	1.90 ohms

The resistance of a 30-meter single wire changes 0.25 ohms for a $40^{o}C$ temperature change. For the two wires attached to the thermistor, each 30 meters long, the resistance change is 0.5 ohms. Therefore, the maximum error at a thermistor temperature of $40^{o}C$ would be $0.007^{o}C$ for a cable temperature change of $40^{o}C$. The possible error indicated of $0.007^{o}C$ was small enough to justify using the two-wire approach.

The current to each thermistor was supplied by the HP 3497 through the scanner contacts. Thus, current was applied to each sensor only during the time it was being read. The scan rate was nominally 10 channels per second.

Control of the HP 3497 was accomplished with the HP 85 computer over the IEEE 488 bus. This control included scan rate, channel selection, current level, system status, and continuous deploy of selected channels. This was all achieved by the program shown in Appendix A. The program also contained the thermistor conversion equation with the individual constants for each thermistor.

Scan rate and monitor channel control were provided by the program through user-defined keys. The resistance and temperature were recorded for each scan both on the internal pointer and on a magnetic tape cartridge.

ERROR ANALYSIS

Since the main components of the system have been defined, it is now possible to make a preliminary estimate of the system error band. The error sources can be described in two areas. The first is the hardware itself, the DVM and power supply, etc. The second is the thermistor and its conversion

method. Table 2 lists the main errors present in the data system exclusive of the thermistor and in the calibration system.

Table 2. The main errors present in the data system, exclusive of the thermistor, and in the calibration system.

Data system errors		Error degrees C
DVM:		
Reading error	90 day ± 5°C	± 0.0062
Temperature	Additional ± 5°C	± 0.0030
Current source:		
Stability	90 day ± 5°C	± 0.0025
Temperature	Additional ± 5°C	± 0.0025
Temperature effect on cable:		+ 0.0075
	Root sum square	0.011
Calibration system errors		
Bath uniformity		± 0.0138
Platinum temperature reference accuracy		± 0.0033
Mueller bridge accuracy		± 0.006
	Root sum square	± 0.015

The thermistor has two main error contributions which must be added to the value shown in Table 2. The first of these is the ± 0.1°C interchangeability error which is the degree of conformity of any thermistor to the published resistance temperature table. The second is the error introduced in the conversion from resistance to temperature. Many conversion routines are available with varying degrees of inaccuracy. One conversion equation offered by YSI is quoted to provide a conversion accuracy of 0.01°C or less over a temperature range of 50°C.

This equation is as follows:

$$1/T = A + B\text{Ln}(R) + C\,[\text{Ln}(R)]^3$$

where: T = temperature, degrees kelvin
R = measured resistance, ohms
A,B,C = thermistor constants

In summarizing the error sources, it is apparent the $\pm$ 0.1°C thermistor conformity error is the most dominant compared to the data system error of $\pm$ 0.011°C. Thus, a significant reduction would have to be achieved in the thermistor error to obtain a comfortable margin in the overall error band.

On this basis it was decided to calibrate the thermistor using the entire system from thermistor to readout as close to its final configuration as possible. This was done with one exception. The thermistors would be mounted on the diagnostic can using an aluminum plate, 1 x 2 x 1/4 inch, with a bolt hole for attachment. For efficiency, it would be better to calibrate all sensors at once. However, if the thermistor were attached to the aluminum the total mass would be too large for the calibration bath. For this reason the calibration was done before the thermistors were attached to the mounting plate.

CALIBRATION SYSTEM

The bath used to provide the temperature environment was a Rosemount Engineering Company Model 913A. Pertinent specifications are:

Nominal Stability:	0.005°C for a period of one hour or more over the range of - 73°C to + 260°C.
Nominal Uniformity:	0.045°C in the bath calibration zone in the temperature range of - 73°C to + 260°C.

The reference instrument which measured the temperature of the calibration bath was a Rosemount Platinum Resistance Temperature Standard, Model 162-C (serial #694). This working standard was calibrated by comparison to a standard calibrated by the National Bureau of Standards. The results of this calibration showed it to be accurate to within 0.003°C at 0°C and 0.0035°C at 100°C.

The instrument used to measure the resistance change of the platinum resistance thermometer was a Leeds & Northrup Model 8069B Mueller Bridge with a worst case accuracy in the range we were reading of $\pm$ 0.006^{o}C.

CALIBRATION PROCEDURE

The calibration was performed by grouping the 30 thermistors around the reference platinum resistance probe. All sensors and the probe were then lowered into the Rosemount bath. The bath was set to a fixed temperature point, and after the temperature had stabilized a period of from 5 to 7 minutes was allowed to elapse before the resistance readings were taken and stored using the HP 3497 system. The Rosemount bath was then programmed to the next temperature and the cycle was repeated. The calibration points were taken every 5^{o}C from 5^{o}C to 40^{o}C and back to 5^{o}C for a total of 15 points per cycle. Four complete cycles were made.

DATA MANIPULATION

After the data of four cycles had been recorded, the individual calibration constants were calculated using the data from the first cycle. This resulted in a set of three constants for each thermistor to be used in the equation above. A typical set of constants is shown below.

$$A = 1.388332 \times 10^{-3}$$
$$B = 2.39692 \times 10^{-4}$$
$$C = 9.39818 \times 10^{-8}$$

Using the individual set of constants for each thermistor in the conversion equation, the resistance values of the remaining three cycles were converted to temperature. These calculated temperature values were then compared to the actual temperatures at the calibration points as determined by the platinum reference sensor. The difference between the two readings was then plotted for each of the three cycles. A typical error plot is shown in Fig. 1. These plots provided not only the absolute error versus temperature but also gave an indication of the repeatability of the data system. This data indicated the worst thermistor error to be + 0.028^{o}C and - 0.018^{o}C over the calibration range of 5^{o}C to 40^{o}C.

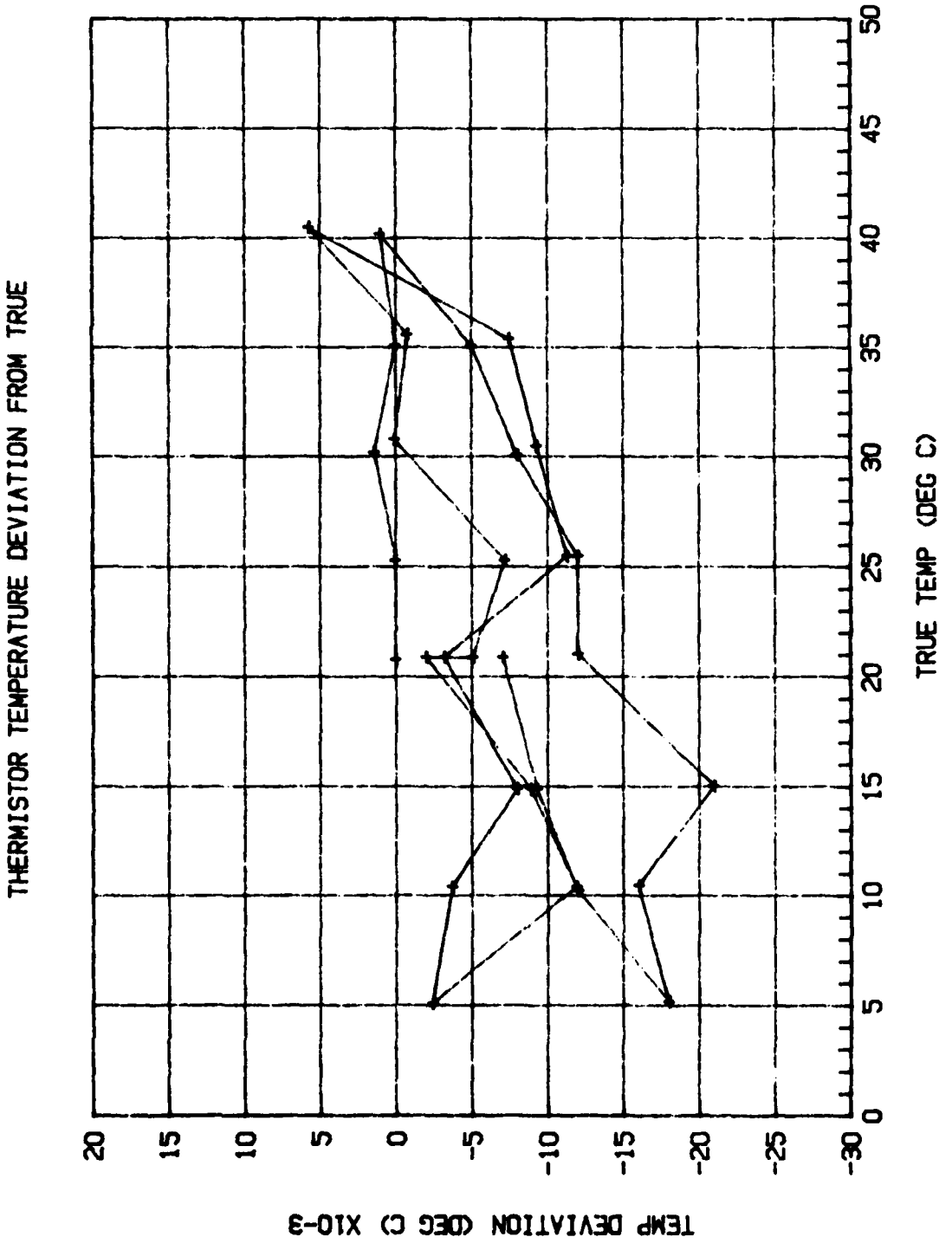
THERMISTOR TEMPERATURE DEVIATION FROM TRUE
TEMP DEVIATION (DEG C) X10-3
20
15
10
5
0
-5
-10
-15
-20
-25
-30
0
5
10
15
20
25
30
35
40
45
50
TRUE TEMP (DEG C)

FIGURE 1

At this point a total system error was calculated by combining the calculated thermistor error with the data system and calibration system errors. The result was a calculated total system error of $\pm$ 0.011^{o}C.

CONCLUSION

The experiment illustrates the use of three powerful techniques to achieve high accuracy and flexibility without sacrificing simplicity and portability. The first of these techniques is the use of a small yet versatile computer, such as the HP 85, to provide three very important functions in a field test of this type. The computer provided the arithmetic capability to do on line conversions of the resistance data to corresponding temperatures. It also provided the real time readout of the converted data and the raw resistance readings on its internal printer. This allowed the experimenters ready access to the data. The final important function was the capability to store the data on its magnetic tape cassette to allow subsequent transfer of the data to a larger computer for use in analysis codes developed for the diagnostic canister.

The second technique is the use of the complete data system in the calibration of the transducer. Many times a transducer is calibrated using a different kind of instrumentation in the calibration laboratory which does not provide as complete a picture of the total system operation.

The third technique is the use of a common power supply in a multi channel resistance measurement application. The combination of a high quality, stable current source and a reliable reed scanner results in a very portable system without sacrificing accuracy. The one drawback to such a system has been stated many times; that is, if the power supply fails all channels are lost. However in a long-term test of this sort, power supply failure is not a serious consideration since the supply could be replaced without the loss of a large amount of data. This pulsing technique is also used with much success in strain gage and potentiometer applications.

```
100 DISP TAB(10);"DATA LOGGER PROGAM"
110 DISP @ DISP "MUST HAVE DATA TAPE WITH CORRECT DATA FILE NAME"
120 DISP "ENTER DATA TAPE FILE NAME "
130 INPUT Z$
140 OPTION BASE 1@ S1=0 @ S2=0
150 S=SPOLL(709)
160 DISP "DO YOU WANT TO RECORD DATA, Y  N "
170 INPUT F$
180 DISP "PRINT # OF SCANS"
190 INPUT S2
200 DISP "ENTER SCAN PERIOD HHMMSS"
210 INPUT T1$
220 T1=VAL(T1$[1,2])
230 T2=VAL(T1$[3,4])
240 T3=VAL(T1$[5,6])
250 T4=T1*60+T2+T3/60
260 DIM S(31),T(31)
270 !
280 !
290 A$="TI"&T1$
300 OUTPUT 709 ;A$
310 OUTPUT 709 ;"  SE010VT2"
320 OUTPUT 709 ;"TE0TE2"
330 OUTPUT 709 ;"ID       "
340 ENTER 709 ; T$
350 ON INTR 7 GOSUB 570
360 ENABLE INTR 7;8
370 IF S1>0 THEN 420
380 GOSUB 580
390 OUTPUT 709 ;"TE0TE2"
400 !
410 !
420 CLEAR @ DISP
430 DISP TAB(12);"TODAYS DATE"
440 DISP TAB(10);T$
450 DISP @ DISP TAB(2);"THE NEXT SCAN IS SCAN #";S1+1;"OF";S2;"SCA
NS"
460 OUTPUT 709 ;"TE"
470 ENTER 709 ; T
480 DISP @ DISP "TO CHANGE SCAN INTERVAL  PRESS KEY #1"
490 ON KEY# 1 GOTO 200
500 DISP @ DISP "TO CONVERT SCAN N TO DEG C PRESS K2"
510 ON KEY# 2 GOSUB 900
520 DISP @ DISP TAB(6);"TIME TO NEXT SCAN IN MIN"
530 T5=T4-T/60
540 DISP USING "12X.2D.2D" ; T5
550 WAIT 3000
560 GOTO 330
570 OUTPUT 709 ;"TE0TE2"
```

```
580 S1=S1+1
590 GOSUB 640
600 IF S1=S2 THEN 810
610 GOTO 330
620 !
630 !
640 !              CHANNEL SCAN SUB
650 STATUS 7,1 : A
660 S=SPOLL(709)
670 OUTPUT 709 ;"AF00AL30S01VC1"
680 FOR I=1 TO 31
690 OUTPUT 709 ;"ASV?3"
700 ENTER 709 ; S(I)
710 S(I)=S(I)/.00001
720 DISP S(I)
730 NEXT I
740 IF F$="N" THEN 760
750 GOSUB 840
760 ENABLE INTR 7;8
770 GOSUB 990
780 RETURN
790 !
800 !
810 END
820 !
830 !
840 !              TAPE STORE SUB
850 ASSIGN# 1 TO Z$
860 PRINT# 1,S1 ; T$,S()
870 RETURN
880 !
890 !
900 !     READ DATA FROM TAPE SUB
910 ASSIGN# 2 TO Z$
920 DISP "ENTER SCAN # TO CONVERT"
930 INPUT Z
940 READ# 2,Z ; T$,S()
950 GOSUB 990
960 RETURN
970 !
980 !
990 !      CONVERT R TO TEMP SUB
1000 PRINT @ PRINT @ PRINT USING "8X,14A,3/" ; T$
1010 FOR I=1 TO 31
1020 READ A,B,C
1030 A=A/1000 @ B=B/10000 @ C=C/100000000
1040 T(I)=1/(A+B*LOG(S(I))+C*LOG(S(I))^3)
1050 T(I)=T(I)-273
1060 PRINT USING 1070 ; I-1,S(I),T(I)
1070 IMAGE "CHAN",X,2Z,4X,4D.2D,4X,3D.3D
```

```
1080 NEXT I
1085 DATA 1.40188,2.37665,9.93118
1090 DATA 1.38838,2.39692,9.39818,1.38779,2.39913,9.13356,1.38955,
2.39833,8.9155
1100 DATA 1.39091,2.39397,9.41929,1.38903,2.39568,9.31026,1.39168,
2.39357,9.35997
1110 DATA 1.39166,2.39275,9.37227,1.38624,2.40122,9.07947,1.38653,
2.40386,8.76517
1120 DATA 1.38573,2.40475,8.80068,1.38858,2.39799,9.22137,1.38697,
2.39953,9.25719
1130 DATA 1.39355,2.38756,9.7743,1.39638,2.38546,9.62025,1.39367,
.39007,9.33268
1140 DATA 1.39095,2.39568,8.95146,1.39004,2.39437,9.46376,1.39148,
2.39332,9.3307
1150 DATA 1.3913,2.39221,9.5255,1.39143,2.39279,9.44942,1.38706,
40125,8.9589
1160 DATA 1.39443,2.38879,9.56103,1.39165,2.3926,9.50617,1.39094,
.39399,9.29265
1170 DATA 1.39392,2.38889,9.55091,1.38976,2.39487,9.45538,1.38945,
2.39687,9.2093
1180 DATA 1.40188,2.37665,9.93118,1.40188,2.37665,9.93118,1.40188,
2.37665,9.93118
1190 RESTORE
1200 RETURN
1210 !
1220 !
1230 !
1240 PRINT USING 1250 ; 1,2,3
1250 IMAGE "CHAN",X,2Z,4X,3D,3D,4X,3D,3D
1260 PRINT USING "4X,14A" ; Z$
1270 GCLEAR @ PEN 1
1280 SCALE -1.1,-1.1
1290 OUTPUT 709 ;"TD"
1300 ENTER 709 ; T$
1310 MOVE -.5,.1
1320 LABEL T$ @ WAIT 2000
1330 GOTO 1270
1340 END
```

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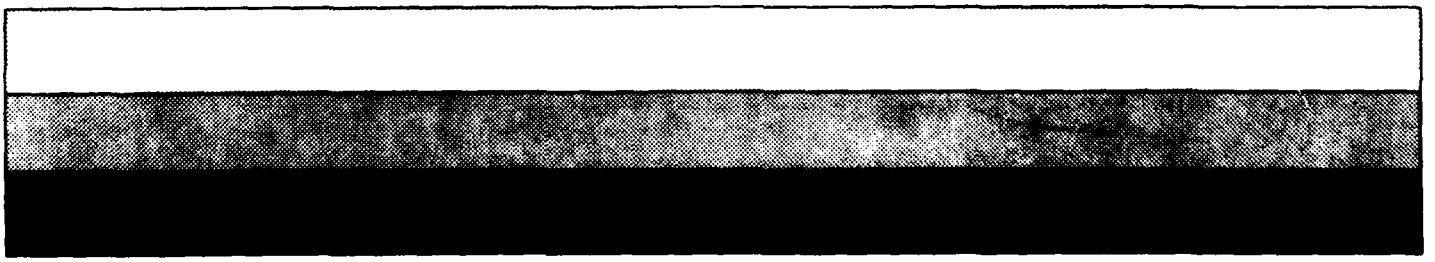


ADP002679

A NEW APPLICATION OF PROXIMITY PROBE MEASUREMENT ON ROLLING ELEMENT BEARINGS

by

Tom McGauvran
Southeast District Sales Manager
Bently Nevada Corporation

Presented at 12th Transducer Workshop, Melbourne, Florida, 7 June 1983.

INTRODUCTION

Flaw detection in rolling element bearings has long presented a difficult challenge to accomplished machinery experts. Due in large part to the complexity of the overall vibration signature, flaw detection has focused on an examination of individual frequency components. The primary instrument for this analysis has been the real time spectrum analyzer.

History of Roller Element Bearing Measurements

Two transducer types have been utilized for the measurement of vibration on machines equipped with roller element bearings. Both the velocity pickup and the accelerometer are seismic type devices that have generally been located on the bearing cap or bearing housing. Due to the mechanical separation between the roller element bearing and the transducer mounting location, a certain amount of signal attenuation takes place.

In addition, the velocity pickup has a limited frequency response as a result of its spring/mass mechanical construction. The frequency range for a typical velocity pickup is approximately 5 Hz to 1 KHz. In many cases this is sufficient to measure the high frequencies associated with roller element bearings. However, on higher speed machines with complex roller element bearings, the frequencies encountered may exceed the measurement capabilities of the typical velocity pickup.

To measure these higher frequencies, the industrial community has looked to the accelerometer. While several types of accelerometers are available, the piezoelectric model is most commonly used. The frequency range for a typical piezoelectric accelerometer is 2 Hz to 30 KHz. While this appears to solve the upper frequency limitations of the velocity pickup, the signal attenuation problem remains. While formal rules for mechanical attenuation are difficult to determine, a 20 db signal loss has been observed on test machines during controlled operation.

New Technology

A recent development in the measurement of roller element bearing motion involved the use of a fiber optic sensor observing the outer race of a bearing. This was originally demonstrated by Gerald J. Philips with the David W. Taylor Naval Ship Research & Development Center in Annapolis, Maryland. The essence of the concept is that the outer race will deflect a measurable amount as a result of the passage of the rolling elements in the bearing. Any defects in the rolling elements, the inner race, or the outer race should also be measurable on the outer race, as the defect passes the observed point.

Bently Nevada Corporation has adapted this concept to industrial applications by the substitution of a high-gain, low noise eddy current proximity probe transducer system to measure outer race deflections. This specialized noncontact transducer system has a linear measurement range of 10 mils and a scale factor of 2000 Mv/mil. With this type of scale factor noncontact measurement capabilities in the microinch range become possible.

Probe Installation

The proximity probe is mounted through the machine bearing cap so that it can directly observe the bearing outer race. To accomplish this, the bearing housing must be drilled and tapped to accommodate the 3/8-24 threaded probe body. If the machine utilizes oversize bearings or operates under low load situations, the amount of outer race deflection can be increased by relieving the bearing housing at the point of outer race observation. Tests by bearing manufacturers' have revealed no adverse effects when the bearing housing is counterbored to a depth of one-eighth inch, with the bore diameter being no greater than one-half the spacing between the roller elements.

For optimum signal response, the proximity probe should be mounted within 45° of the load zone. On large, well aligned machines, the load zone is generally determined by the gravity preload on the system. For other machine configurations, such as chain or belt drives, the load zone may be determined by other external influences.

Bearing Failure Modes

It is well documented that there are two basic reasons for rolling element bearing failures. The first has to do with the bearing itself. Insufficient lubrication, an incorrect lubricant, or various foreign particles can all bring about the demise of a roller element bearing. A lack of lubrication or an external contaminant will eventually cause a mechanical defect in one of the bearing races or in one or more roller elements. After the first mechanical defect appears in the bearing, it is simply a matter of time until it produces a multitude of defects and the bearing is destroyed.

These types of defects or flaws are readily observed by the proximity probe system. If a roller element encounters a flaw in either the inner or outer race, the impact that is created is transmitted through the outer race as a displacement shock with a very short time duration. These short duration spikes are easily observed through the use of a standard oscilloscope. The frequencies generated by these internal bearing flaws are generally three times the roller passage frequency or higher. Typical deflections of the outer race are on the order of 2 to 100 microinches.

The second cause for bearing failures is related to the machine rotor. Specifically, the roller element bearing will break down when its load carrying capacity is exceeded by forces generated from the rotor assembly. These excessive loads can be a result of mass imbalance, misalignment, bowed rotors, out-of-round inner races, or cocked bearings. The frequencies encountered by rotor related malfunctions are generally less than three times the roller passage frequency.

As the spectral content of the proximity probe system is less complex than that of an accelerometer or velocity pickup, the classification of "rotor related" or "bearing related" problems becomes a reasonable objective. If a rotor related malfunction is detected in its early stages, it is now possible to diagnose and correct the problem before it graduates to an irreversible bearing related problem.

Summary

Field testing of proximity probe monitoring on roller element bearings is currently underway at the Naval Research Center in Annapolis, Maryland, at several Midwestern bearing manufacturers, and at more than two dozen end user plant sites throughout the United States and Europe. Although no final results have been formalized as of this date, many preliminary reports are very encouraging. The direct observation of microinch outer race excursions may well prove to be the best answer to the early detection of rolling element bearing failures.

List of References

1. Rotating Machinery Bearing Analysis, G. J. Philips and Fritz Hirschfeld. Mechanical Engineering, July 1980.

2 . The Fiber Optic Bearing Monitor, Gerald J. Philips. ISA, 1982.

3. Cost Effective Continuous Monitoring of General Purpose Rotating Machinery, Donald E. Bently and Roger C. Harker. Bently Nevada Corporation, November 1982.

4. REBAM - A Technical Review, Donald E. Bently, J. Steven Hansen, Frank Howard, and Joseph Modarelli. Bently Nevada Corporation, May 1983.

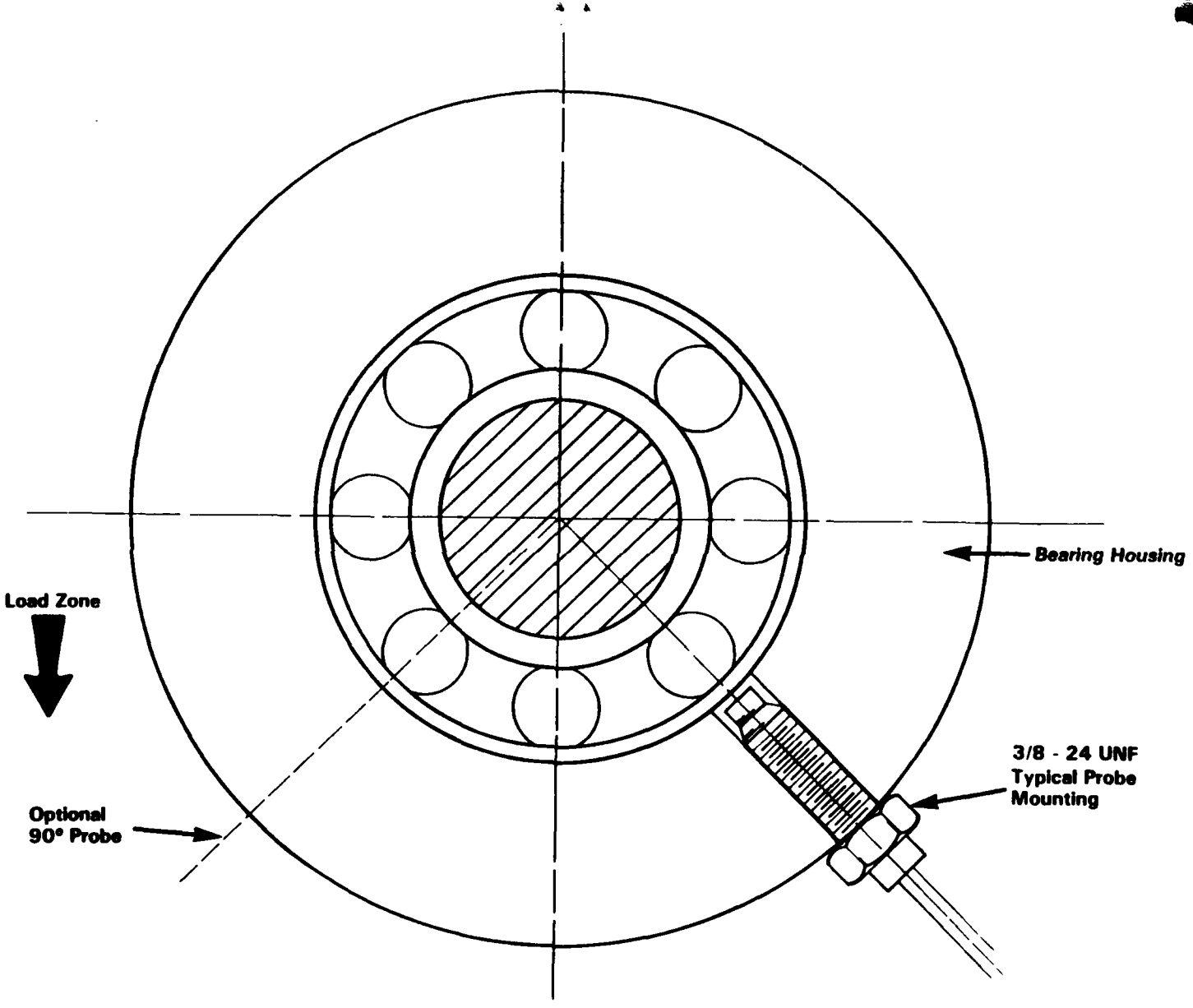

Bearing Housing
Load Zone
3/8 - 24 UNF
Typical Probe
Mounting
Optional
90° Probe

Figure 1

TIME BASE SIGNAL COMPARISON
INNER RACE FLAW

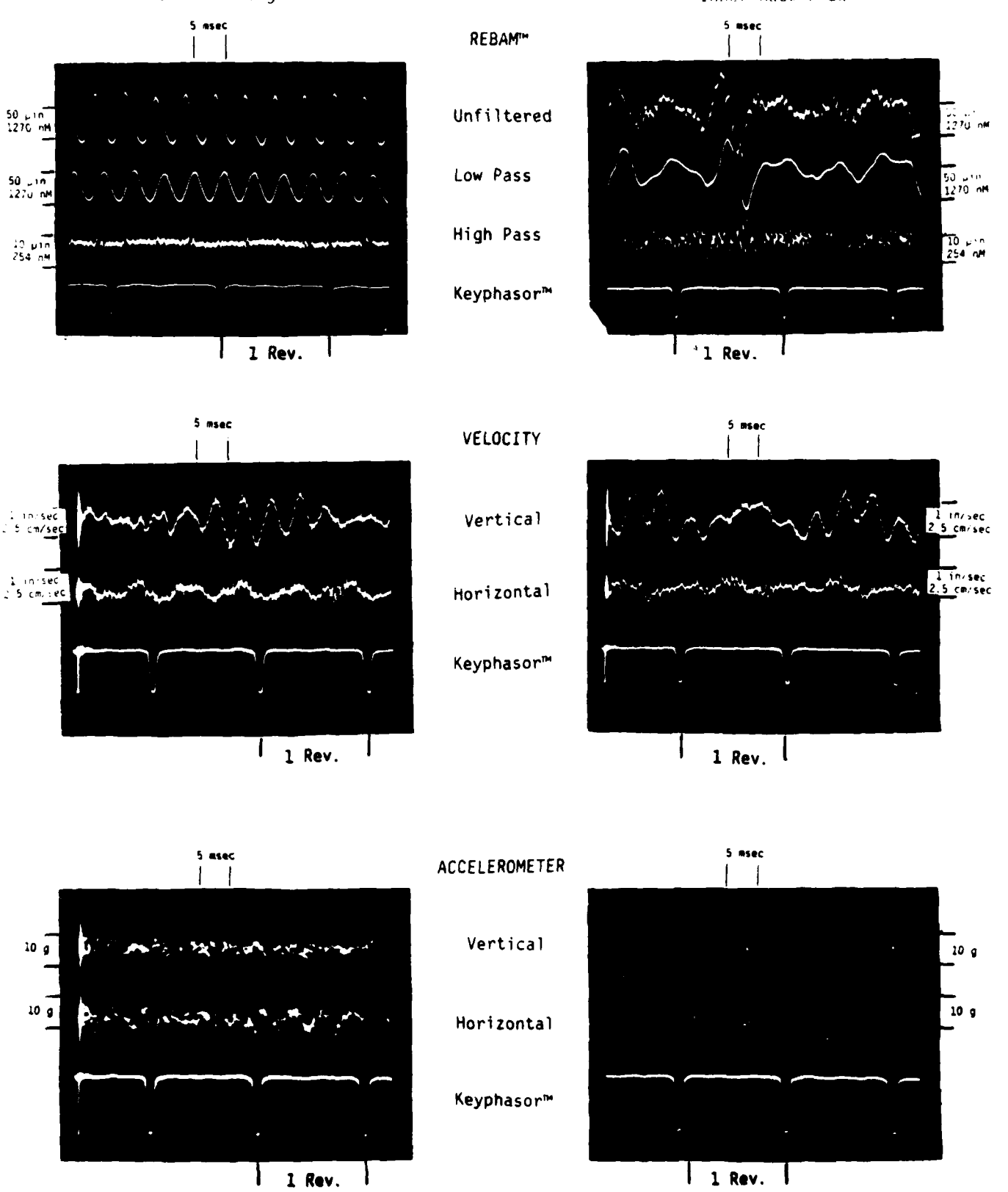


Figure 2

TIME BASE SIGNAL COMPARISON
OUTER RACE FLAW

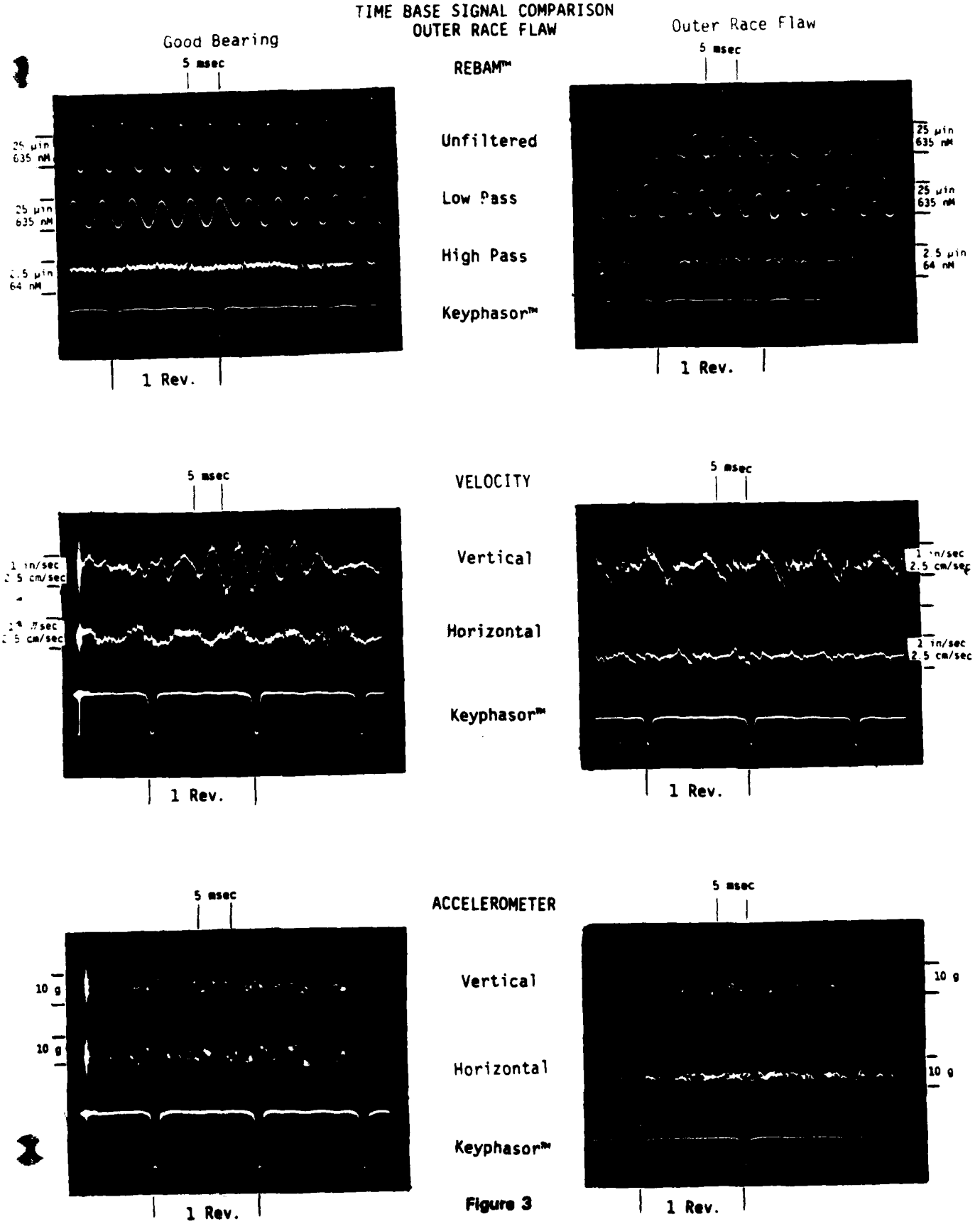


Figure 3

TIME BASE SIGNAL COMPARISON
BALL FLAW

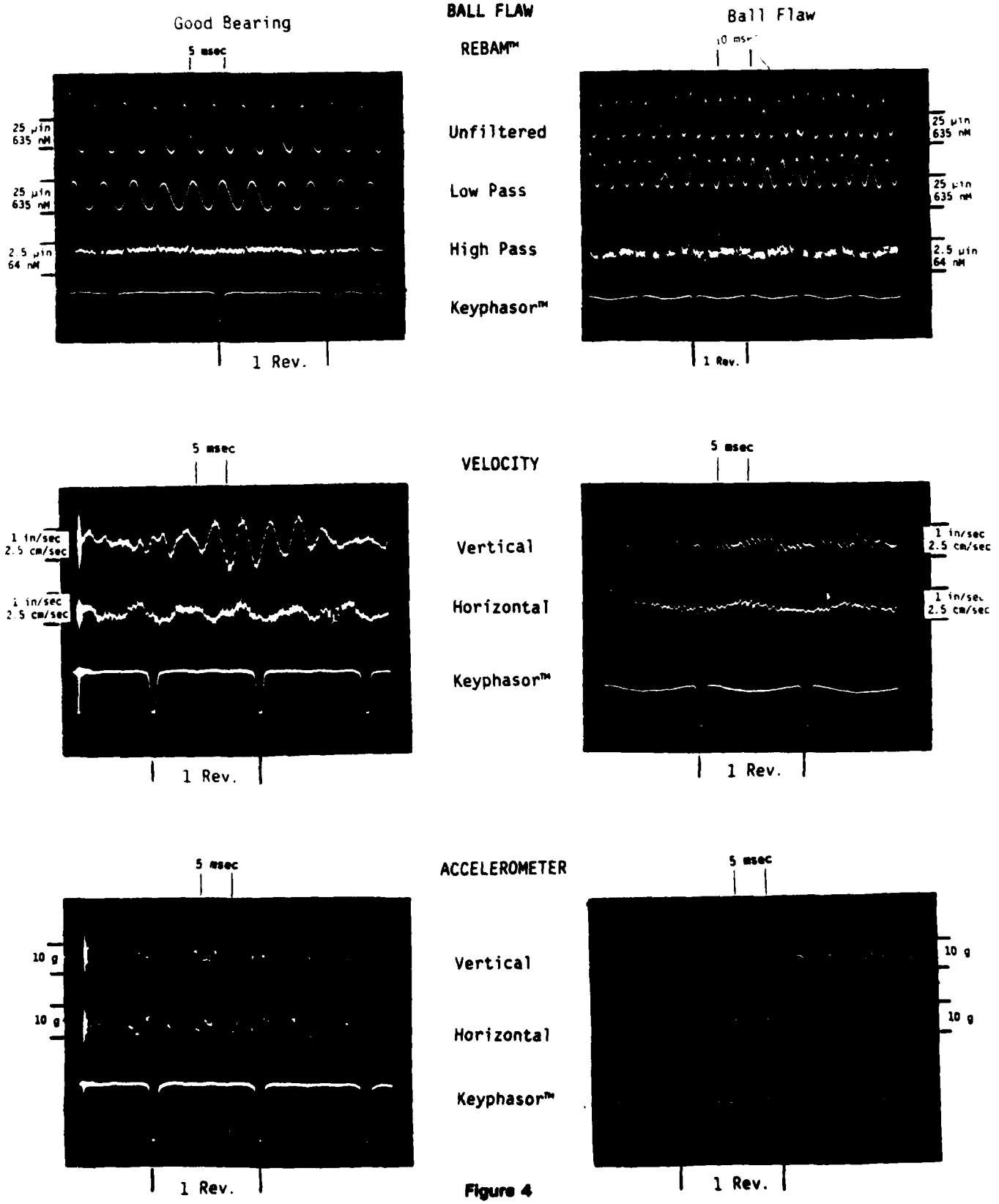


Figure 4

AD P002680

SPACE SHUTTLE MAIN ENGINE TURBOPUMP TRANSDUCER

by Tom Peterson
Rocketdyne Division
Rockwell International

Introduction:

Part of the credit for the success of America's Space Shuttle goes to the operation of the Rocketdyne-built Space Shuttle Main Engines (SSME). Three Main Engines along with the Solid Rocket Boosters, have powered the Space Shuttle's Columbia and Challenger to orbit several times; with more to come. (Figure 1) The reusability of the SSME has been demonstrated by the success of the first five flights of the Columbia using the same three SSMEs.

Advances in liquid rocket engine technology were required to meet the life and reusability criteria set by the Space Shuttle Program for the SSME. To verify the SSME design life, extensive development testing and hardware inspection was required.

Each SSME has four turbopumps which are used to pump propellant for combustion. One of these turbopumps which pumps liquid oxygen is the High Pressure Oxygen Turbopump (HPOTP). Using a two-stage turbine, the HPOTP produces 29,410 horsepower to pump 69.6 pounds per second of liquid oxygen. (Figure 2) One area of hardware inspection and testing to insure engine life and operation was in the area of the rocket engine turbopump bearings. Bearing life is critical to the overall reusability of the HPOTP.

After each development test of the SSME, inspection of many engine parts are made. During inspection of the HPOTP it was observed that some of the bearings in the pump were wearing excessively. The bearings in question were the number 3 and 4 bearings in the pump. (Figure 3) To determine the cause of the wear, one HPOTP would be instrumented to monitor the bearing conditions.

Transducer Design Considerations:

Before the HPOTP could be instrumented, a means to monitor the bearing load conditions was devised. Considerations were made with respect to the operating conditions of the HPOTP and the type and placement of the instrumentation.

The regions around the bearings and the bearings themselves are cooled with liquid and gaseous oxygen. The temperature ranges from ambient to -273°F. The area is pressurized up to 400 psig during the HPOTP operation. Because of the Liquid Oxygen (LOX) environment, all instrumentation placed in the pump would have to be compatible with LOX or be covered to protect it from the LOX.

A protective coating was proposed that would cover the instrumentation to protect it from the LOX environment. The coating, supplied by Raybestos-Manhattan called Refset, was used to cover non-LOX compatible materials. Raybestos-Manhattan recommended the Refset compound as the most suitable for a pressurized LOX environment. Further laboratory tests by Rocketdyne verified the use of Refset in the HPOTP. The tests included LOX impact, thermal shock and strain transfer tests.

The LOX impact test verified the impact resistance of Refset in a pressurized LOX environment. The test impacted a sample of Refset with 72 ft-lbs of energy. The environment around the sample was controlled to -220°F and pressurized to 600 psig. Twenty impacts were made without a Refset reaction.

The thermal shock test determined the thermal sensitivity of Refset. A test bar coated with Refset was submerged in liquid nitrogen. Strains up to 6000 micro in./in. were then applied to the Refset area of the Test bar. The test was repeated four times. After the tests, the Refset coating was examined for cracks or loss of adhesiveness. No visual or microscopic indications of cracking, peeling or any other evidence of loss of adhesion was found.

The strain transfer test verified the use of Refset with strain gages. A test bar was straingaged and placed in a tensile test machine. Strains were recorded as load was applied with and without a Refset coating over the strain gages. The test data showed no difference in recorded in strain between the uncoated and coated strain gages. It was concluded from these tests that Refset would be acceptable as a protective coating over non-Lox compatible instrumentation.

The type and placement of the instrumentation in the HPOTP was the next consideration. Several methods were reviewed to monitor the load on the bearing in the HPOTP. Figure 4 shows the use of a small load cell (piezioelectric type) to measure loads applied to the bearings. As shown in Figure 3, the cartridge support is attached to the HPOTP housing and the bearing cartridge acts as a spring to allow the HPOTP to travel axially. The axial movement is plus and minus forty thousandths of an inch from the zero position. One of the axial travel stops is the cartridge support. The other stop is a HPOTP part that hooks over the edge of the bearing cartridge. The load cell would be placed on the cartridge support to measure the load as the bearing cartridge bottoms while traveling toward the Turbine End. Advantages to the loadcell method would be that the load cell could be calibrated independent of the pump and the loadcell could be matched to the estimated bearing load. By selecting the proper loadcell range, the signal output could be optimized. The disadvantages of the loadcell are that load measured is in only one direction and the little availability of the loadcell with the proper range and size from a supplier.

The next two methods were derivatives of the loadcell idea. (Figures 5 and 6) Each used a load column to sense the bearing load. Both methods removed the doubt of loadcell availability. The loadcell would be manufactured "in house" but the load measured was still only in one direction. The design and installation of the load columns also was complex with anti-rotation tangs and retainer rings.

The next method (Figure 7) uses the cartridge support as a spring elemen.. Stress concentration holes were devised to try to increase the strain output but with little success. Less than 0.025 mV/V output was calculated using the estimated bearing loads. Because of the low signal output and the one direction load, this method was not used. The last two methods that were reviewed incorporated the use of the Bearing Cartridge as the spring element. Figure 8 shows a strain gage easily placed on the pump end of the Bearing Cartridge. This location would sense applied bearing loads in both directions and would require minimum rework of the HPOTP hardware. The disadvantage was the questionable low signal output.

Figure 9 is similar and requires little hardware modification but some doubt as to the signal output.

After studying the last two methods it was observed that during bearing loading the strains in the Bearing Cartridge of the last two proposed locations were opposite in direction. That is, as the load was applied toward the turbine end of the HPOTP, the strain gage location in Figure 8 would be in compression and the strain gage location in Figure 9 would be in tension. By using the two locations and wiring them in the same Wheatstone instrumentations bridge, an additive output could be gained. This additive signal output would overcome the concern of low output from only one location.

To verify the signal output of the last two methods, a bench test was made using the Bearing Cartridge. Strain gages were installed on the Bearing Cartridge in the two designated locations. The Bearing Cartridge, mounted in fixtures to simulate the HPOTP, was loaded up to 3000 pounds in both axial directions. Strains up to 1200 μin./in. were records from the individual locations.

As the bearing load strain gage locations were being specified, a secondary objective of monitoring HPOTP shaft axial travel was suggested. By knowing the location of the shaft axially in the HPOTP, it would verify the direction of the bearing load and provide information on the HPOTP operation. The slotted area of the Bearing Cartridge became an ideal area for the strain gages to monitor shaft axial movement.

The layout of the two channels of shaft travel monitoring strain gages (Bridges No. 2 and No. 5) and the three channels of load monitoring strain gages (Bridges No. 1, No. 3 and No. 4) are shown in Figure 10. The Bearing Cartridge was modified slightly to allow for easier wire routing of the load monitoring strain gages.

Strain gages were used as the monitor sensor for several reasons. The installation of the strain gage required very little hardware modification.

Also, Rocketdyne was familiar with strain gage installations and the accompanying instrumentation.

The next step in the design considerations to monitor bearing load and shaft travel was to specify the type of strain gages and epoxy to use. The first consideration would be the environment where the strain gage would operate and the material to which it will be bonded. The temperature around the Bearing Cartridge during operation ranges from ambient to -273°F The Bearing Cartridge material is Inconel 718 with a coefficient of expansion of 7.8 ppm/°F. Due to the low temperature extreme of the Bearing Cartridge, a nickel-chromium alloy foil gage with a self-temperature compensation (S-T-C) of 13 was specified. The S-T-C of 13 supplies the best fit of the apparent strain curve on Inconel 718 at the low temperature end of the HPOTP operating range. The alloy foil was also specified on a glass reinforced epoxy-phenolic resin backing since strains of less than 1% were to be encountered. The strain gage size was limited to what would fit the locations. With these considerations in mind, the strain gages called for use on the Bearing Cartridge were SK-13-031DE-350 and SK-13-031EC-350 by Micro Measurements. M-Bond 610 was designated as the bonding agent because of its outstanding job at cryogenic temperatures.

The strain gages were applied to the Bearing Cartridge as identified on Figure 10, curing the M-Bond 610 at 350°F for two hours and post-curing at 400°F for two hours. Figures 11, 12, 13 and 14 show the actual strain locations and wire routing. The strain gages and wires were then coated with Refset.

Transducer Calibration and HPOTP Assembly:

The instrumented Bearing Cartridge was ready for calibration and installation in the HPOTP. A bench calibration of the Bearing Cartridge was made on an Instron Machine using fixtures to simulate the HPOTP housing and bearing. Loads up to 5000 pounds were applied while deflection and strain measurements were made. The bench calibration was performed at ambient and liquid nitrogen temperatures. The strain verse load or deflection was then plotted. (Figure 15)

The Bearing Cartridge was then cleaned and installed in a HPOTP. The strain gage wires were routed out of the HPOTP through two Conax fittings (see Figure 7) After installation, the Bearing Cartridge calibration was checked by applying loads to the HPOTP's shaft and monitoring the strain gage output. This load application was performed at ambient and liquid nitrogen temperatures also.

HPOTP Engine Testing and Data Discussion:

After complete assembly, the instrumented HPOTP was shipped to the Santa Susana Field Laboratory of Rocketdyne for installation into an SSME. After installation, the deflection monitoring strain gages were checked for a "zero" reading. This verified that the HPOTP had been installed properly and the shaft was not already bottomed. A total of twenty-two "hot fire" tests were made with the instrumented HPOTP in an SSME. The test time varied from 1.5 to 200 seconds and included testing the HPOTP in three different SSMEs.

From the test data, plots of the HPOTP shaft travel and bearing load versus time were made. One test is depicted in Figure 16. At the start of the test the HPOTP is bottomed against the turbine end stop. After about 3 seconds into the test the shaft moves away from the stop and is axially balanced during changes in Engine power level. At cut-off, the shaft again bottoms against the turbine end stop. With the shaft moving on and off the stops, a verification of the strain gage calibration was made.

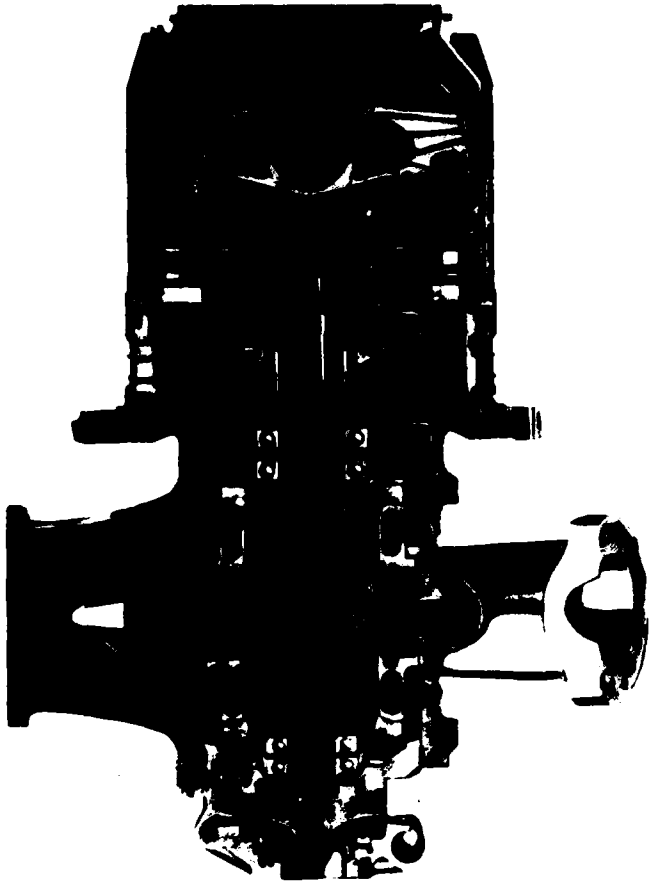
Figure 17 depicts bearing load and shaft position as monitored by the instrumented Bearing Cartridge. At engine start, the HPOTP shaft is again bottomed against the turbine end stop. Load can be noted being applied to the bearings of up to 2000 pounds. After leaving to stop, the shaft is again balanced axially and the load monitoring channel is essentially zero. At cut-off, the shaft bottoms on the turbine end stop and a large load of about 6000 pounds is applied to the bearings. After four seconds, the shaft moves to the pump end stop and another load is applied to over 4000 pounds on the bearings.

As the engine test data was reviewed from the instrumented HPOTP, insight was gained and corrective action was taken to lower HPOTP bearing loads. By lowering the bearing loads the life of the bearings was increased. After a small engine cut-off valve sequence change, the loads to the bearing were cut to below 1000 pounds. Other changes were made to insure that the bearing loads in the HPOTP remain low.

Designing, building and using the instrumented Bearing Cartridge provided the needed data to insure proper bearing life in the HPOTP. This type of testing insures the SSME will meet the expected design life required by the Space Shuttle Program.

figure 1

[redacted] PRESSURE OXYGEN TURBOPUMP



KEY PERFORMANCE PARAMETERS				
	RPL		FPL	
	MAIN	BOOST	MAIN	BOOST
PUMP INLET FLOWRATE (LB/SEC)	1067.1	108.7	1158.8	124.3
PUMP INLET PRESS.(PSIA)	405.2	4146.1	423.0	4635.6
PUMP DISCHARGE PR (PSIA)	4283.7	7329.4	4762.5	8116.3
PUMP EFFICIENCY	0.678	0.807	0.675	0.809
TURBINE FLOWRATE (LB/SEC)	62.1		69.6	
TURBINE INLET PR (PSIA)	4969.9		5553.0	
TURBINE INLET TEMP (DEG R)	1399.2		1467.6	
TURBINE PRESS RATIO	1.495		1.523	
TURBINE EFFICIENCY	0.812		0.828	
TURBINE SPEED (RPM)	27885		29961	
TURBINE HORSEPOWER	23950		29410	

LC90-58

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figure 2

AD-A137 304 TRANSDUCER WORKSHOP (12TH) HELD AT MELBOURNE FLORIDA ON 7-9 JUNE 1983(U) RANGE COMMANDERS COUNCIL WHITE SANDS MISSILE RANGE NM TELEMETRY GROUP L BATES ET AL. JUN 83 3/9

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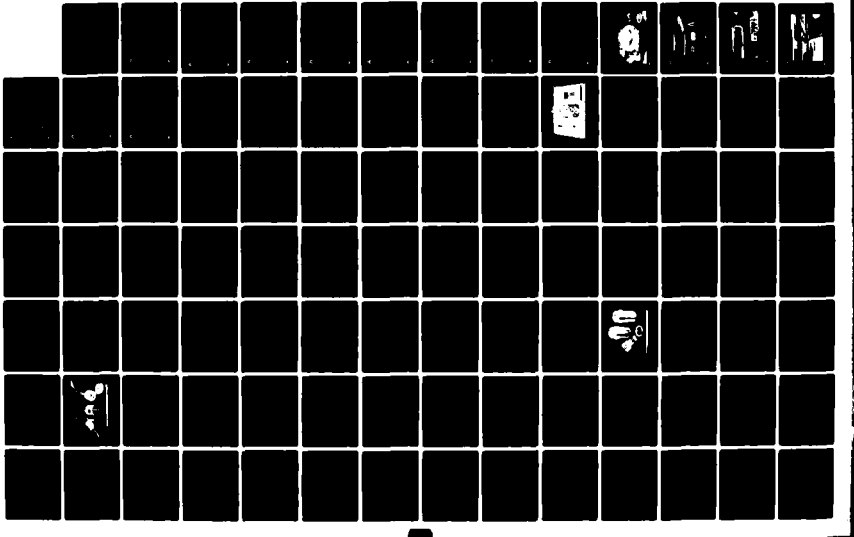
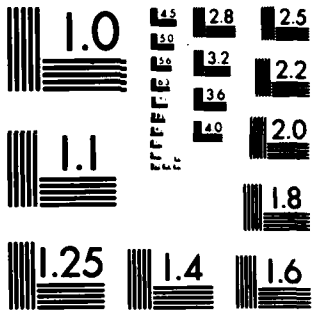
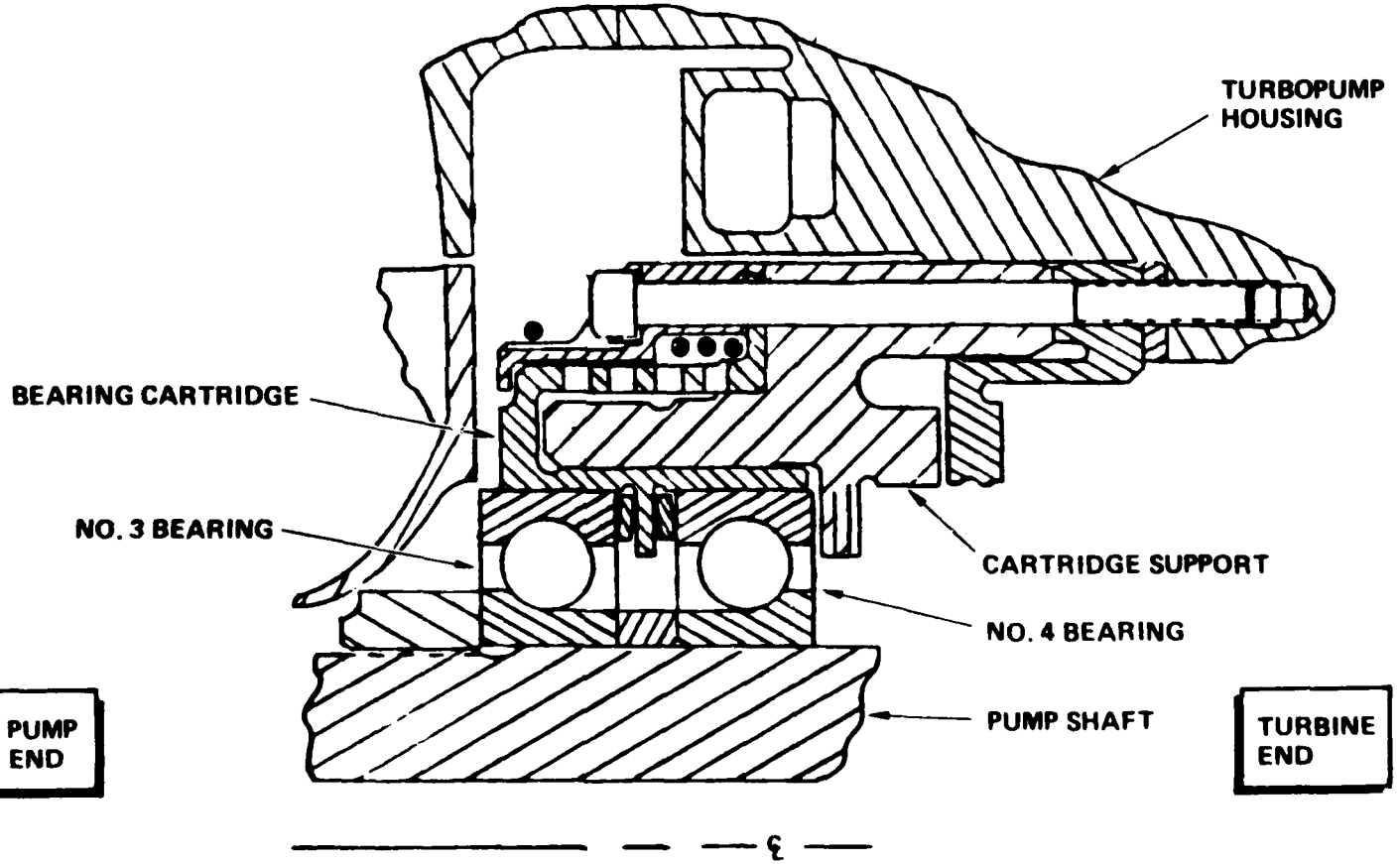




MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

INSTRUMENTED HPOTP BEARING CARTRIDGE



435-268

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figure 3

INSTRUMENTED HPOTP BEARING CARTRIDGE

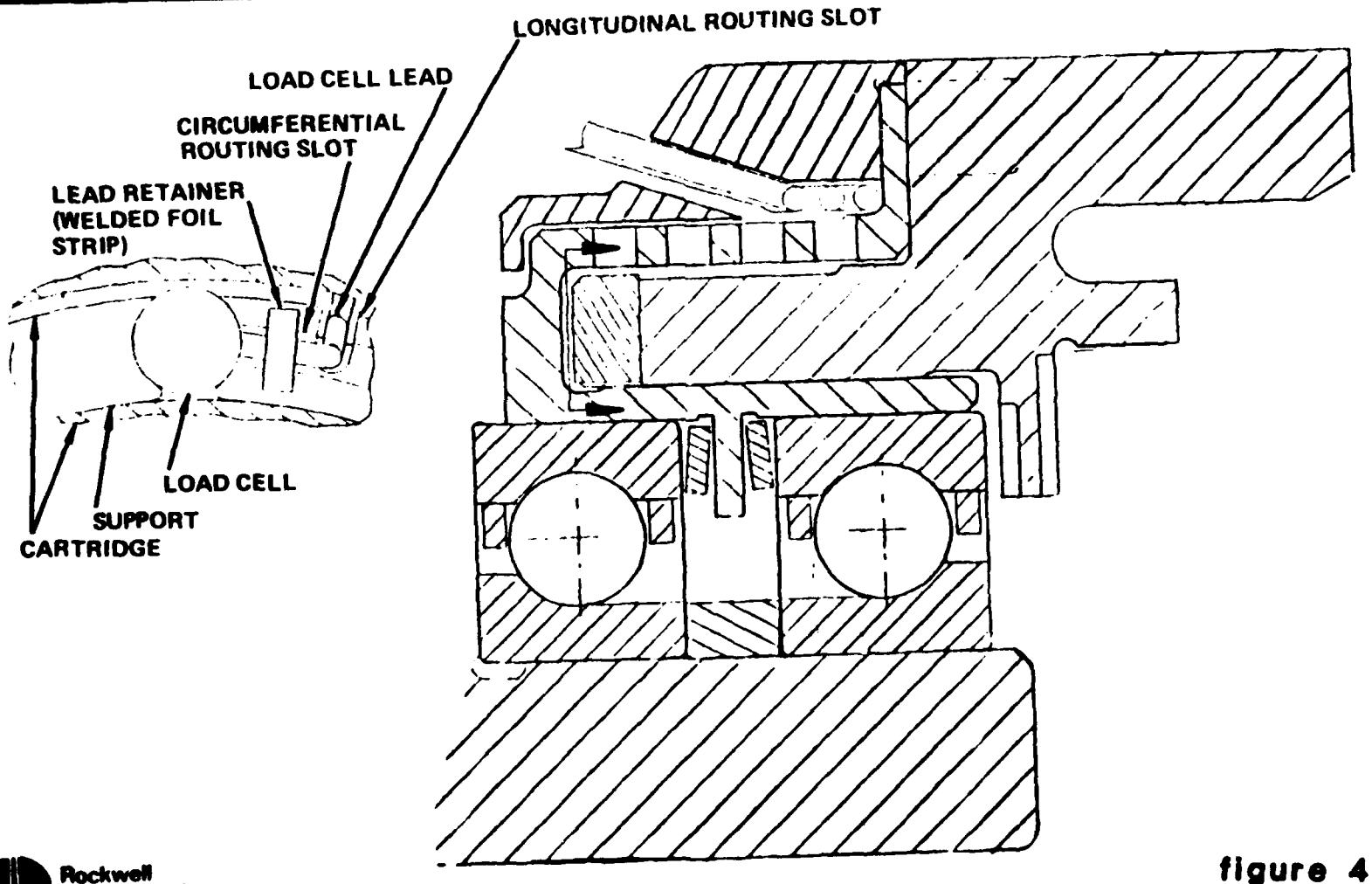

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figure 4

INSTRUMENTED HPOTP BEARING CARTRIDGE PROPOSED STRAIN GAGE LOCATIONS

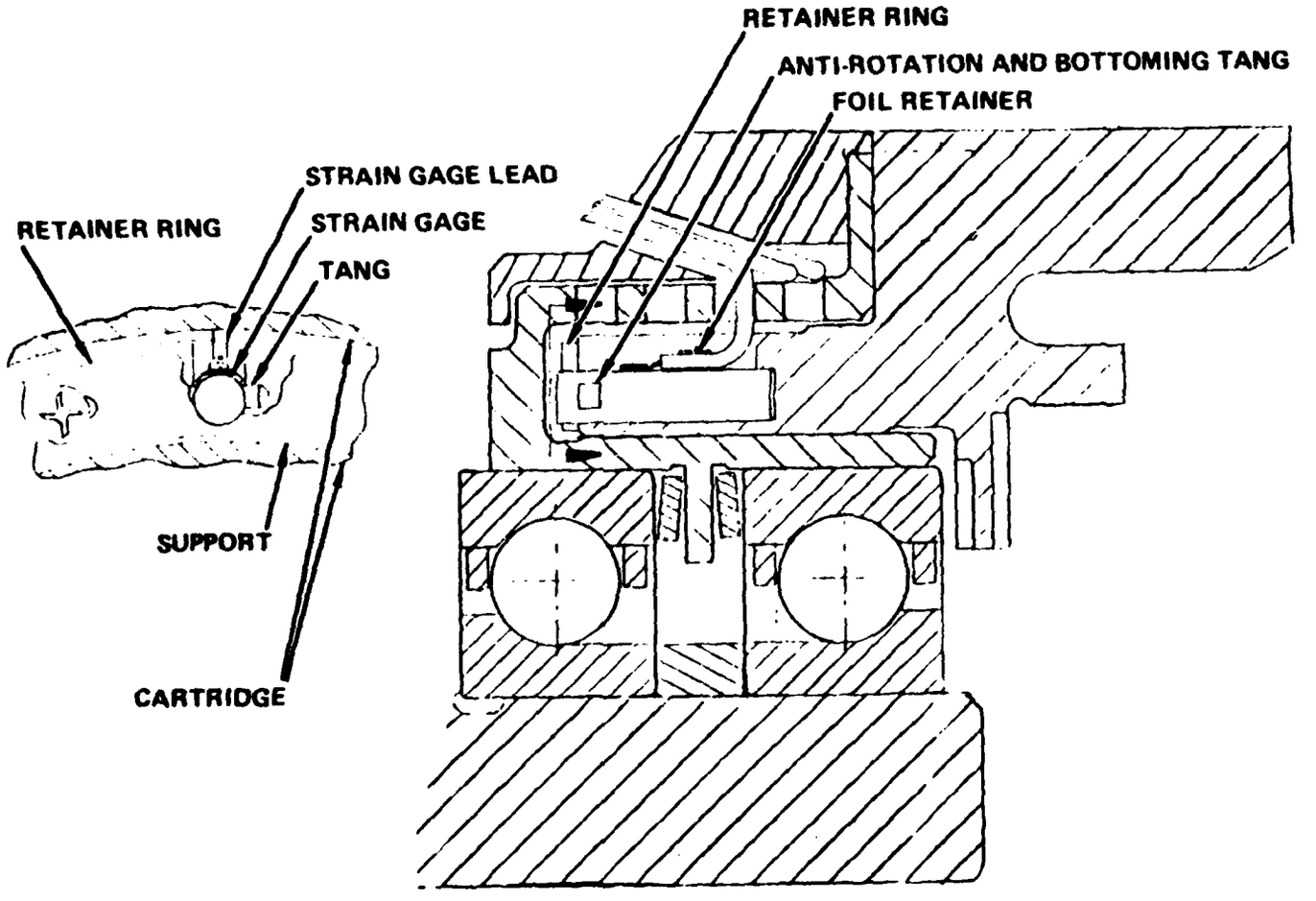

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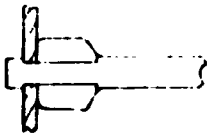
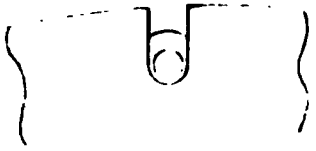
figure 5

INSTRUMENTED HPOTP BEARING CARTRIDGE



VIEW A–A



VIEW B–B

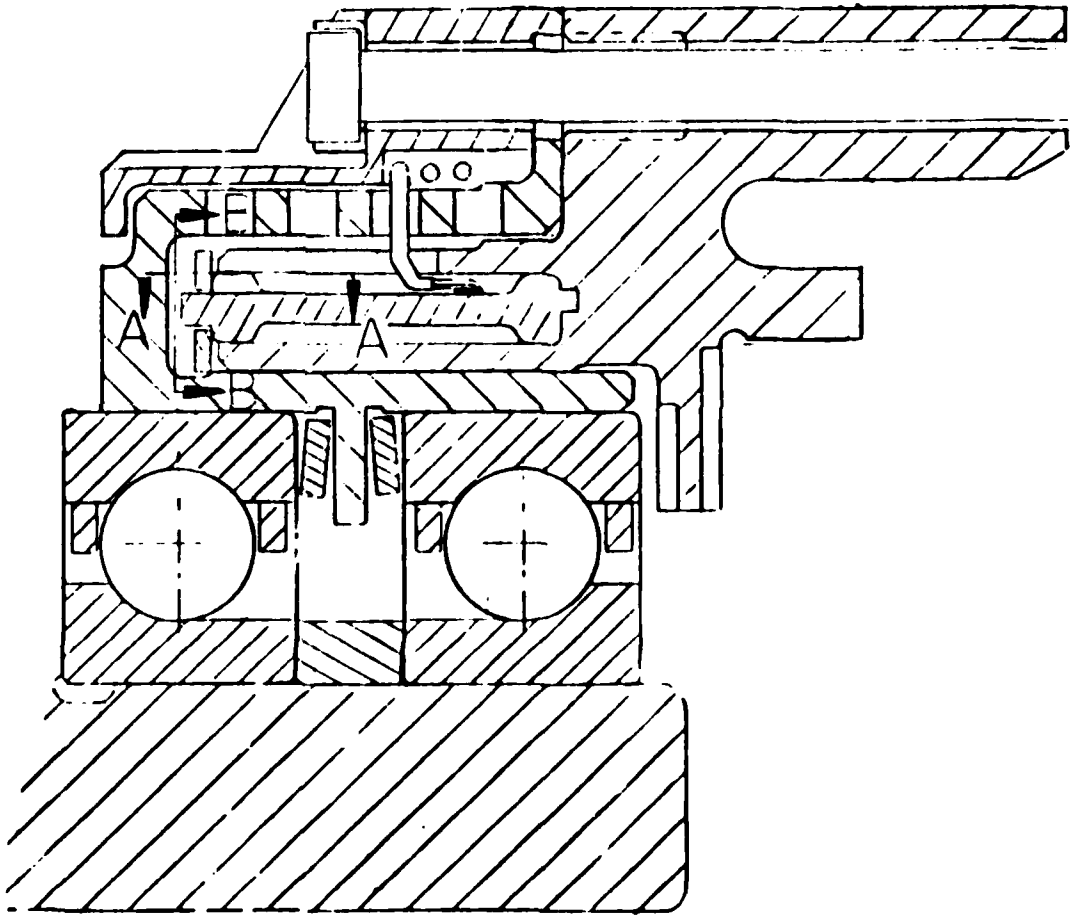


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figure 6

INSTRUMENTED HPOTP BEARING CARTRIDGE PROPOSED STRAIN GAGE LOCATIONS

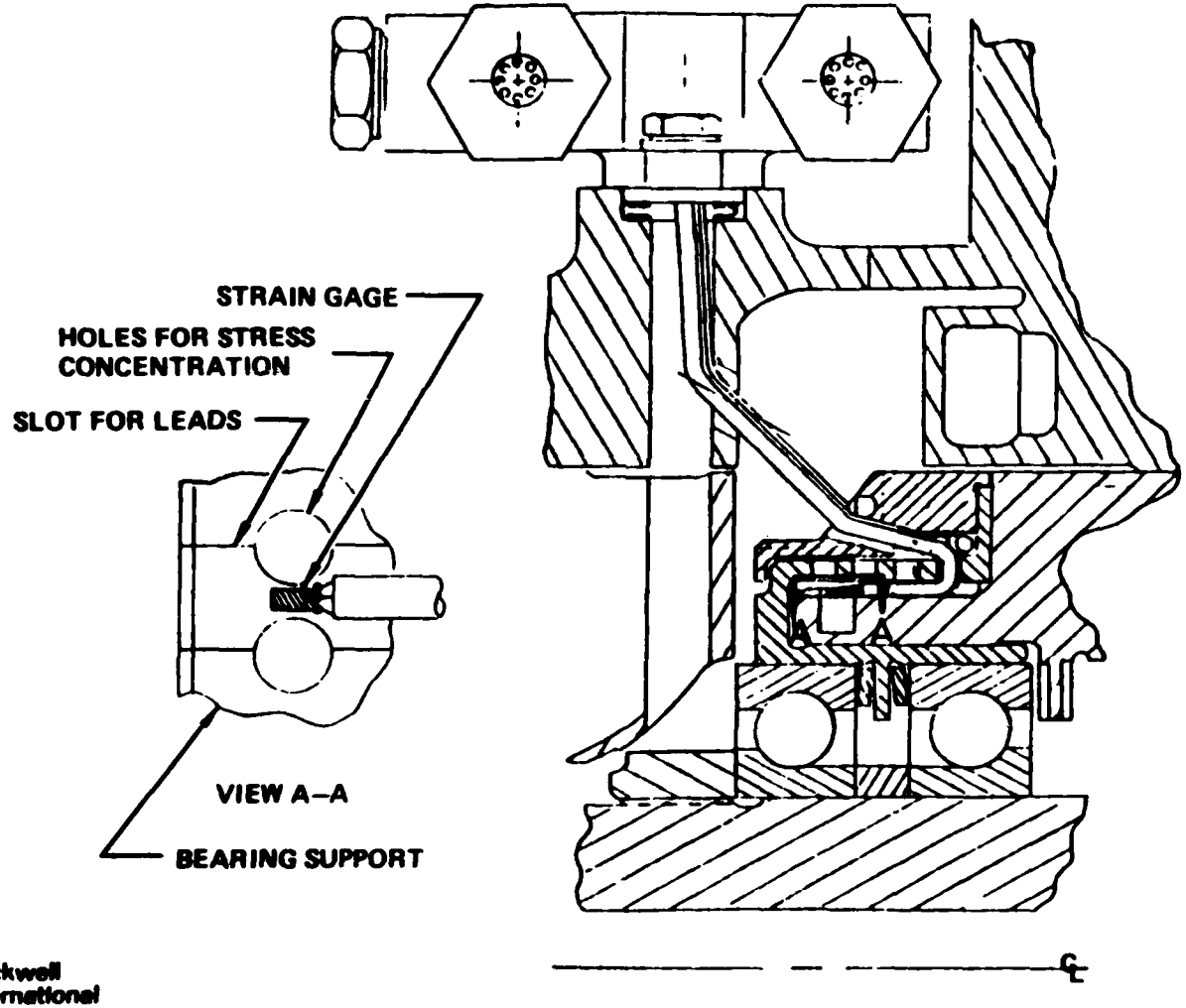

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figure 7

INSTRUMENTED HPOTP BEARING CARTRIDGE PROPOSED STRAIN GAGE LOCATIONS

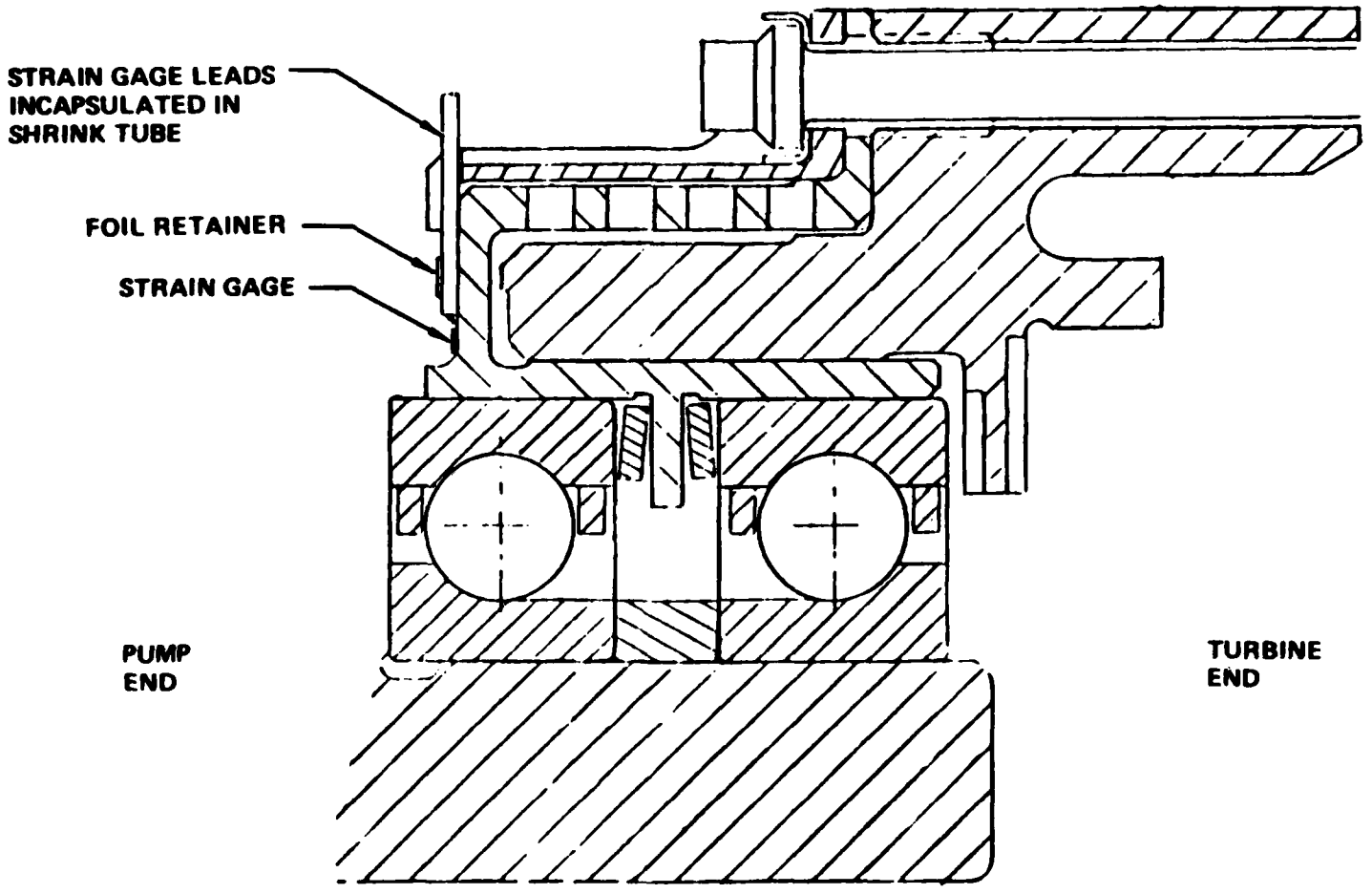

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figure 8

INSTRUMENTED HPOTP BEARING CARTRIDGE PROPOSED STRAIN GAGE LOCATIONS

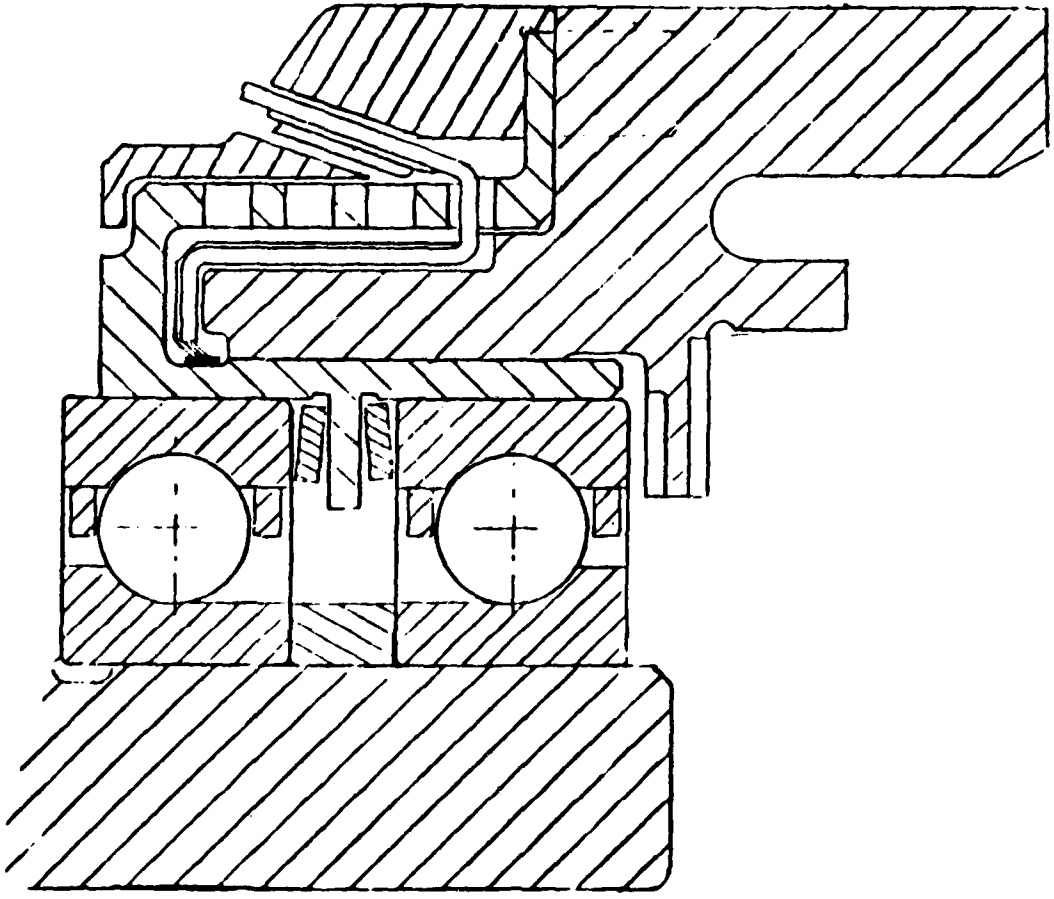

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figure 9

INSTRUMENTED HPOTP BEARING CARTRIDGE STRAIN GAGE INSTALLATION

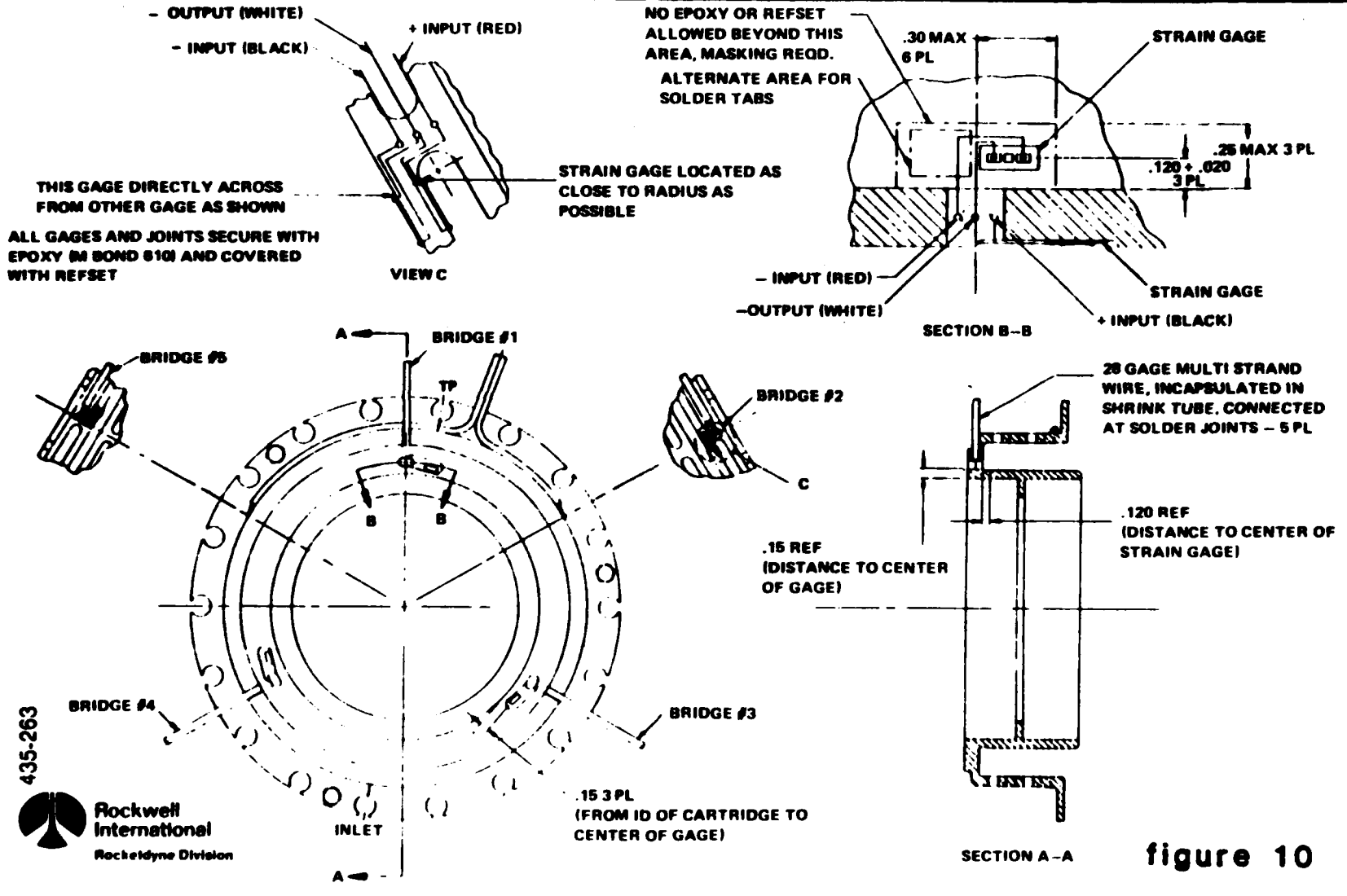

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figure 10

HPOTP BEARING CARTRIDGE

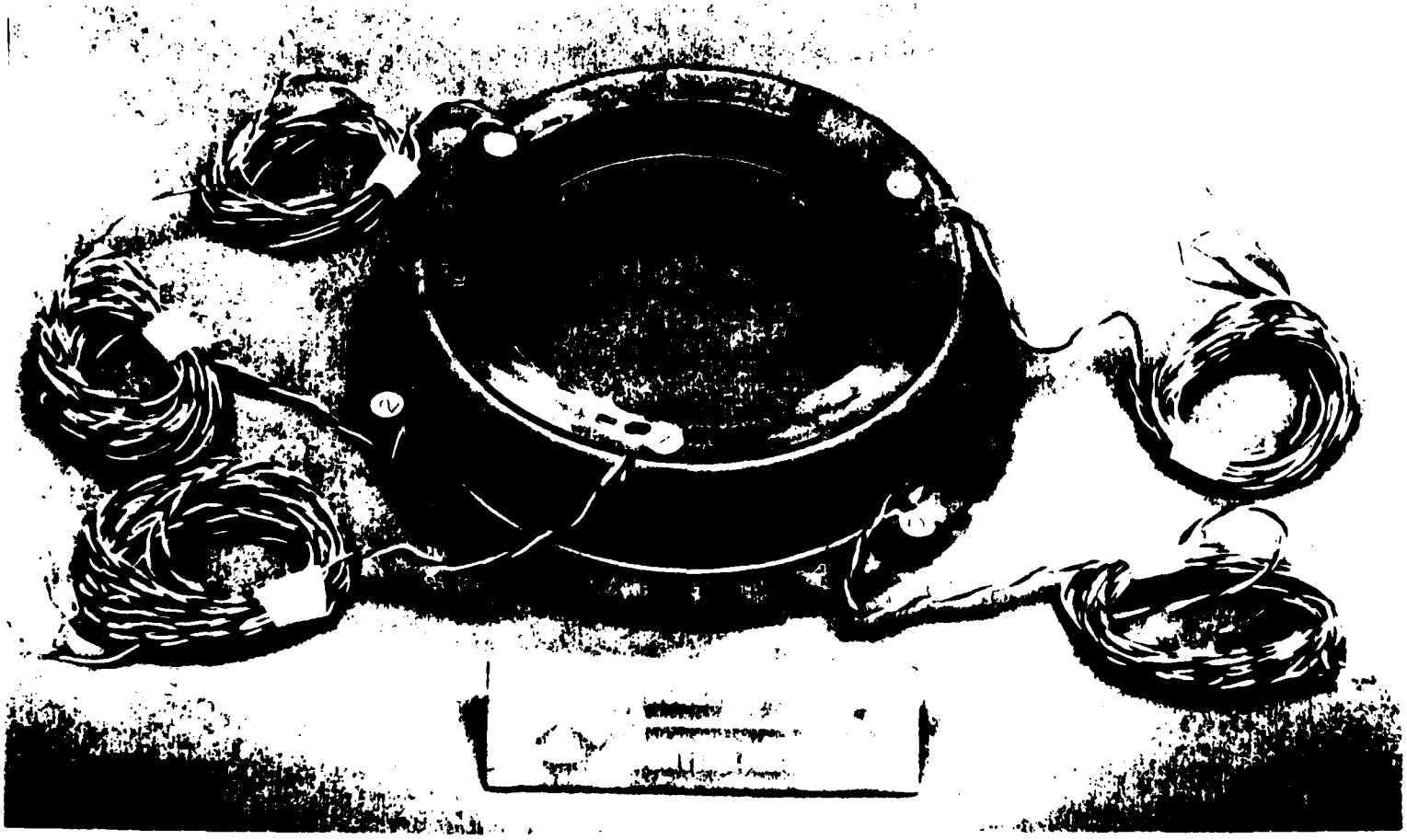

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figure 11

HPOTP BEARING CARTRIDGE

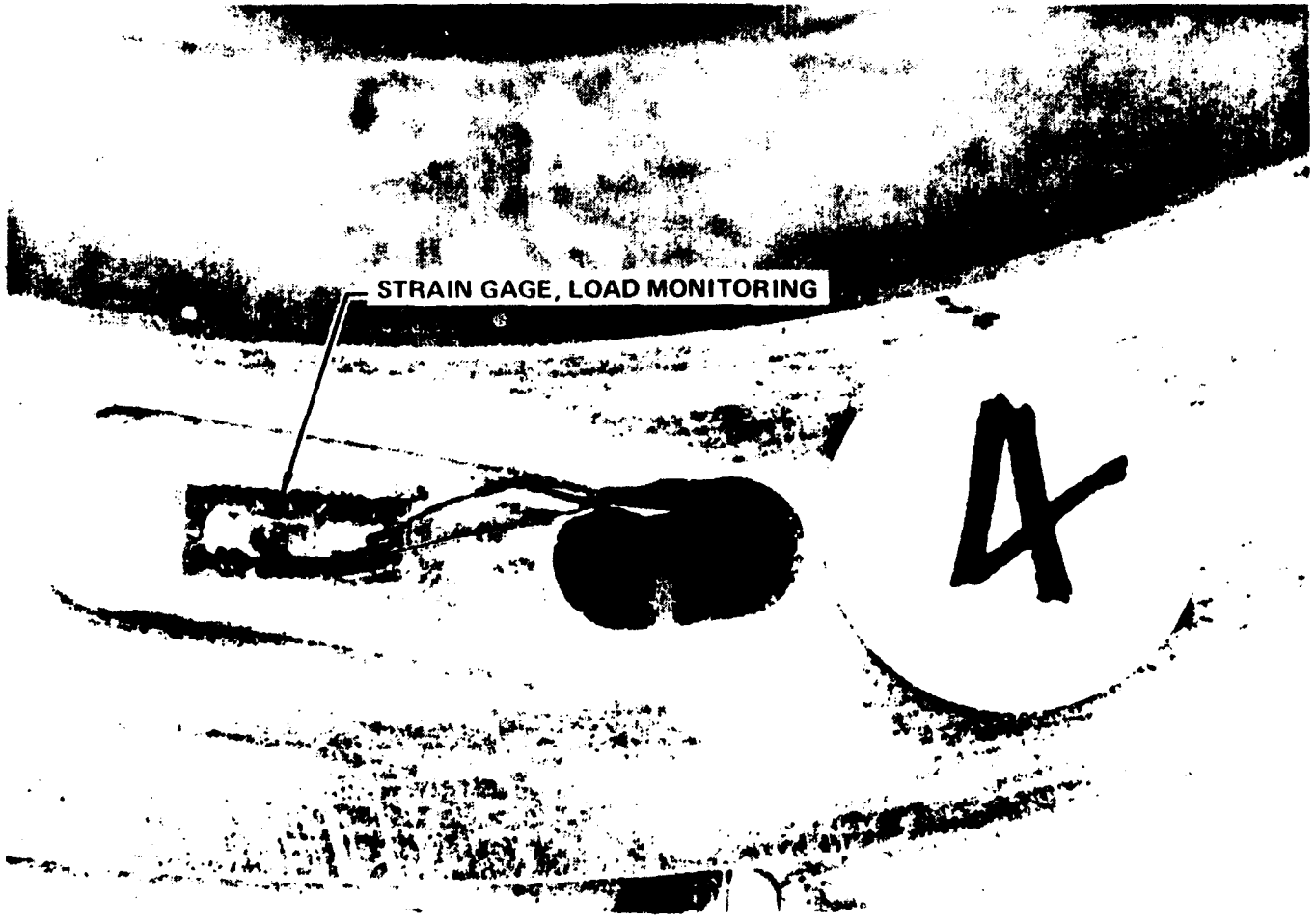

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figure 12

HPOTP BEARING CARTRIDGE

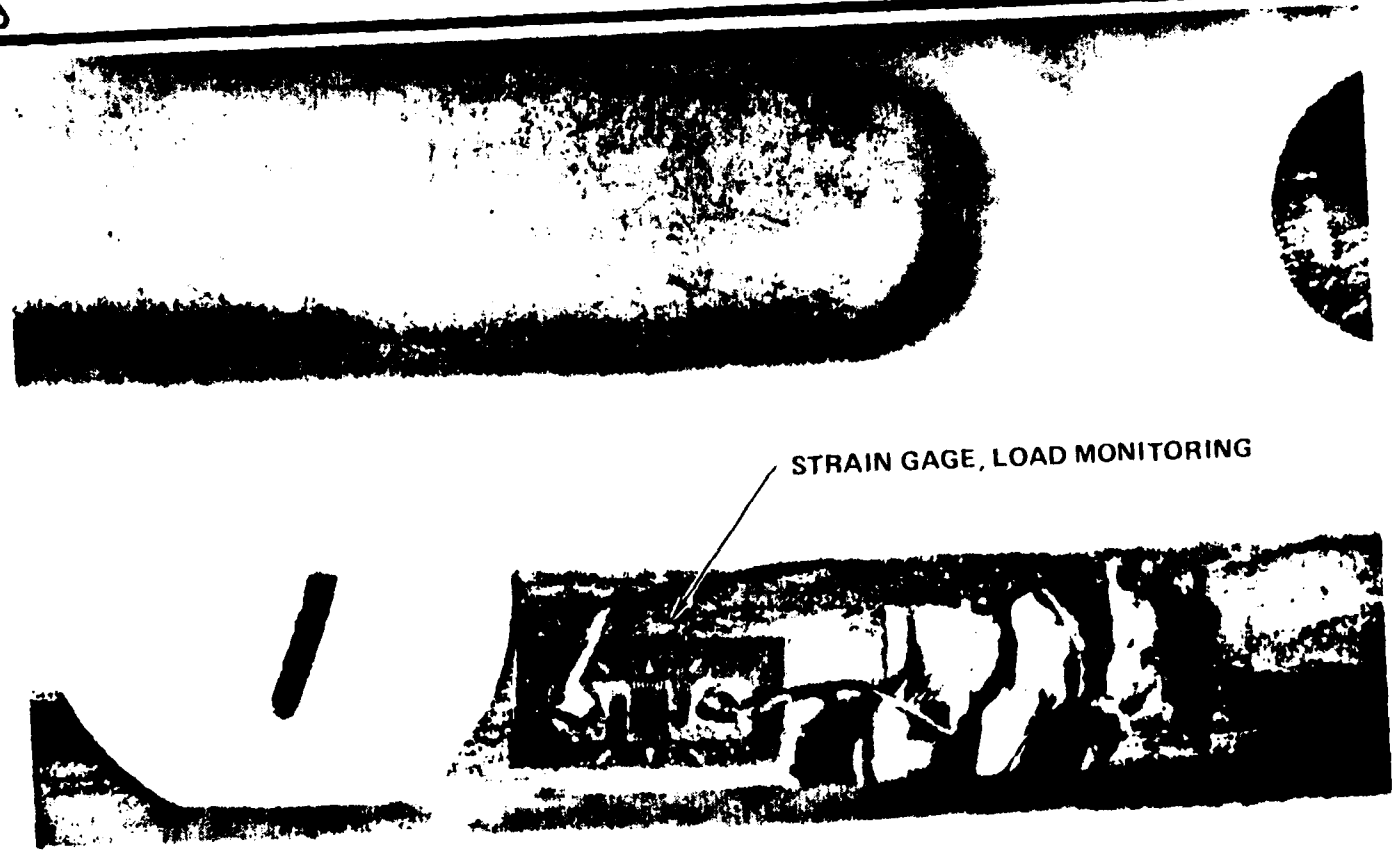

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figure 13

HPOTP BEARING CARTRIDGE

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figure 14

INSTRUMENTATED HPOTP BEARING CARTRIDGE CALIBRATION

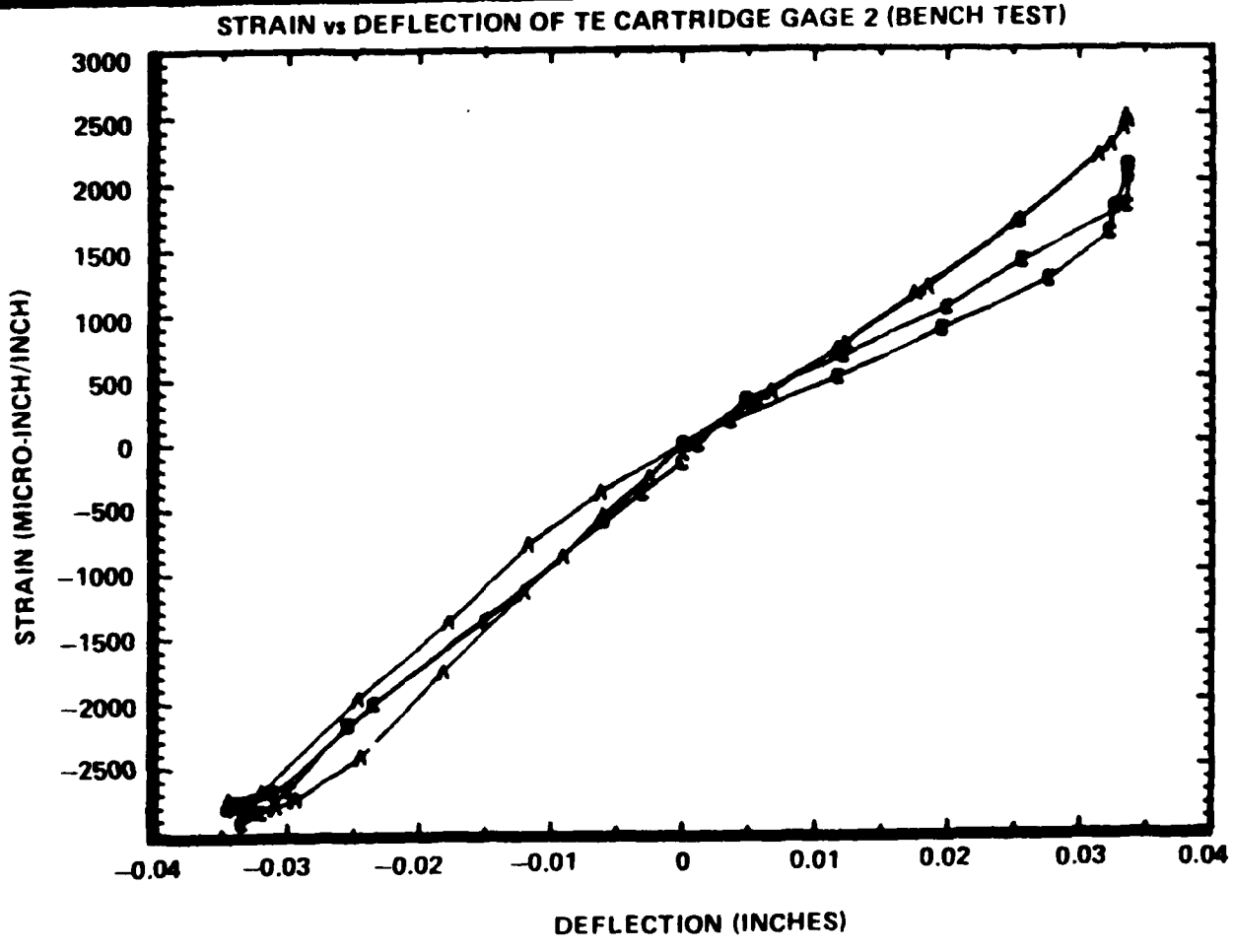

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figure 15

INSTRUMENTED HPOTP BEARING CARTRIDGE SSME ENGINE TEST

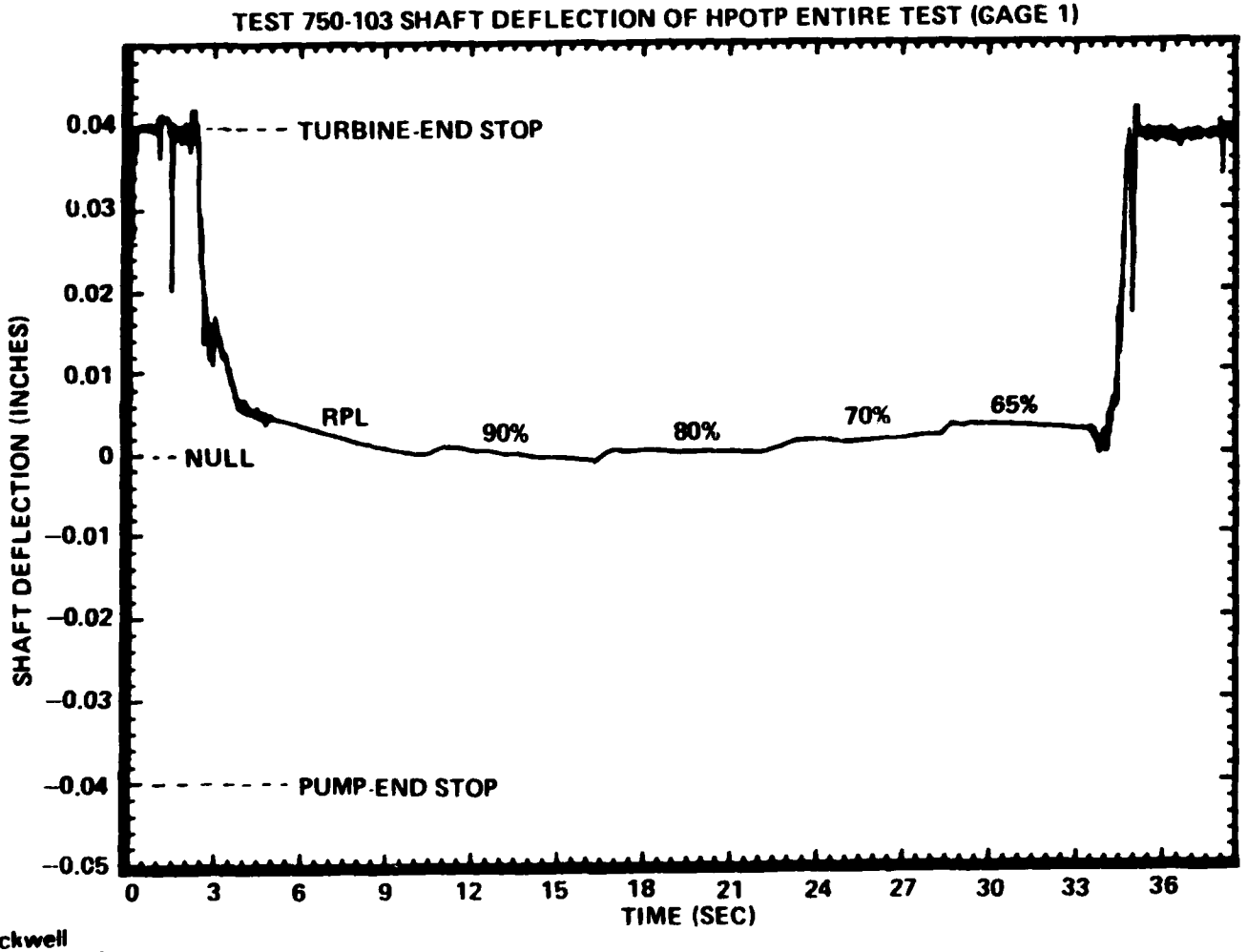

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figure 16

INSTRUMENTED HPOTP BEARING CARTRIDGE SSME ENGINE TEST

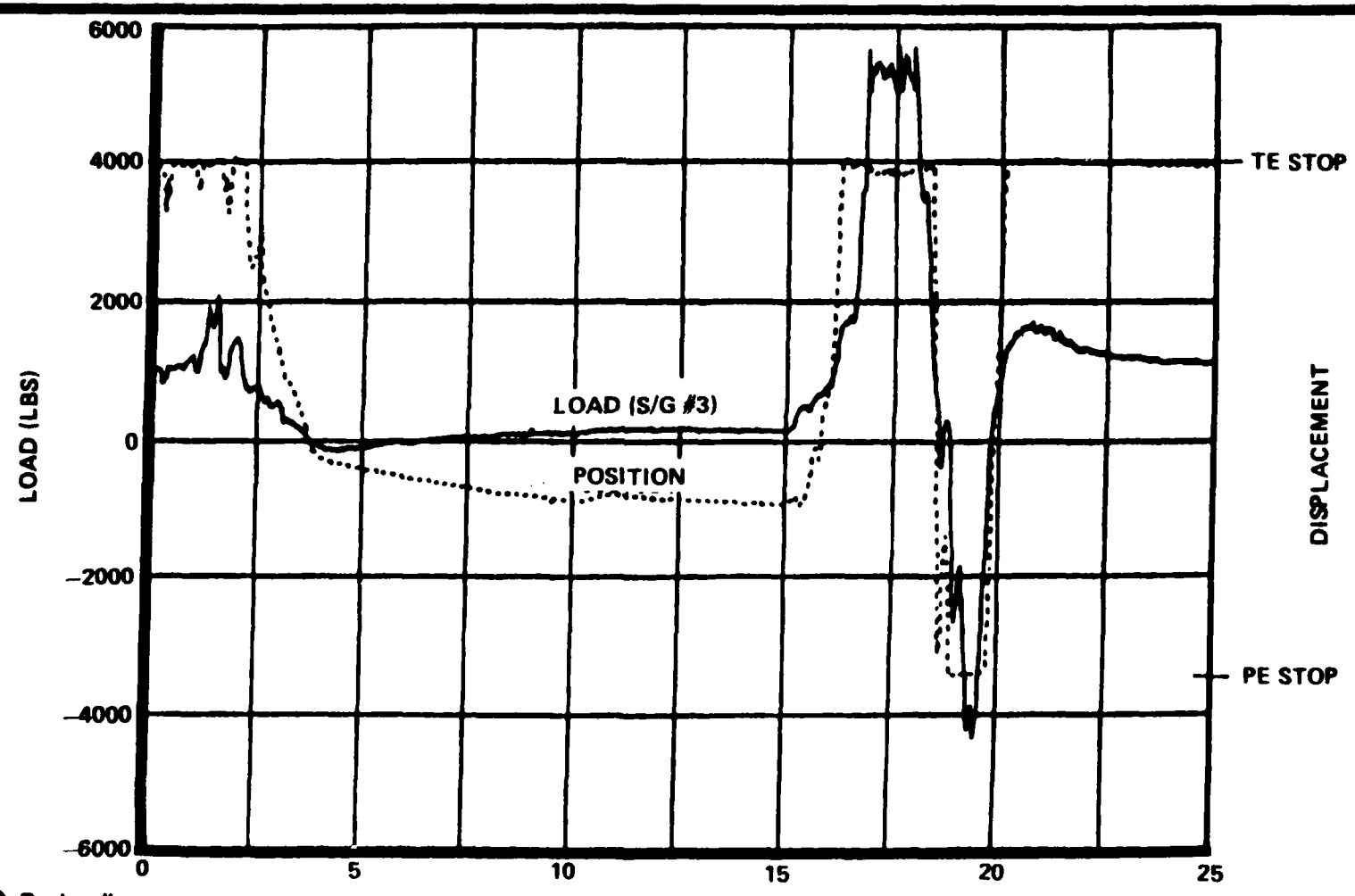

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figure 17

AD P002681

Utilization of Double Integration Methodology to Determine an Aircraft's Vertical Displacement

By

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Patuxent River, Maryland

ABSTRACT

In an effort to improve the measurement of the vertical displacement of aircraft which are catapulted off aircraft carriers, an accelerometer based system is being developed. Currently, this measurement is mechanized via camera-based data which is reduced after shipboard tests. This turns out to be a significant problem in terms of rapid buildup in determining aircraft minimums (minimum airspeeds).

The basic approach taken is to double integrate a gyro stabilized vertical accelerometer. The resulting package is then incorporated into the subject aircraft's instrumentation system. The displacement data is telemetered and displayed in real time via a portable ground station located aboard the aircraft carrier.

The data signal spectrum has significant components roughly around .1 hertz. To minimize drift problems, an AC type integration is employed. Due to the abnormally low data frequencies and the time constants associated with the electronics, analysis of the signals is difficult and time-consuming. Numerous problems exist in the areas of component size, drift, transients, and calibration. This paper will attempt to highlight and solve these problems.

INTRODUCTION

1. One of the functions of the Naval Air Test Center (NAVAIRTESTCEN) is the determination of the suitability and operating parameters of Naval aircraft operating aboard aircraft carriers. A subset of this function is the determination of minimum airspeeds (minimums) for various aircraft in various configurations when catapulted off aircraft carriers. An important variable in this process is the minimum vertical displacement of the aircraft after being catapulted off the bow. Ideally, this displacement is referenced to the vertical position of the flight deck at the instant the aircraft departs the flight deck.

BACKGROUND

2. For roughly 20 years, NAVAIRTESTCEN has been interested in an accurate real-time measurement of "Sink Off The Bow" (SOB). A couple of methods are currently being utilized. One of these methods is the use of a spotter, who, from the vantage point of a catapult walk, visually estimates vertical displacement. Obviously, this is not a very accurate measurement. However, the utilization of spotting does allow for a cautious rapid buildup to a minimum. The second method involves the use of a 35 millimeter camera mounted with the lens parallel to the flight deck and run at a speed of 100 frames/second during catapult launches. The data is reduced via a digital film reader with the known distance between the aircraft's landing gear used as a calibration factor to scale vertical displacements on the film. Aircraft roll angle and yaw angle and camera pitch angle, roll angle, and yaw angle are assumed to be zero in this analysis. Vertical plane movement of the flight deck after launch is probably the largest source of error in camera-based data. No known estimates of this error exist at this time. Since camera film has to be developed and, consequently, is not available in real time, this data is used predominantly for postflight test analysis and report data.

NEW APPROACH

3. Recently a new approach to the SOB problem was undertaken. The procedure is to double integrate a vertically-oriented accelerometer mounted in the test aircraft. A gyro stabilized accelerometer package was identified and subsequently procured from Humphrey, Incorporated (Model Number SA07-0115-1). The block diagram for this new system is shown in figure 1.

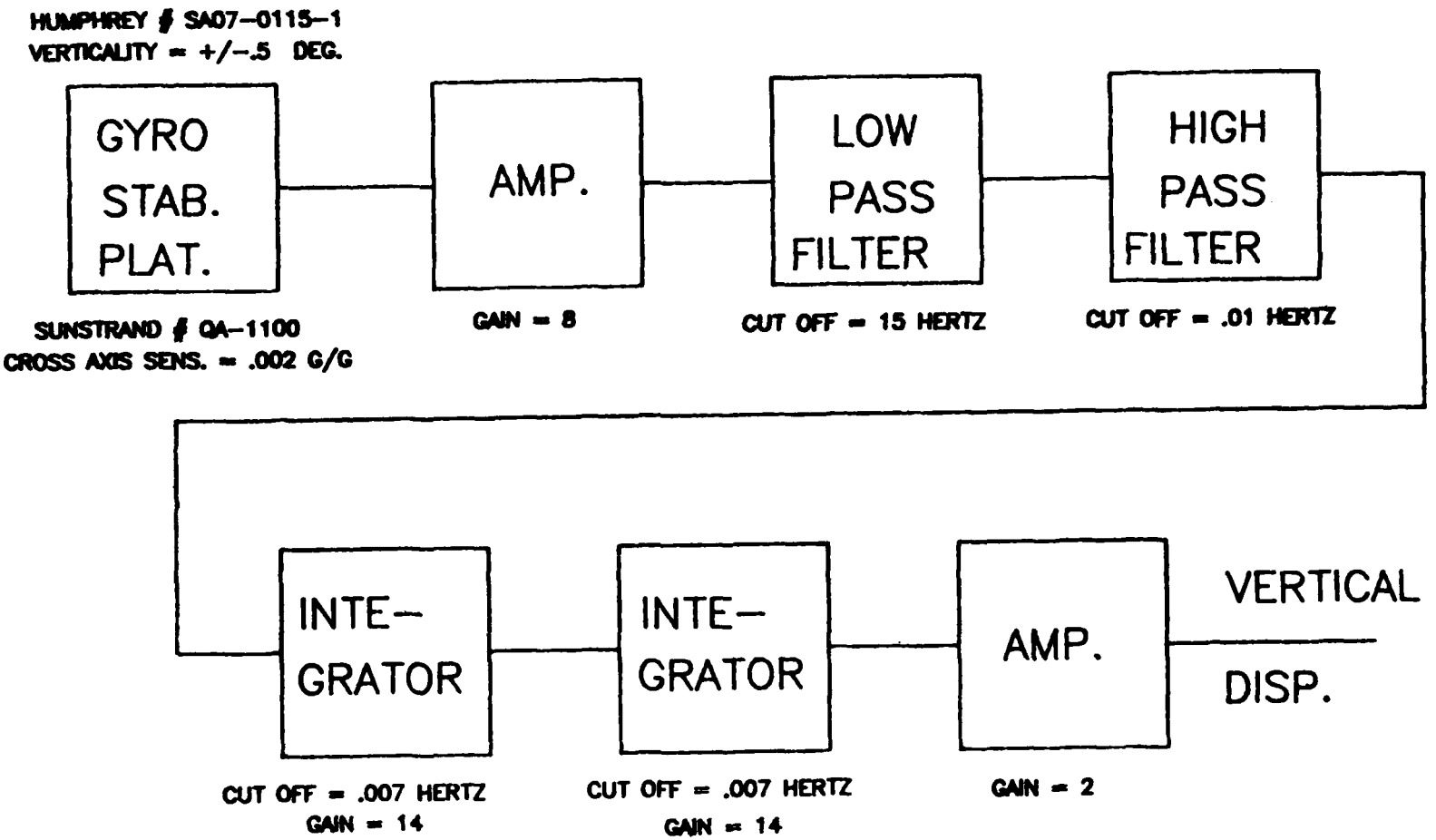

Figure 1
SOB BLOCK DIAGRAM

4. The electronics were implemented utilizing operational amplifier-based circuitry. The schematic is shown in figure 2.

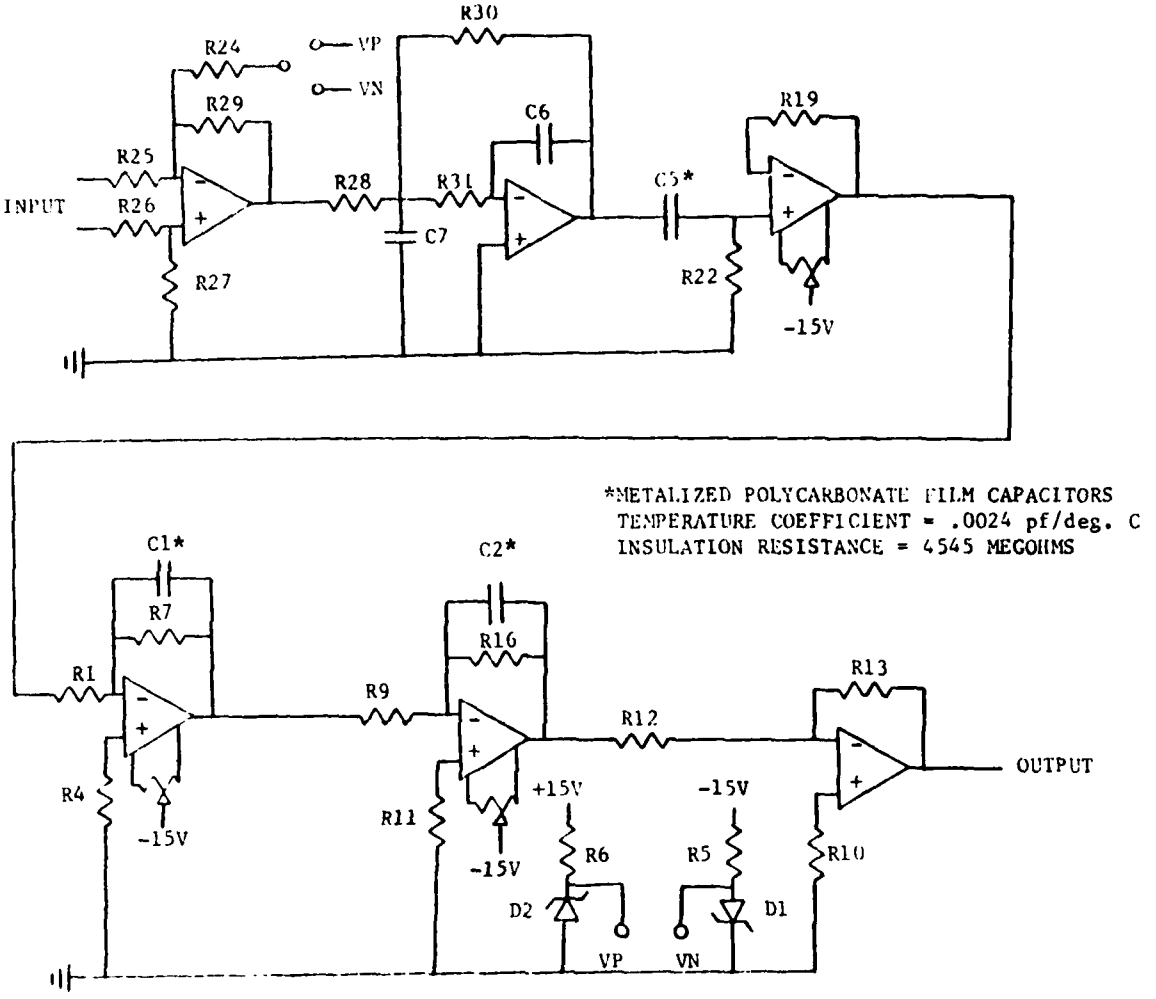

Figure 2
SOB CIRCUIT SCHEMATIC

5. Discussions with NAVAIRTESTCEN carrier suitability test engineers indicated that vertical accelerations would range from one half G to one and a half G's. No information was available on the spectral characteristics of the signal. The vertical accelerometer was scaled for plus or minus 10 V at plus or minus 10 G's and then rescaled by the first stage amplifier. This scaling provides reasonable protection for the accelerometer during landings. The low pass filter is present to limit the vibration spectrum, the high pass filter to remove the DC component from the input of the first integrator and reduce drift, and the final stage to provide for scaling flexibility of the displacement output. AC type integrators are utilized to reduce drift. The AC integrations are implemented as single pole low pass filters. Comparison of ideal integrator and actual integrator characteristics is demonstrated in figure 3.

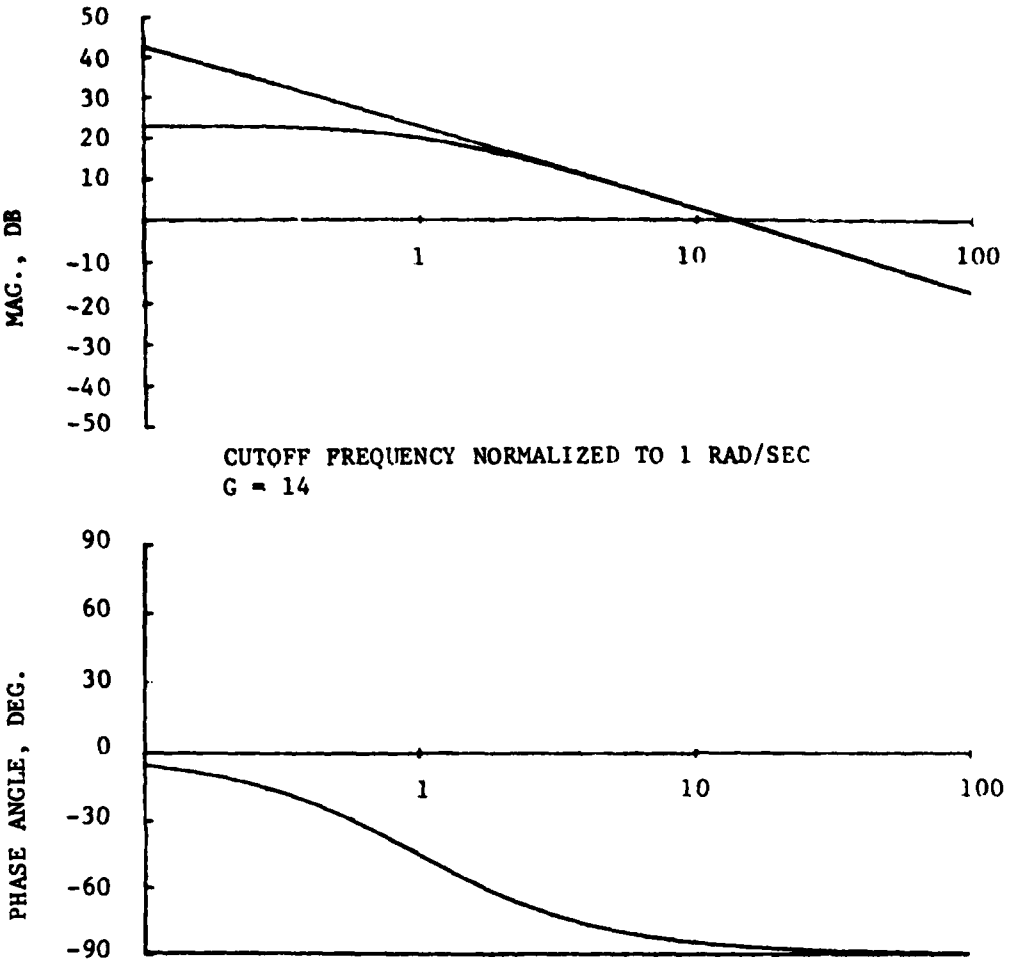

Figure 3
COMPARISON OF IDEAL AND ACTUAL INTEGRATOR CHARACTERISTICS

6. At two octaves from the cutoff frequency, the magnitude is within -.3 dB of ideal and the phase is approximately 14 degrees from ideal. Obviously, accurate integration occurs only at frequencies considerably above the cutoff frequency. Therefore, it is desirable to adjust the cutoff frequency as low as is possible relative to the data spectrum to be integrated.

CALIBRATION

7. Calibration of the system was necessary to ensure proper operation and accuracy. Many methods of calibration were considered. The most obvious method involved displacing the package a known vertical distance and correlating that distance to the output. This method was discarded primarily due to the difficulty of generating and measuring exact displacements over the frequency range of interest. However, it was agreed that moving the package from a table top to the floor and seeing the appropriate

output for this displacement would generate a warm feeling of confidence in the design team. After some minor difficulties (i.e., thinking the table top was 4 feet high when it actually was only 3), this was successfully accomplished.

8. The most practical method of calibration involved doing a voltage substitution at the accelerometer input to the integration electronics. The accelerometer was calibrated separately in a standard manner for transducers of this type. Knowing the calibration for the acceleometer, a function generator could then be set up to simulate the accelerometer at a fixed frequency and amplitude. The signal from this function generator was then used as a calibration input to the electronics. The block diagram for this setup is shown in figure 4.

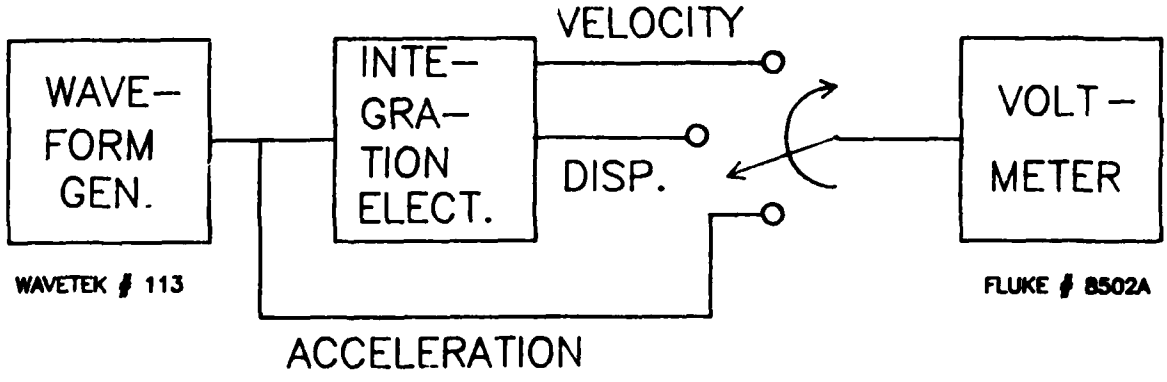

Figure 4
CALIBRATION SETUP

9. The Fluke digital voltmeter employed incorporated a peak to peak voltage function which was based on digital sampling and storage. This allowed for accurate measurement of the amplitudes of the acceleration, velocity, and displacement outputs. Utilizing this instrument, the simulated acceleration, velocity, and displacement outputs were carefully measured and recorded for several different amplitudes and at several different frequencies. Using this data calibration plots and equations relating voltage outputs to engineering units were derived for vertical velocity and vertical displacement.

F/A-18 TESTS

10. In August 1982, the first flight test of the SOB package aboard the USS KENNEDY was conducted. The package was configured as shown in figure 1. A schematic of the electronic circuitry is shown in figure 2. Figure 5 is a picture of the actual package that was placed in an F/A-18. The package was placed in the radar compartment in the nose of the aircraft. This placed the gyro stabilized accelerometer approximately 20 feet in front of the center of gravity. The optimum position for the gyro stabilized accelerometer is at the center of gravity. Since rotation tends to occur around the center of gravity, this eliminates problems associated with integrating vertical accelerations due to the pitching motion of the aircraft. If the pitching motion related accelerations are not within the spectrum that is being integrated, errors will result. This effect must be taken into account in analysis of the test data.

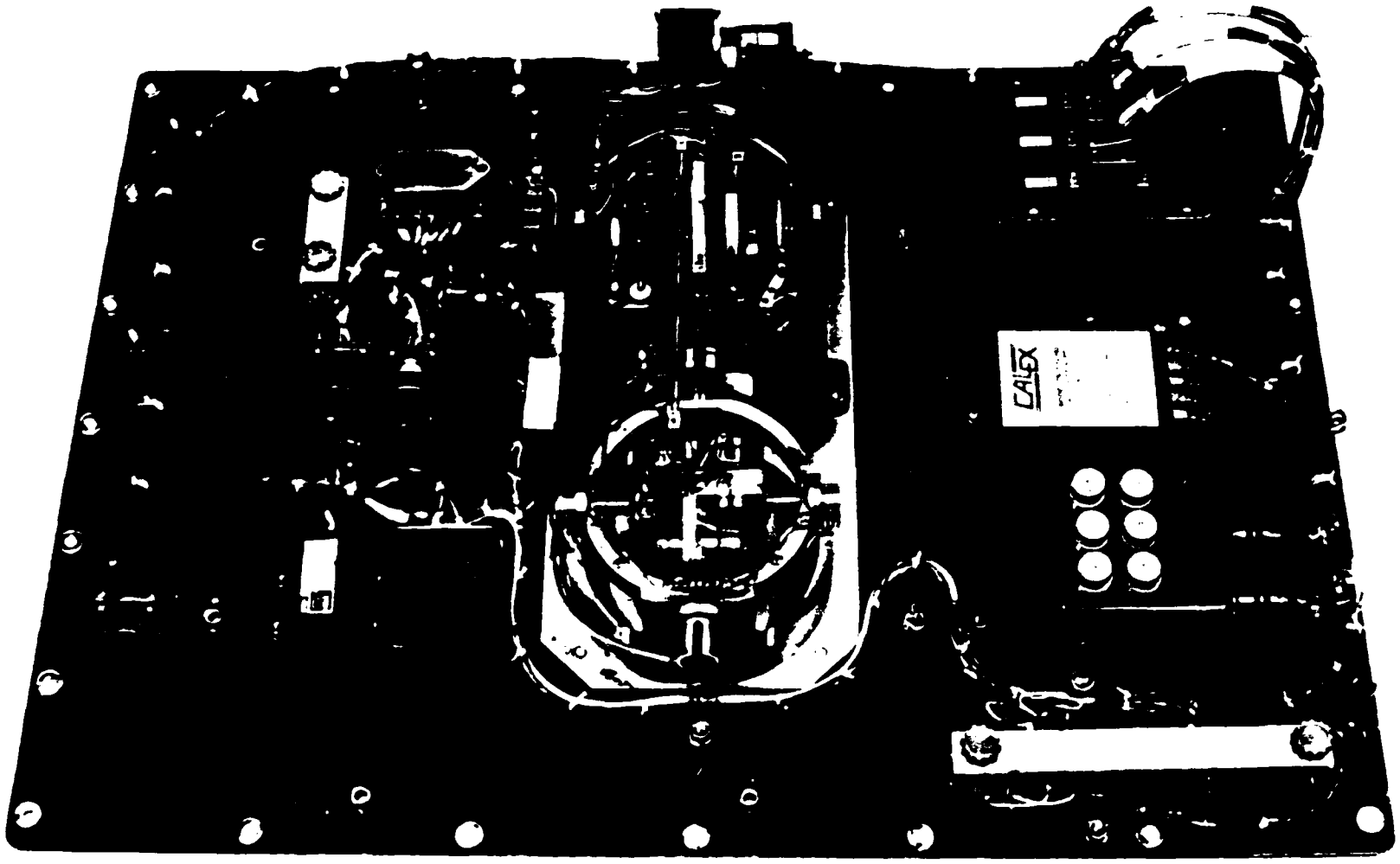

Figure 5
F/A-18 PACKAGE PHOTO

11. During the course of the flight tests, PCM encoded data was recorded on magnetic tape for evaluation. A sample of the data obtained from one of the flights is shown in figure 6. During the time from 0 to 9 seconds (refer to figure 6), the aircraft is sitting on the deck of the aircraft carrier awaiting the catapult shot. The slight up and down movement of the vertical displacement seen in this time period is simply the movement of the flight deck as the carrier moves through the water. At approximately 9 seconds, in preparation for the catapult shot, the pilot brings the engines from idle to full military power. In the time period from 9 to 29 seconds, the aircraft is sitting on the catapult with engines at full military power making a final preflight check. Looking at the vertical displacement during this period, a large output is seen when in fact the aircraft did not move. This is actually a transient in the electronics that was caused by a virtual step increase in the magnitude of vibrations. This phenomenon has been verified by data taken during test and evaluation of the F/A-18 aircraft. An in-depth mathematical analysis of this effect is done in the transient analysis section of this paper. At approximately 29 seconds, the catapult is released and the aircraft begins its take off. The catapult stroke terminates at approximately 31.5 seconds. Significant apparent vertical movement occurs in the displacement trace during the period of the launch. This effect is due to the nonverticality and cross axis sensitivity of the accelerometer. Longitudinal accelerations on the order of 3 or 4 G's occur during launch and are coupled into the gyro stabilized accelerometer. The gyro nonverticality is also enhanced by precessional forces present during the launch. The final dip in the displacement trace from 31.5 to 33 seconds is caused by the actual vertical displacement of the aircraft. However, the accuracy at 33 seconds is degraded by the recovery of the preceding vibration and launch transients.

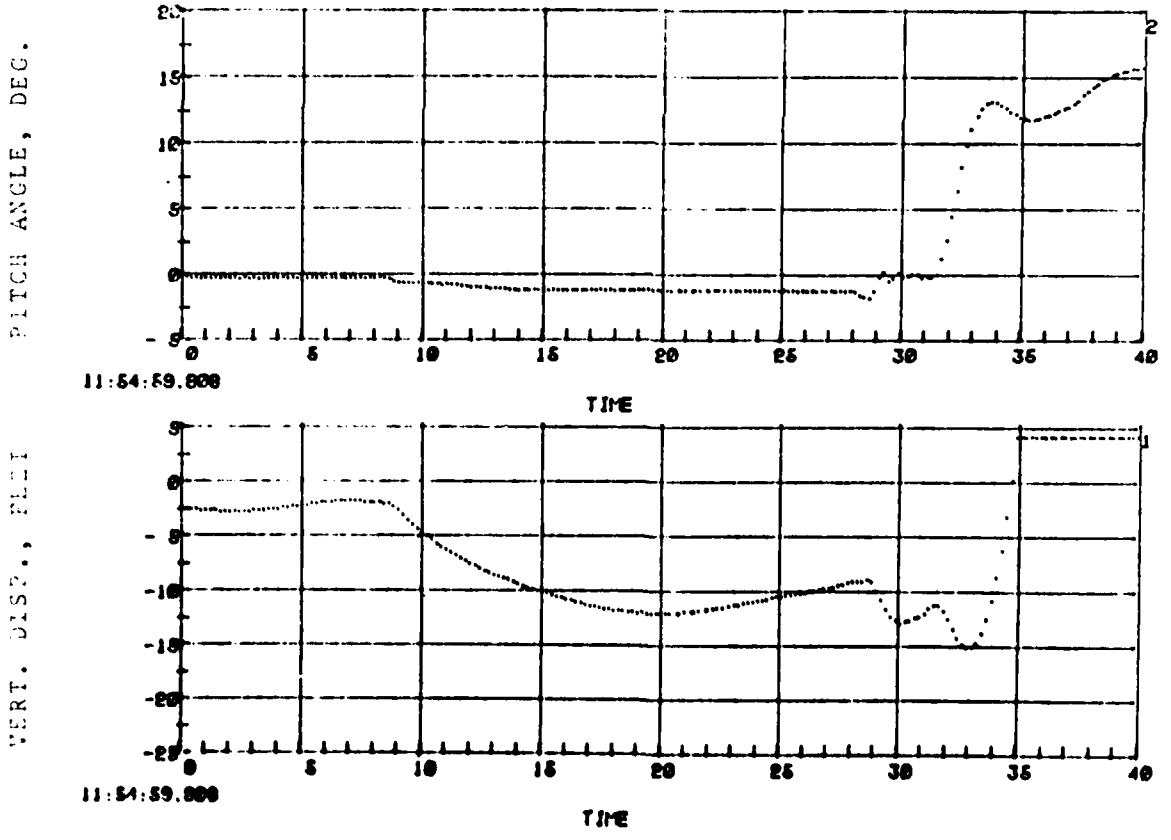

Figure 6
F/A-18 TEST DATA

TRANSIENT ANALYSIS

12. As a result of the F/A-18 tests, it was obvious that attention should be focused on the response of the electronics to transients originating from vibration, shock, etc. Potentially, the effects of these transients could be minimized via circuit configuration and component value adjustments.

13. The transfer functions for the low pass and high pass filters incorporated in the design are

$$LP = -G \frac{\omega_c}{s + \omega_c} \text{ and } HP = G \frac{s}{s + \omega_c}$$

Where: G = gain
ω_c = radian cutoff frequency

Consider the following block diagram consisting of some combination of a single pole low pass and a single pole high pass filter.

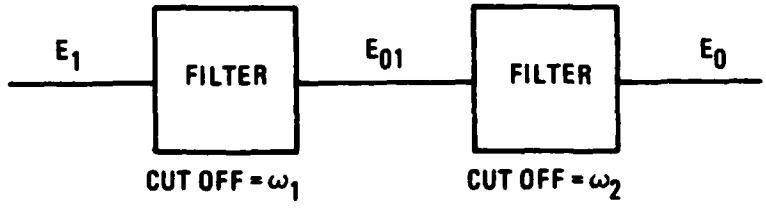

Figure 7

If a transient of the form

$\frac{E\omega}{s^2 + \omega^2}$ (A step sinusoid of frequency ω which might arise from a rapid change in vibration levels)

is applied to this configuration, the output time response from the first stage can be derived as follows:

LOW PASS IN STAGE 1

$$E_{01}(s) = -G \frac{\omega_c}{s + \omega_c} \left(E \frac{\omega}{s^2 + \omega^2} \right) = \frac{A}{s + \omega_c} + \frac{Bs + C}{s^2 + \omega^2}$$

Solving this equation for A, B, and C yields

$$A = -\frac{GE\omega_c\omega}{\omega_c^2 + \omega^2} \quad , \quad B = \frac{GE\omega_c\omega}{\omega_c^2 + \omega^2} \quad , \quad C = -\frac{GE\omega_c^2\omega}{\omega_c^2 + \omega^2}$$

$$E_{01}(s) = -\frac{\frac{GE\omega_c\omega}{\omega_c^2 + \omega^2}}{s + \omega_c} + \frac{\frac{GE\omega_c\omega s}{\omega_c^2 + \omega^2}}{s^2 + \omega^2} - \frac{\frac{GE\omega_c^2\omega}{\omega_c^2 + \omega^2}}{s^2 + \omega^2}$$

$$e_{01}(t) = -\frac{GE\omega_c}{\omega_c^2 + \omega^2} \left(\omega e^{-\omega_c t} - \omega \cos \omega t + \omega_c \sin \omega t \right)$$

Since $A\cos \omega t + B\sin \omega t = \sqrt{A^2 + B^2} \cos\left(\omega t - \tan^{-1} \frac{B}{A}\right)$

$$e_{01}(t) = -\frac{GE\omega_c\omega}{\omega_c^2 + \omega^2} e^{-\omega_c t} + GE\omega_c \left(\omega_c^2 + \omega^2\right)^{-1/2} \cos\left(\omega t + \tan^{-1} \frac{\omega_c}{\omega}\right) \qquad (1)$$

Transient Term — Steady State Term

HIGH PASS IN STAGE 1

$$E_{01}(s) = G \frac{s}{s+\omega_c}\left(E \frac{\omega}{s^2+\omega^2}\right) = \frac{A}{s+\omega_c} + \frac{Bs+C}{s^2+\omega^2}$$

$$A = -\frac{GE\omega_c\omega}{\omega_c^2+\omega^2}, \quad B = \frac{GE\omega_c\omega}{\omega_c^2+\omega^2}, \quad C = GE\omega - \frac{GE\omega_c^2\omega}{\omega_c^2+\omega^2}$$

$$E_{01}(s) = -\frac{\frac{GE\omega_c\omega}{\omega_c^2+\omega^2}}{s+\omega_c} + \frac{\frac{GE\omega_c\omega s}{\omega_c^2+\omega^2}}{s^2+\omega^2} + \frac{GE\omega - \frac{GE\omega_c^2\omega}{\omega_c^2+\omega^2}}{s^2+\omega^2}$$

$$e_{01}(t) = \frac{GE\omega_c}{\omega_c^2+\omega^2}\left(-\omega e^{-\omega_c t} + \omega\cos\omega t + \frac{\omega_c^2+\omega^2}{\omega_c}\sin\omega t - \omega_c \sin\omega t\right)$$

Since $A\cos\omega t + B\sin\omega t = \sqrt{A^2+B^2}\cos\left(\omega t - \tan^{-1}\frac{B}{A}\right)$

$$e_{01}(t) = -\frac{GE\omega_c\omega}{\omega_c^2+\omega^2} e^{-\omega_c t} + GE\omega_c\left(\omega_c^2+\omega^2\right)^{-1/2}\cos\left(\omega t + \tan^{-1}\frac{\omega_c}{\omega}\right) + GE\sin\omega t \qquad (2)$$

Transient Term — Steady State Terms

Note that the form of the transient terms in equation 1 and equation 2 are identical. However, equation 2 also contains as its output an additional steady state term equal to the sinusoidal input multiplied by the gain of the high pass filter. This fact is probably the most important result obtained from the transient analysis section. The sinusoidal term at the output of the high pass filter causes additional transient problems in any following stages. While not detailed explicitly here or in the remaining parts of the transient analysis section, the high pass filter's contribution to the transient problem is considerably reduced if it is located after the integrators vice in front of the integrators. This has been corroborated by transient tests conducted on the F/A-18 SOB electronics. The high pass filter was added to the F/A-18 electronics to remove the DC input from the input of the first integrator and to reduce drift. These same functions can be accomplished by offset control incorporated into the first stage of the electronics and by placing the high pass filter after the integrators.

14. Now consider the transient response of the second stage when subject only to the step exponential which exists at the output of the first stage. The following analysis assumes that both stages are low pass filters and therefore the step sinusoid at the output of the first stage can be neglected because of its small amplitude (assumes the frequency of the step sinusoid is much greater than the cutoff frequency of the first stage).

Exponential Transient
from First Stage

$$E_0(s) = -G_2 \frac{\omega_2}{s+\omega_2}\left(\frac{E_1}{s+\omega_1}\right) \qquad \text{Where } E_1 = -\frac{G_1 E \omega_1 \omega}{\omega_1^2 + \omega^2}$$

$$E_0(s) = \frac{A}{s+\omega_2} + \frac{B}{s+\omega_1} = \frac{\frac{-G_2 E_1 \omega_2}{\omega_1 - \omega_2}}{s+\omega_2} + \frac{\frac{-G_2 E_1 \omega_2}{\omega_2 - \omega_1}}{s+\omega_1}$$

$$e_0(t) = -\frac{G_2 E_1 \omega_2}{\omega_2 - \omega_1}\left(e^{-\omega_1 t} - e^{-\omega_2 t}\right)$$

$$e_0(t) = \frac{G_1 G_2 E \omega_1 \omega_2 \omega}{(\omega_1^2 + \omega^2)(\omega_2 - \omega_1)}\left(e^{-\omega_1 t} - e^{-\omega_2 t}\right) \qquad (3)$$

A plot of equation 3 is shown in figure 8.

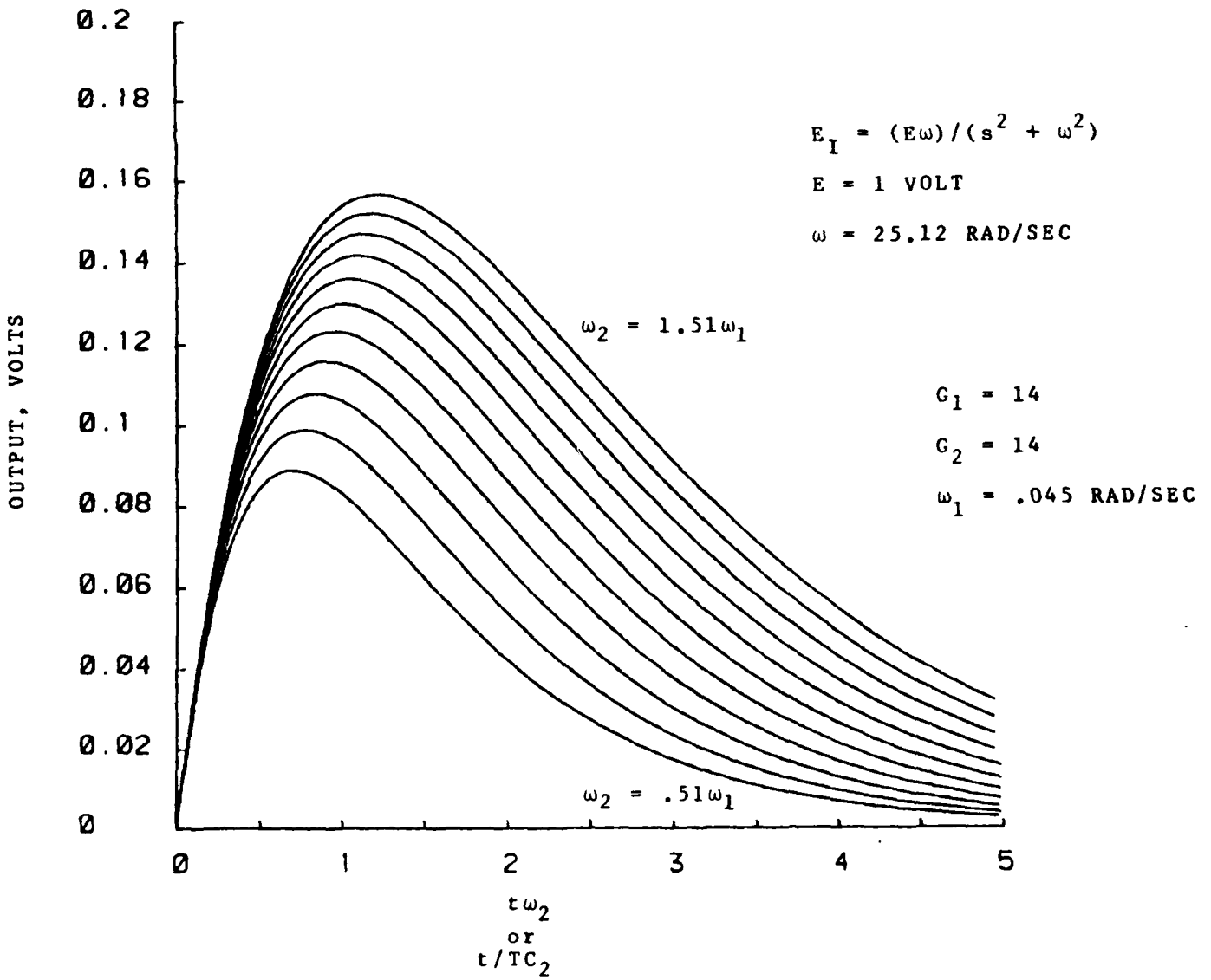

Figure 8
TWO STAGE LOW PASS TRANSIENT RESPONSE

Figure 8 indicates that, to substantially reduce peak magnitude of the transient output, omega 2 must be much less than omega 1. But, since lowering the cutoff frequency expands the time scale, this fact must be carefully applied. At the time of interest, a lower magnitude may be realized with a higher cutoff frequency.

15. Now consider the following block diagram.

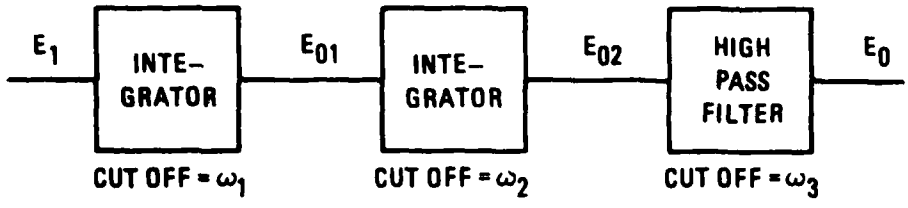

Figure 9

$$E_0(s) = G_3 \frac{s}{s + \omega_3} \left(E_2 \left(\frac{1}{s + \omega_1} - \frac{1}{s + \omega_2} \right) \right)$$

$$\text{Where } E_2 = - \frac{G_2 E_1 \omega_2}{\omega_2 - \omega_1} \quad , \quad E_1 = - \frac{G_1 E \omega_1 \omega}{\omega_1^2 + \omega^2}$$

$$E_0(s) = \frac{G_3 E_2 s}{s + \omega_3} \left(\frac{1}{s + \omega_1} - \frac{1}{s + \omega_2} \right)$$

$$E_0(s) = G_3 E_2 \left(\frac{\frac{-\omega_3}{-\omega_3 + \omega_1}}{s + \omega_3} + \frac{\frac{-\omega_1}{-\omega_1 + \omega_3}}{s + \omega_1} - \frac{\frac{-\omega_3}{-\omega_3 + \omega_2}}{s + \omega_3} - \frac{\frac{-\omega_2}{-\omega_2 + \omega_3}}{s + \omega_2} \right)$$

$$e_0(t) = G_3 E_2 \left(\frac{\omega_3}{\omega_3 - \omega_1} e^{-\omega_3 t} - \frac{\omega_1}{\omega_3 - \omega_1} e^{-\omega_1 t} \right) - G_3 E_2 \left(\frac{\omega_3}{\omega_3 - \omega_2} e^{-\omega_3 t} - \frac{\omega_2}{\omega_3 - \omega_2} e^{-\omega_2 t} \right) \quad (4)$$

Interpretation of equation 4 is not straight forward. However from a spectral viewpoint and from the previous contrasting development involving two low pass filters, it follows that omega 3 should be much larger than omega 1 and omega 2. Making omega 3 larger reduces the overall system bandwidth. Therefore, this fact must be cautiously applied.

RECONFIGURATION

16. Some rather interesting facts fall out of the transient analysis. From a transient point of view, it is desirable for the second integration stage to have a much lower cutoff frequency than the first integration stage. In addition, the transient analysis indicates that, if a high pass filter is used to minimize drift, it is considerably better to locate it after the integraters vice before the integraters. The reason for this is that, if the high pass is located upstream of the integrators, an exponential transient is created at its output and, in addition, the step sinusoidal input is propagated to the high pass filter's output essentially unmodified in amplitude. The step sinusoid then propagates through the integrators causing additional problems. Locating the integrators upstream of the high pass filter virtually eliminates this problem.

17. The undesirable output created by the catapult launching of the aircraft is a difficult problem. At the heart of this problem is the inherent nonvertically of any gyro-based system. This nonverticality is accentuated by precessional forces present during the launch. The gyro stabilize platform utilized in the F/A-18 tests has a verticality specification of plus and minus one half a degree. Under normal operating conditions, however, from some rather crude examinations of this platform, it is felt that non-verticalities on the order of several degrees may be present during launch. Since the aircraft has gyros onboard of high quality, especially those associated with the inertial navigation system, consideration has been given to using these systems. However, at this time, this approach is not being seriously pursued due to the variance in the characteristics of these systems from aircraft type to aircraft type and due to accessible problems associated with the signals from these gyros from aircraft type to aircraft type.

18. In an effort to keep the measurement system as self contained as possible and to improve the effective verticality, a strap down system is currently being pursued. If three mutually perpendicular accelerometers are mounted in an aircraft aligned with the aircraft's body axes, the vertical acceleration can be computed from the following equation:

$$\begin{aligned} a_v = \; & a_x \sin A \cos C + a_x \cos A \sin B \sin C \\ & -a_y \sin A \sin C + a_y \cos A \sin B \cos C \\ & + a_z \cos A \cos B \end{aligned} \qquad (5)$$

Where: a_v = vertical component of acceleration

Where A, B, and C are the pitch angle, roll angle, and yaw angle, respectively

Assuming B and C are approximately zero, equation 5 reduces to

$$a_v = a_x \sin A + a_z \cos A \qquad (6)$$

The block diagram based on equation 6 is shown in figure 10. Several candidate gyros are being considered for this system. It is estimated that verticalities on the order of several tenths of a degree may be achievable with the configuration shown in figure 10.

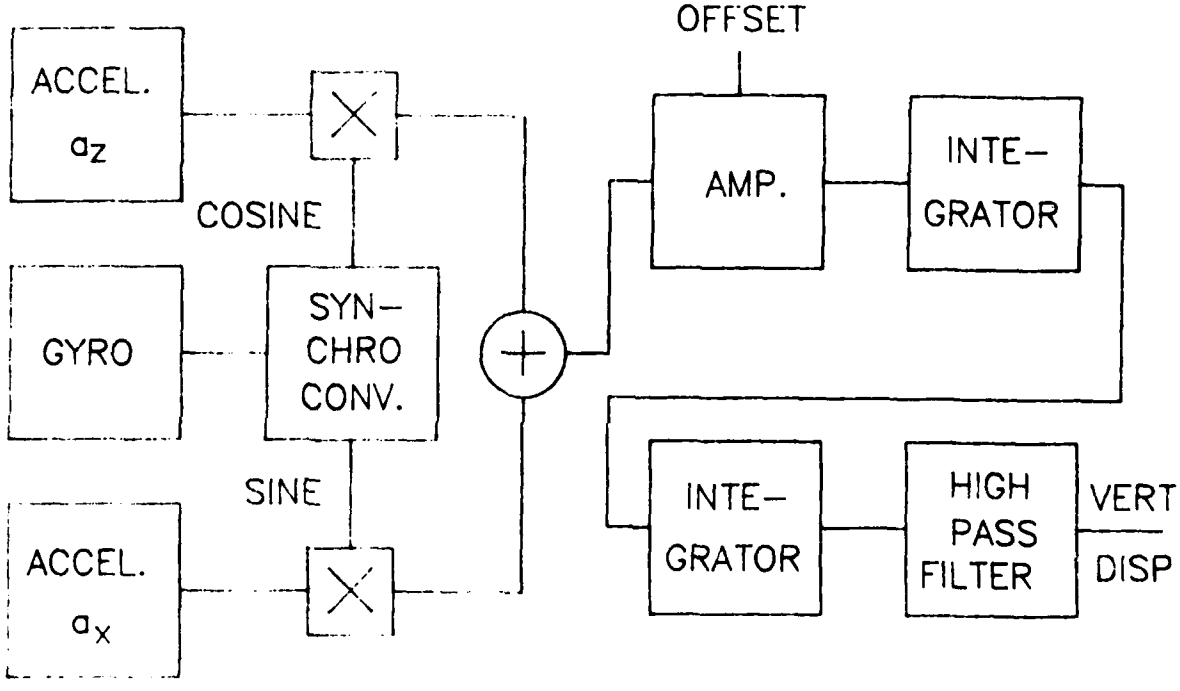

Figure 10
STRAP DOWN SYSTEM

CONCLUSION

The jury is still out as to whether a double integration of the vertical component of aircraft acceleration is a practical approach for the determination of vertical displacement. Tests of the strap system indicated in figure 10 on an E2 type aircraft are planned tentatively during the summer of 83. Hopefully, these tests will shed some more light on this subject.

ACKNOWLEDGEMENT

I wish to express my gratitude to Mr. Daniel S. Skelley. His efforts have been invaluable both in the conduct of this project and in the preparation of this paper.

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AN ANGULAR VELOCIMETER FOR AEROSPACE APPLICATIONS

by

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Submitted to

12th Transducer Workshop
7-9 June 1983
Melbourne, Flordia

ABSTRACT

Low-level broad-band angular vibration measurement applications are continually developing. This has generated a pressing need for a low-level angular vibration sensor capable of measuring 10^{-6} radians at frequencies from 0 to 10kHz, with a total size of the sensor on the order of a cubic centimeter. The device described in this paper has potential for satisfying such a need. Only three design parameters are required to address the minimum sensitivity level, and alternate designs with dynamic ranges and durability similar to piezoelectric accelerometers could be developed capable of measuring angles down to 10^{-6} radians. Since the device is based on measuring accelerations using piezoelectric crystals, linearity, dynamic range, hysteresis, and stability qualifications, as well as cost of production are anticipated on the order of conventional piezoelectric accelerometers.

INTRODUCTION

Aerospace vehicles continue to be used as platforms for pointing and tracking. As the distance to the target increases, the low-level angular disturbance to the vehicle degrades the pointing accuracy more severely. This has generated a need for an angular vibration transducer which is capable of measuring angular amplitudes as low as 10^{-6} radians over frequencies from 0 to 10kHz. This presents a challenging engineering problem which has not generally been solved as yet, although there are a number of techniques for measuring angular motion. Most of those approaches involve devices which are too large, too narrow-band, or not sensitive enough. The instrument described in this paper is believed to have potential as an engineering solution to the low-level broad-band angular vibration measurement problem.

One of the more successful angular vibration sensors is described in Reference [1]. A cubic device with 8.4 centimeters outside dimension is described having a frequency response of from 3 to 2000 Hz and capable of measuring angles in the 10^{-6} radian range. However, its relatively large size would limit its usefulness in some aerospace applications involving light weight structure. As with most sensors, there are other design considerations having to do with linearity, durability, and error sources which the interested reader could find from Reference [1]. It is the relatively large size which prevents this sensor from being suited to every application.

Reference [2] is a survey of various available techniques for measuring angular motion in aerospace vehicles. Rate gyroscopes are generally narrow-band (on the order of 100 Hz) and bulky, and to achieve the 10^{-6} radian range would require excessive cost. Another popular class of devices, the fluid inertial sensor such as described in Reference [1], requires that the fluid be

maintained at a specified temperature. For aerospace applications this adds to the mass of the sensor. A number of other approaches are mentioned in Reference [2], but none of them resemble the device described here.

Reference [3] gives the theory behind a class of devices called vibratory sensors, since the basic sensing element is a vibrating beam or wire. The claim is made that the vibratory angular tachometer could be a low-cost replacement for the gyroscope, but development problems have apparently prevented that from happening. Gyroscopes are still being widely used in aerospace guidance and control applications. The critical difference between the device in Reference [3] and the one described here is that Reference [3] includes a torsion bar which senses the twist in a vibrating tuning fork. This angular velocimeter senses angular motion by measuring the acceleration of the tuning fork tine tip. Measuring acceleration is inherently more broad-band than measuring displacement.

References [4] and [5] are the descriptions of another instrument which was intended to replace the gyroscope. That instrument is identical to the class of devices of Reference [3], using an electromagnetically excited tuning fork to sense angular motion through the twist of a torsion bar. Although similar to the broad-band angular velocimeter described in this paper in that a vibrating tuning fork is used, the rest of the details are entirely different.

The broad-band angular velocimeter described in this paper can be made quite small, and by selection of design parameters can be made to measure angles as low as 10^{-6} radians. In theory, the velocimeter operates from DC up to the upper frequency limit which is a function of the design parameters. It is believed that the angular velocimeter described here is a low-cost, low-level, miniature broad-band angular sensor. The technical details and theory of application are given in the next section.

ANALYSIS

A new angular rate sensor has been described in Reference [6] with technical details summarized below. Consider a tuning fork vibrating at its natural frequency as indicated in Figure 1. The tines will move along the y-axis with a displacement given by:

$$\bar{r}_p = (\frac{d}{2} + ae^{j\Omega t})\hat{\jmath} \quad . \tag{1}$$

When the tuning fork experiences an angular velocity about the Z-axis, the tines will accelerate according to:

$$\bar{A}_p = \ddot{\bar{r}}_p + 2\bar{\delta}x\dot{\bar{r}}_p + \dot{\bar{\delta}}x\bar{r}_p + \bar{\delta}x(\bar{\delta}x\bar{r}_p). \tag{2}$$

If two accelerometers were mounted on one of the tines to measure motion in the X and Y directions,

$$\bar{A}_p = b_1(t)\hat{\imath} + b_2(t)\hat{\jmath}. \tag{3}$$

Combining equations (2) and (3) and carrying out the indicated cross product, the result is:

$$b_1(t) = -j\omega_o\delta_o\frac{d}{2}e^{j\omega_o t} - j(2a\delta_o\Omega+\omega_o\delta_o a)e^{j(\Omega+\omega_o)t} \tag{4a}$$

$$b_2(t) = -a\Omega^2e^{j\Omega t} + \delta_o^2(\frac{d}{2} + ae^{j\Omega t})e^{j2\Omega t}. \tag{4b}$$

In equations (4), $\bar{\delta}=\delta_o e^{j\omega_o t}\hat{k}$. Then $b_1(t)$ and $b_2(t)$ have the frequency spectrums indicated in Figure 2. Figure 2a shows that the signal sensed by the accelerometer $b_1(t)$ is an amplitude modulation of the input angular rate where the carrier frequency is the tuning fork resonant frequency. This is significant since it transfers the desired information to a higher frequency

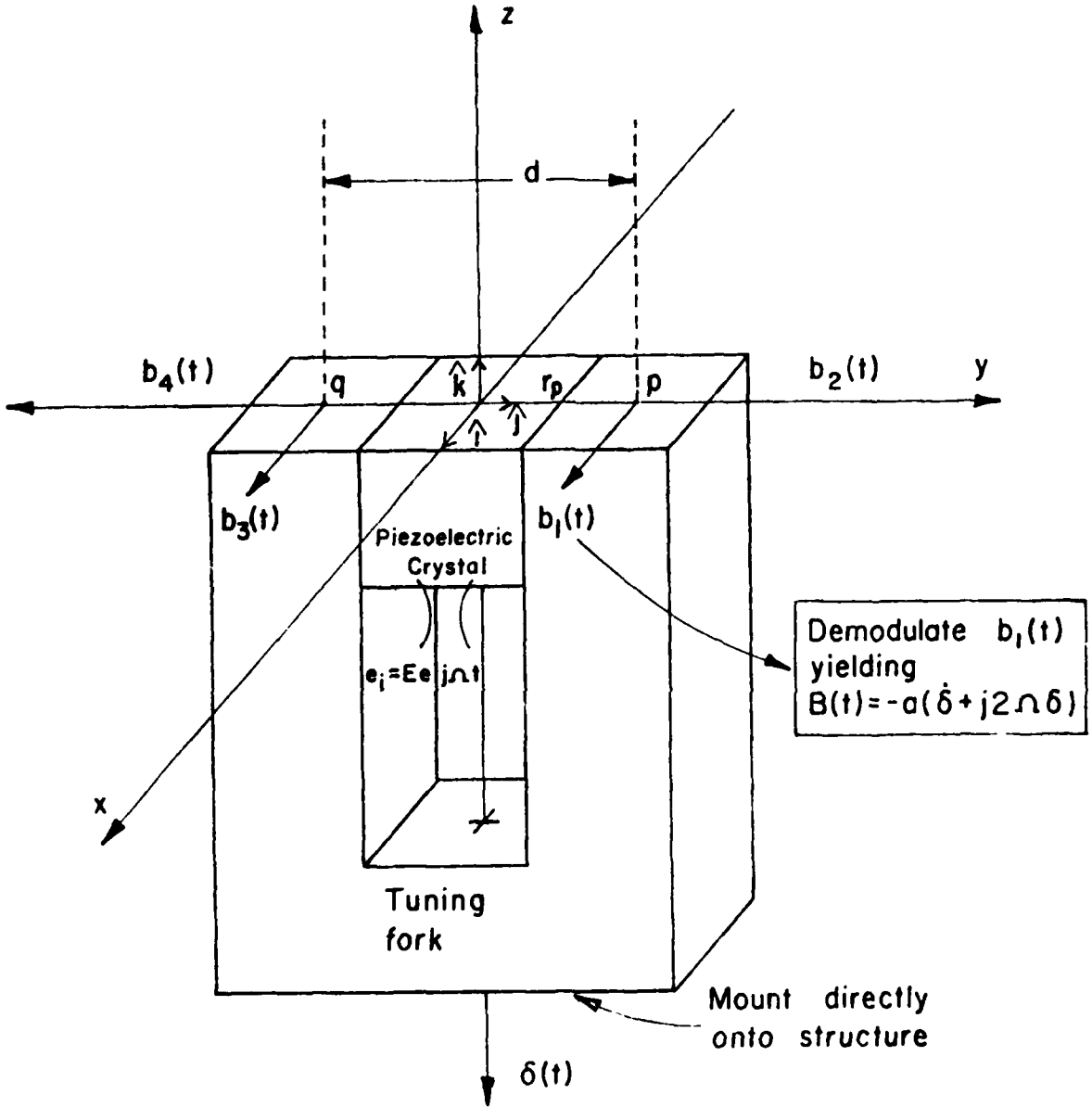
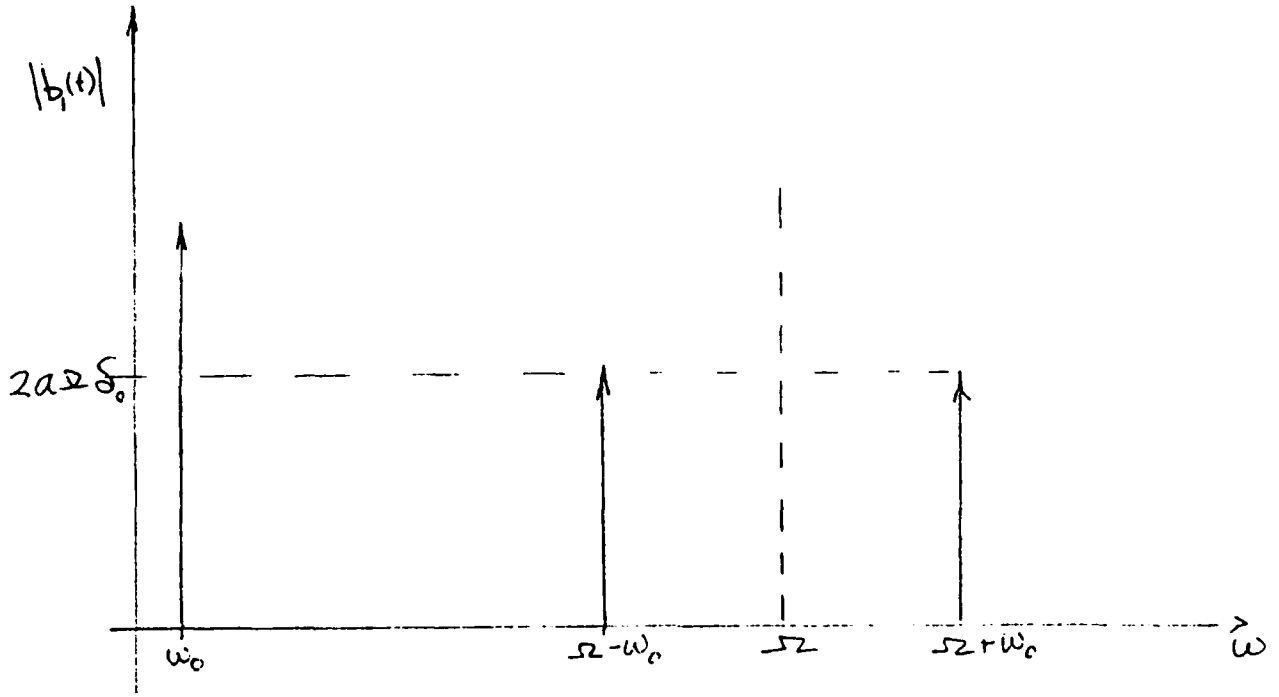
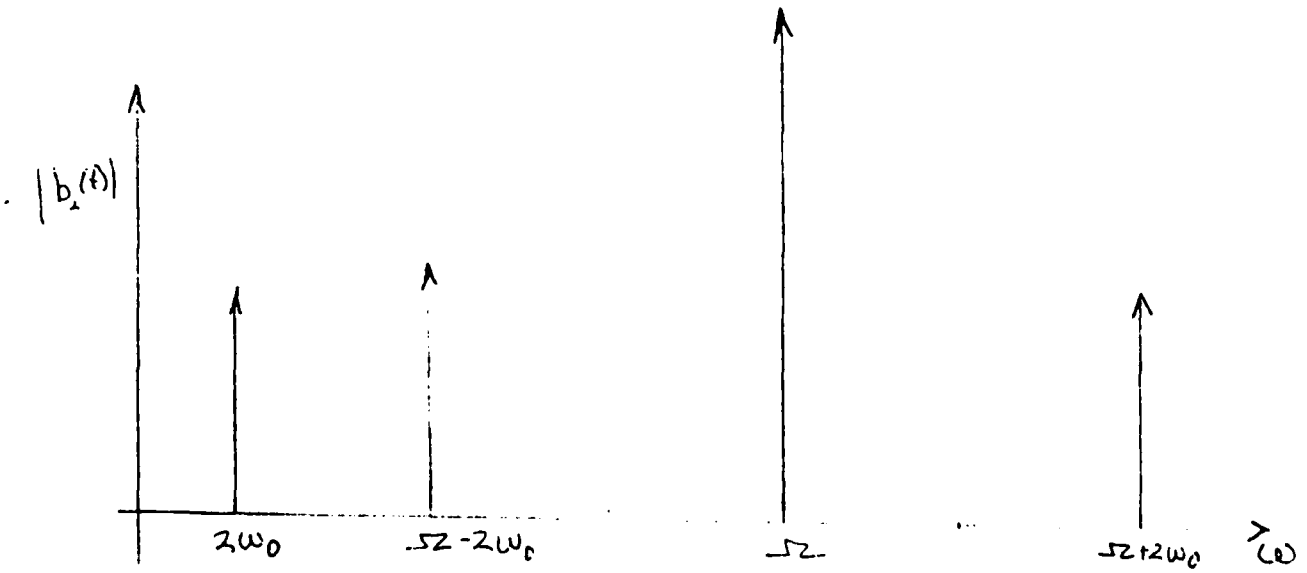


Figure 1. Schematic diagram of the Amplitude Modulated Broadband Vibration Velocimeter.



a. Frequency Spectrum of $b_1(t)$



b. Frequency Spectrum of $b_2(t)$

Figure 2 Frequency Content of the Acceleration of the Tuning Fork Tine Tip

where accelerometers are more sensitive. When the output signal $b_1(t)$ is demodulated, the desired sinusoidal angular motion is:

$$B(t) = \sqrt{(2a\Omega\delta_o)^2 + (a\omega_o\delta)^2}\, e^{j(\Omega+\omega_o)t} . \qquad (5)$$

In order for amplitude modulation to be successful, $\omega_o << \Omega$, so equation (5) is approximately [7]:

$$B(t) \approx 2a\Omega\delta_o e^{j(\Omega+\omega_o)t} .$$

Therefore the amplitude of the output is a constant with respect to frequency. As long as the tuning fork resonant frequency is high, the angular measurement will be broad band.

A few simple calculations can reveal the practical significance of this approach. Suppose that a piezoelectric exciter is capable of providing 10^{-6} m of amplitude and suppose the resonant frequency were 10kHz. If the accelerometer noise floor were 10^{-4}g, the minimum angular rate which could be measured would be:

$$\delta_{min} = \frac{10^{-4}g}{2a\Omega} = 7.81\times10^{-3}\ \frac{rad}{sec} .$$

At 100 Hz this corresponds to about 12.4×10^{-6} radians. The basic sensing element is a piezoelectric crystal, so the dynamic range would be about the same as conventional piezoelectric accelerometers. Since this is a rate sensor, the sensitivity increases with frequency. This indicates that if it is possible to design a tuning fork which resonates at a sufficiently high amplitude at a sufficiently high frequency, the accurate measurement of 10^{-6} radians is within reason. Note that two parameters completely describe the sensitivity of the rate sensor: resonant frequency and resonant amplitude.

Laboratory measurements on two prototype tuning forks have been made. Those measurements reveal some practical constraints which must be considered in the design. Those laboratory measurements are described in the next section.

EXPERIMENTAL RESULTS

Two prototype angular velocimeters have been constructed in the laboratory. The first one was machined from steel with the gap between the tines adjustable, and excited by a solenoid between the tine tips. The second one was machined in one piece from magnesium and excited by a solenoid behind the tuning fork. The results given here indicate that the theory of operation is sound, and that the tuning fork should be machined from a single piece of stock. The particular type of material does not seem to matter, since for most metals E/P is approximately constant.

The steel tuning fork was subjected to an angular excitation using a linkage system connected to a shaker as shown in Figure 3. The locations of the tuning fork tines were adjustable to allow the correct air gap for maximum response. In addition, slots were machined into the base of the tines to adjust the stiffness of the tines, thus providing an adjustment for the resonant amplitude "a". The base of the device, also made of steel, was connected by two bearings to a rigid platform. An aluminum arm was used to connect to a shaker, providing the input angle δ. Figure 4 shows the instrumentation block diagram for the experimental investigations.

According to Reference [5], the output spectrum of an amplitude modulated signal will be the measured spectrum reflected about the carrier frequency. Figure 5 is the zoom transform of $b_1(t)$ for a 25 Hz excitation frequency with a carrier frequency of 1120 Hz. The noise threshold of the accelerometer is 0.358×10^{-3}g. Other measurement data is summarized below:

$$a = 1.21 \times 10^{-7}$$

$$\delta_0 = 2.838 \text{ rad/sec}$$

$$\omega = 25 \text{ Hz}$$

$$\Omega = 1120 \text{ Hz}$$

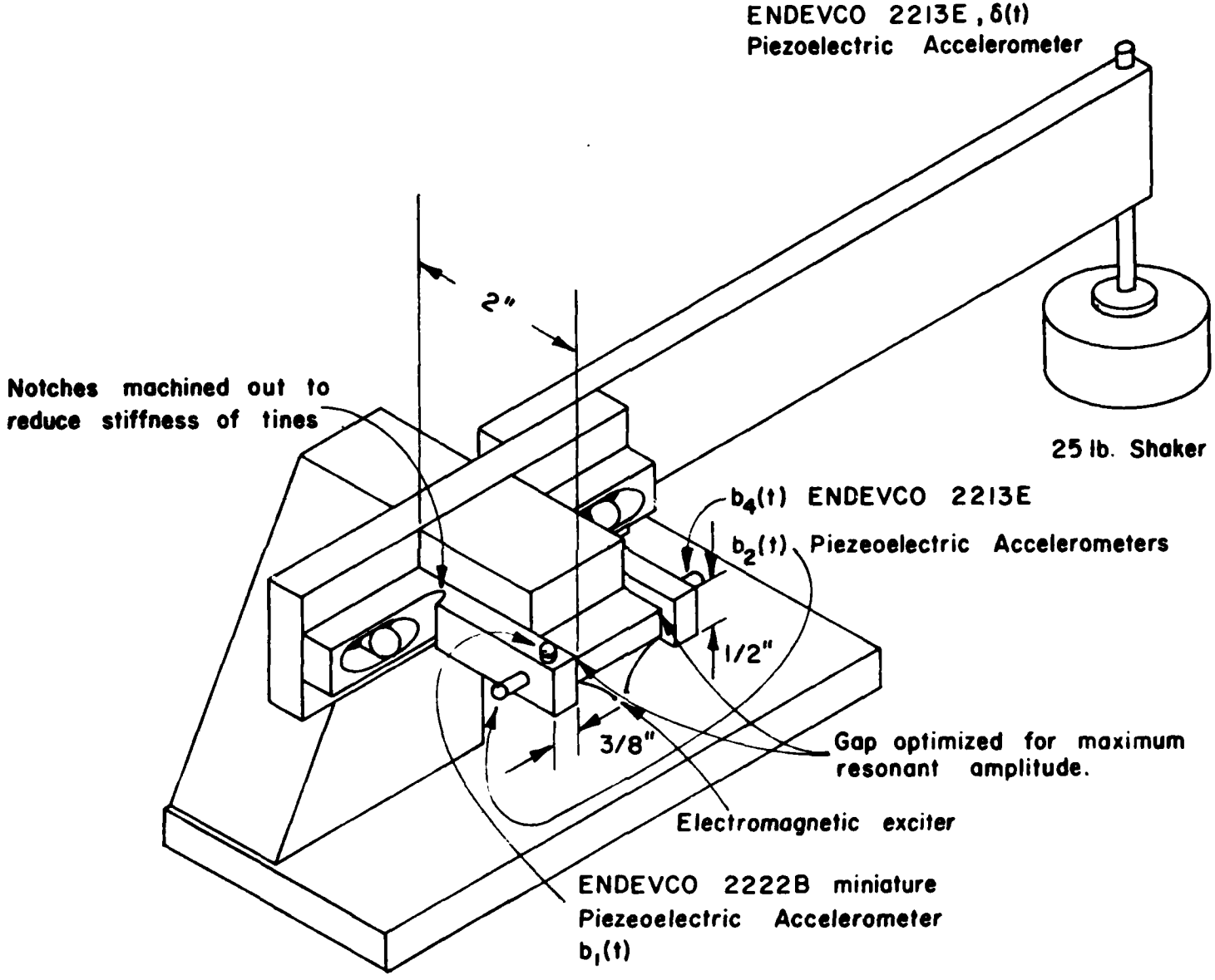


Figure 3. Schematic of the prototype angular velocimeter.

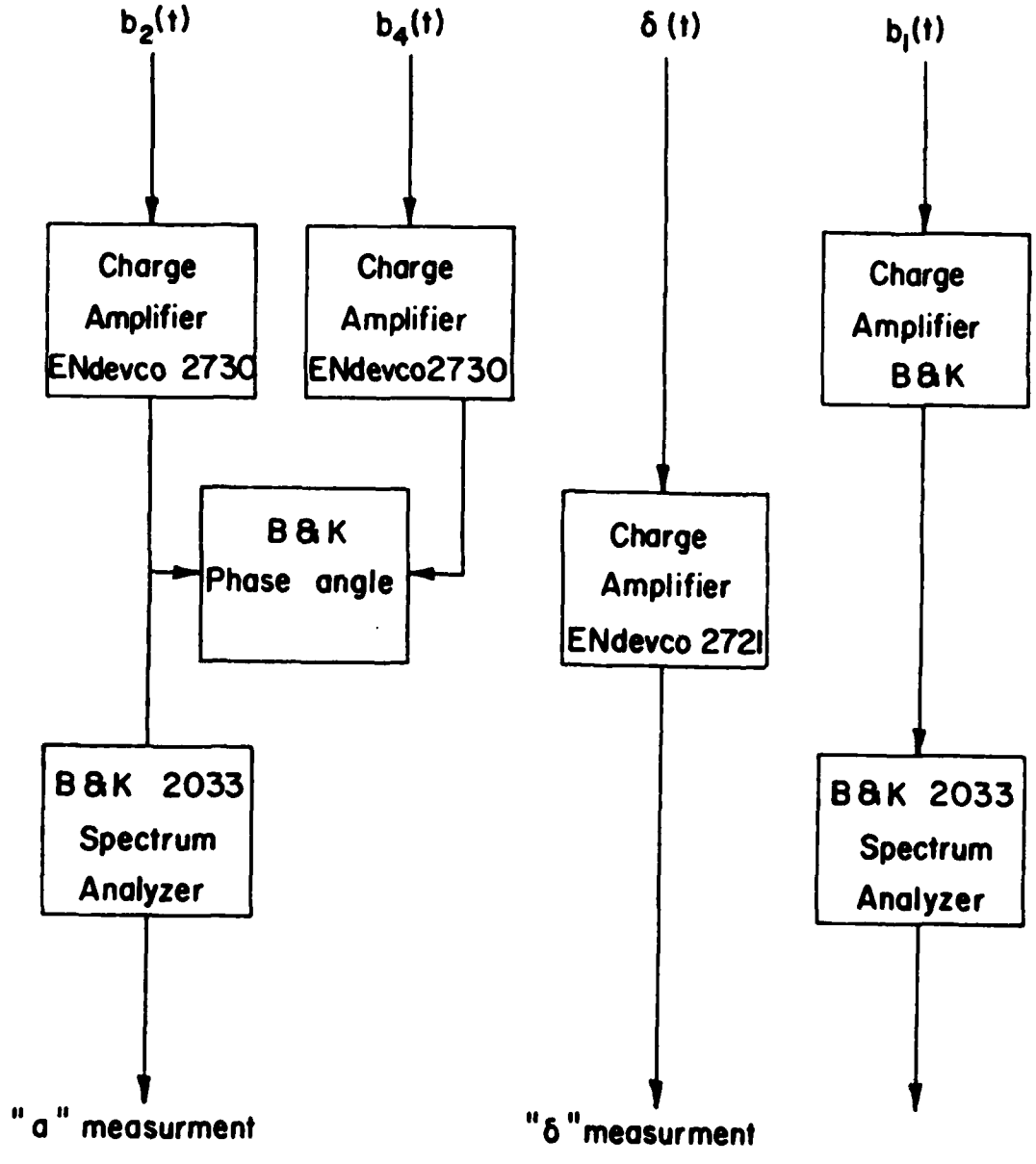


Figure 4. Instrumentation diagram.

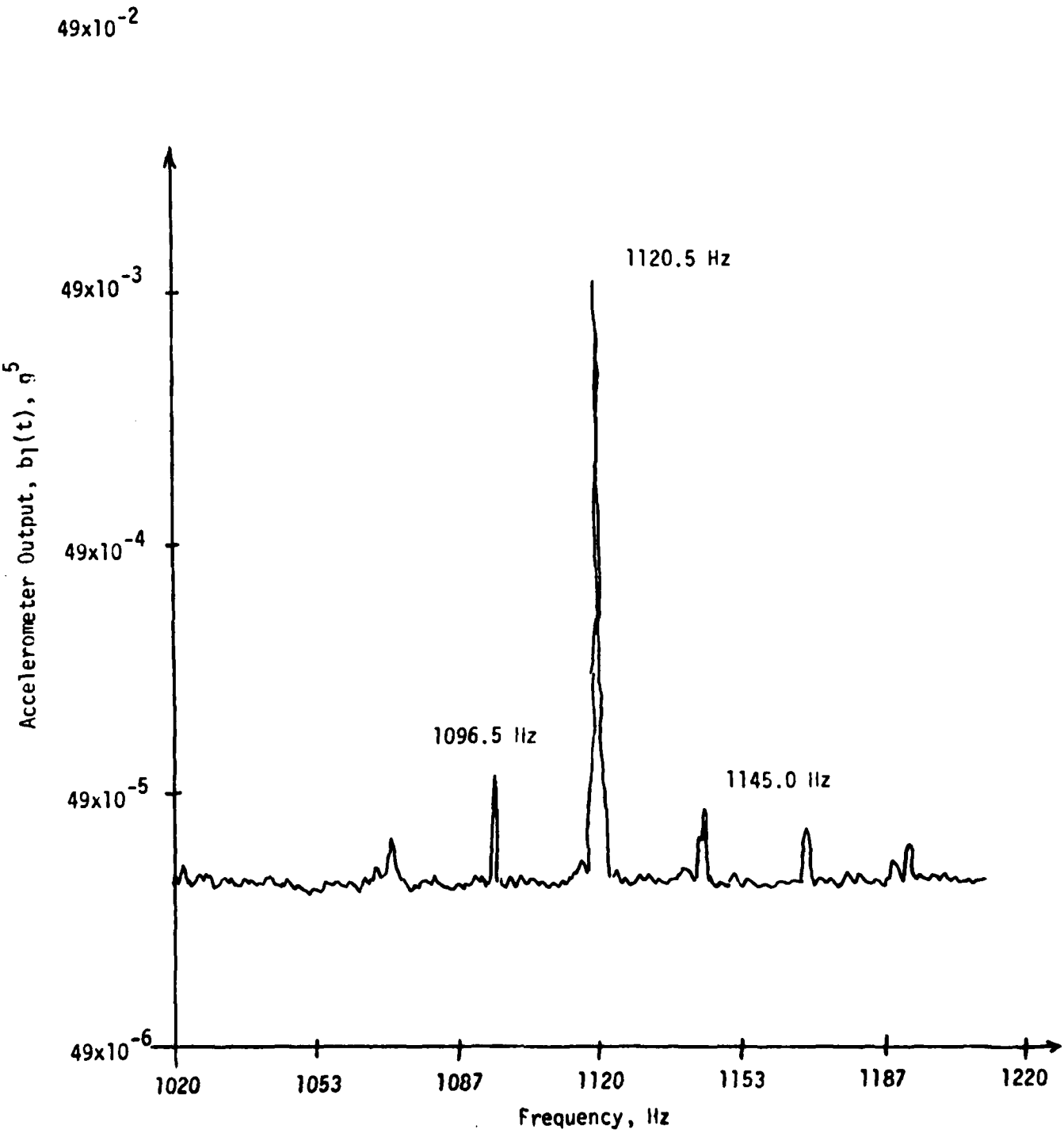


Figure 5. Zoom Transform of $b_1(t)$

The measured value of $b_1(t)$ at $\Omega + \omega = 1145$ Hz is 0.0052m/sec^2. The theoretical value is $2a\Omega\delta_0 = 0.0049$, for an error of 7.3%.

Note that $\Omega/10$ is over 100 Hz for this case, but the shaker used to generate δ also generated significant harmonics, limiting the upper frequency limit to below 100 Hz. It would be expected that by increasing Ω this limitation would not be as severe. Note also that for this case, the signal-to-noise ratio is much less than 20 dB. That is because of limitations on the displacement of the shaker head.

Figure 5 reveals that the output amplitude modulated signal is corrupted with noise. Also, although the theory does not predict a component of $b_1(t)$ at the resonant frequency, due to the accelerometer cross axis sensitivity there is a significant signal there which interferes with the amplitude demodulation. Finally, the resonant amplitude is too small because of friction losses at the base of the adjustable tines. Electronic filtering might be used to improve the noise problems, and a different structure for the tuning fork can reduce the friction losses, reducing the damping and increasing the resonant amplitude.

A second prototype tuning fork was machined out of a single piece of magnesium as indicated in Figure 6. The "H" shape of Figure 6 was selected in order to provide symmetric tines with the small bridge between tines providing coupling without excessive stiffness. The small solenoid was a standard 24V comercially available unit. Since the sensitivity depends on the product $a\Omega$, the physical dimensions of the tuning fork were varied with the following results. As expected, the tuning fork resonant frequency is proportional to h and inversely proportional to ℓ^2. The width of the tines, b, does not affect the natural frequency but does affect the stiffness which must be overcome by the solenoid in generating a large resonant amplitude. Therefore,

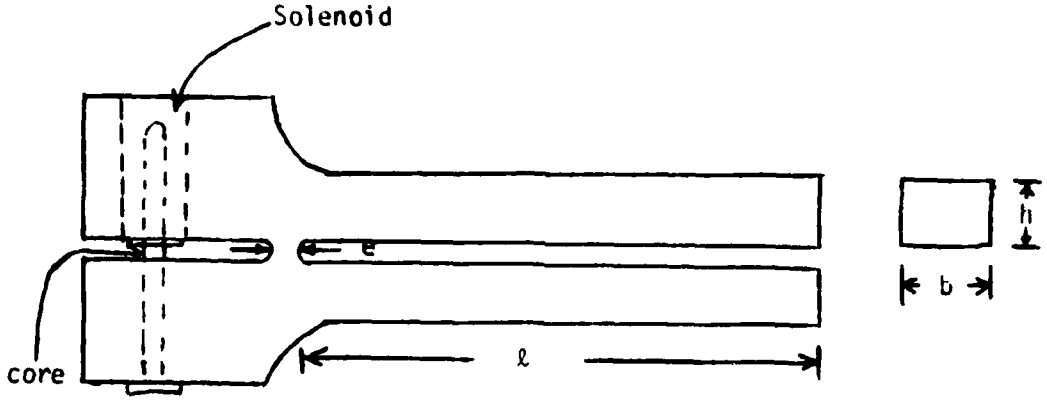


Figure 6. Detailed Geometry of a Single-unit Prototype.

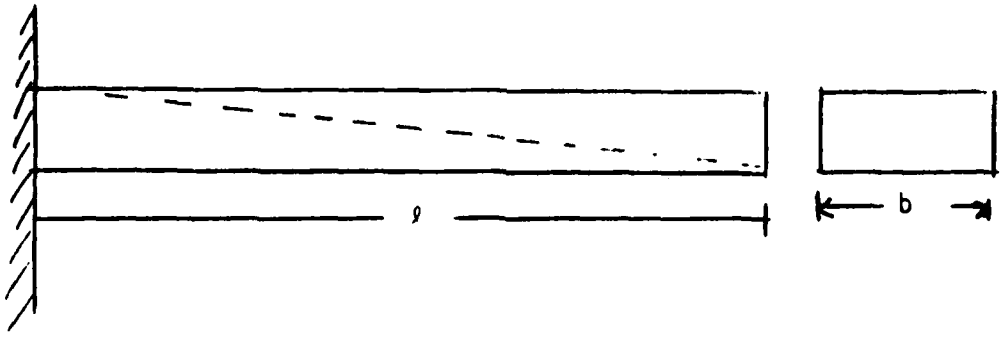


Figure 7. Cantilever Beam Model for One of the Symmetric Tines.

b should be made as small as possible without allowing the cross-axis stiffness of the tuning fork to become smaller than the resonant stiffness. This would corrupt the acceleration measurement by allowing the tines to deflect in the direction of $b_1(t)$. Finally, the value of e has been found to influence the tuning fork resonant frequency only slightly, while reducing the stiffness significantly thus providing for larger resonant amplitude. Therefore the value of e should be adjusted to give the desirable resonant amplitude.

This demonstrates that the theory of operation is sound for this instrument. In the next section, a discussion of design parameters will be given and recommendations for the next generation prototype will be discussed.

DISCUSSION OF DESIGN PARAMETERS

In the previous section it was demonstrated that in order to maximize the sensitivity of this angular velocimeter it is necessary to maximize the product $a\Omega$. In this section, the analysis of structural modifications to accomplish that are given. An approximate model for one of the symmetric tines would be a cantilever beam as indicated in Figure 7. The first natural frequency of a constant thickness cantilever beam is:

$$\omega_1 = \frac{1.76h}{\ell^2}\sqrt{\frac{E}{3\rho}} \quad . \tag{6}$$

In order to maximize the natural frequency given by equation (6) h should be increased while ℓ is decreased. That process is limited by the requirement that the system behave like a beam requiring that ℓ/h be large. Also, the resonant frequency should be increased without substantially decreasing the resonant amplitude. The resonant amplitude depends on the damping and on the resistance to bending of the tine tip. The stiffness of the tine tip in Figure 7 is:

$$k = \frac{Eb}{4}\left(\frac{h}{\ell}\right)^3 \quad . \tag{7}$$

If the tine were tapered, indicated by the dotted line in Figure 7, the stiffness is reduced to:

$$k = \frac{Eb}{6}\left(\frac{h}{\ell}\right)^3,$$

which is about 50% less. This indicates that a higher resonant amplitude is possible from tapering. The new resonant frequency is [8]:

$$\omega_1 = \frac{2.66h}{\ell^2}\sqrt{\frac{E}{3\rho}} \quad ,$$

which is about 50% higher than the uniform beam. Tapering therefore increases the product $a\Omega$ by 2.25, more than doubling the sensitivity.

A uniform tuning fork machined according to Figure 6 had a resonant frequency of 610 Hz with a resonant amplitude of 8.0×10^{-8}m. After tapering, the resonant frequency was increased to 640 Hz and the resonant amplitude to 3×10^{-7}m. This increased the resonant amplitude by a factor of about 3.75 and the resonant frequency by only about 5%. That is probably because the fork was not tapered to a point since that would not provide a platform for the accelerometer. The resonant amplitude increase was much greater than expected probably because at resonance the damping controls the amplitude, while stiffness was used in a qualitative sense.

It is necessary to comment that this engineering trade-off involves mutually contradictory trends. All resonating vibratory systems are found to have reduced amplitudes of vibration as their frequencies increase. This is because physical structures act as low-pass filters, preferring information at low frequencies. In order for this idea to be practical, it must be shown that a sufficiently high resonant amplitude can be excited at a sufficiently high frequency. From Figure 1, a natural alternative might be to choose a piezoelectric material as the resonating basis of the instrument in Reference [6], especially since piezoelectric materials have very high resonant frequencies. However, such materials are very stiff and therefore have very low resonant displacements. Therefore, the preferred configuration might be to use the tuning fork as a displacement amplifier and use the piezoelectric exciter to stiffen the tuning fork, pushing the resonant frequency upward. This can be done by carefully selecting the location of the piezoelectric exciter such that maximum power is transferred. This can be done by matching the impedances of the piezoelectric crystal and the tuning fork.

Consider a tuning fork with the piezoelectric exciter located between the tines as in Figure 8. There will be some location X_o which corresponds to a maximum displacement of the tuning fork tines and simultaneously a maximum resonant frequency. The optimum configuration corresponds to the appropriate choice for X_o. A simplified analysis can be conducted by considering that the tuning fork is symmetric and analyzing one tine as a cantilever beam excited by a concentrated force acting through a spring as indicated in Figure 7. The piezoelectric crystal is modeled as a spring since it is anticipated that the system resonant frequency will be much smaller than the piezoelectric crystal resonant frequency and therefore the exciter will be stiffness controlled. The impedance match will be carried out by assuring that the resonant displacement of the beam corresponds to the deflection of the exciter at the beam resonant frequency.

The differential equation of motion for the beam of Figure 7 is:

$$EI\frac{\partial^4 y}{\partial x^4} + FI\frac{\partial^5 y}{\partial x^4 \partial t} + \rho A\frac{\partial^2 y}{\partial x^2} = Z(x)P_o e^{j\Omega t} \tag{8}$$

The solution to equation (8) is

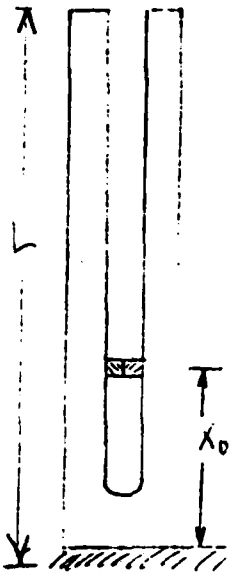
$$y(x,t) = \sum_{i=1} \phi_i(x) q_i(t), \tag{9}$$

where $q_i(t)$ is a solution to:

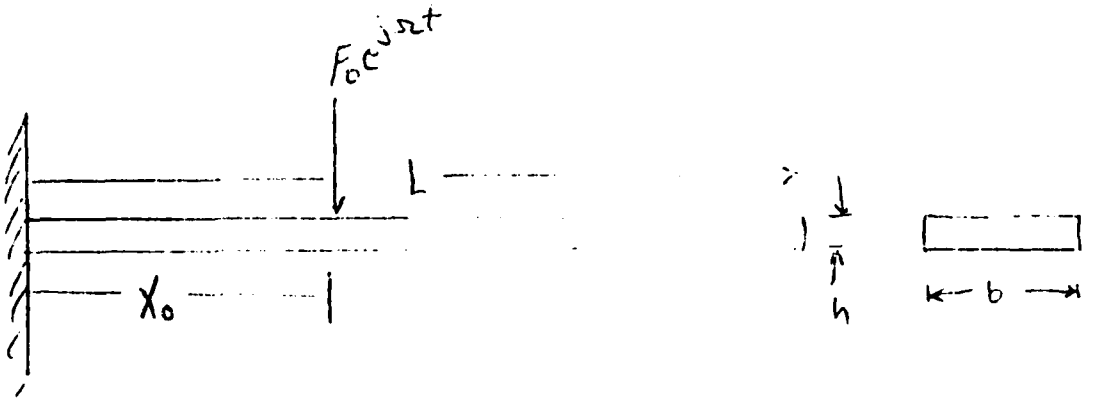
$$\ddot{q}_i + 2\xi_i\omega_i\dot{q}_i + \omega_i^2 q_i = \frac{1}{\rho AL}\int_0^L \phi_i(x)\delta(x-x_o)dx P_o e^{j\Omega t}. \tag{10}$$

In equation (10) $Z(X) = \delta(X-X_o)$ has been substituted. Taking the first mode,

$$q_1 = \frac{\phi_1(x_o)P_o}{\rho AL}\,\frac{e^{j\Omega t}}{\omega_1^2 - \omega^2 + j2\xi_1\omega_1\omega},$$



a. Tuning Fork Excited by a Piezoelectric Crystal



b. Cantilever Beam Model of half a Tuning Fork Excited by a Piezoelectric Crystal

Figure 8. Tuning Fork with Piezoelectric Crystal Located Between the Tines

then the resonant deflection is:

$$y = \phi_1(x) \frac{\phi_1(x_o)P_o}{\rho AL} \frac{e^{j\Omega t}}{\omega_1^2 - \omega^2 + j2\xi_1\omega_1\omega} .$$

Since the piezoelectric crystal is operating well below its resonant frequency, the position X_o is selected such that:

$$\frac{P_o}{k_s} = \frac{[\phi_1(x_o)]^2 P_o}{\rho AL\sqrt{(\omega_1^2 - \omega^2)+(2\xi_1\omega_1\omega)^2}} . \tag{11}$$

Now since the tuning fork is to be vibrated at resonance, $\omega = \omega_1$, and X_o is chosen to satisfy:

$$k_s[\phi_1(x_o)]^2 = \rho AL\omega_1 2\xi_1 . \tag{12}$$

Equation (12) is a transcendental function since ω_1 and ϕ_1 depend on X_o. Therefore it is necessary to solve the eigenvalue problem by using boundary conditions to evaluate the homogeneous solution to equation (8). The procedure is taken from Reference [9], and uses the following boundary conditions with a piecewise mode shape function.

(a) $y(o) = 0$

(b) $\frac{\partial y}{\partial x}(o) = 0$

(c) $\frac{\partial^2 y}{\partial x^2}(\ell) = 0$

(d) $\frac{\partial^3 y}{\partial x^3}(\ell) = 0$

At $X = X_o$, the mode shape must be continuous. From equation (9),

$$y(x,t) = \phi_1(x)q_1(t) = \begin{Bmatrix} \bar{\phi}_1(x) , & 0 \le x \le x_o \\ \bar{\phi}_2(x) , & x_o < x \le \ell \end{Bmatrix} q_1(t) \tag{13}$$

The continuity conditions are:

(e) $$\bar{\phi}_1(x_o) = \bar{\phi}_2(x_o)$$

(f) $$\frac{d\bar{\phi}_1(x_o)}{dx} = \frac{d\bar{\phi}_2(x_o)}{dx}$$

(g) $$\frac{d^2\bar{\phi}_1(x_o)}{dx^2} = \frac{d^2\bar{\phi}_2(x_o)}{dx}$$

(h) $$EI\left[\frac{d^3\bar{\phi}_1(x_o)}{dx^3} - \frac{d^3\bar{\phi}_2(x_o)}{dx^3}\right] = k_s\bar{\phi}_1(x_o)$$

The piecewise mode shapes, $\bar{\phi}_1$ and $\bar{\phi}_2$ can be written in terms of arbitrary constants as follows:

$$\bar{\phi}_1(x) = A_1(\sin kx-\sinh kx) + A_2(\cos kx-\cosh kx), \qquad (14a)$$

$$\bar{\phi}_2(x) = B_1\sin kx + B_2\cos kx + B_3\sinh kx + B_4\cosh kx. \qquad (14b)$$

Equations (a) and (b) have been used in equation (14a) to reduce the number of arbitrary constants to six. The result is a set of six equations:

$$A_1(\sin kx_o-\sinh kx_o) + A_2(\cos kx_o-\cosh kx_o) = B_1\sin kx_o + B_2\cos kx_o + B_3\sinh kx_o + B_4\cosh kx_o \qquad (15a)$$

$$A_1(\cos kx_o-\cosh kx_o) - A_2(\sin kx_o+\sinh kx_o) = B_1\cos kx_o - B_2\sin kx_o + B_3\cosh kx_o + B_4\sinh kx_o \qquad (15b)$$

$$-A_1(\sin kx_o+\sinh kx_o) - A_2(\cos kx_o+\cosh kx_o) = -B_1\sin kx_o - B_2\cos kx_o + B_3\sinh kx_o + B_4\cosh kx_o \qquad (15c)$$

$$\frac{k^3\ell^3}{} [-A_1(\cos kx_o+\cosh kx_o) + A_2(\sin kx_o-\sinh kx_o) -$$

$$(-B_1\cos kx_o + B_2\sin kx_o + B_3\cosh kx_o + B_4\sinh kx_o)] = \tag{15d}$$

$$\frac{k\ell^3}{EI}_s [A_1(\sin kx_o-\sinh kx_o) + A_2(\cos kx_o-\cosh kx_o)]$$

$$-B_1\sin k\ell - B_2\cos k\ell + B_3\sinh k\ell + B_4\cosh k\ell = 0 \tag{15e}$$

$$-B_1\cos k\ell + B_2\sin k\ell + B_3\cosh k\ell + B_4\sinh k\ell = 0 \tag{15f}$$

If $X_o = 0$, equations (15) reduce to the familiar cantilever beam roots. Given X_o/ℓ, $k_s\ell^3/EI$ equations (15) represent an eigenvalue problem where the roots (natural frequencies) correspond to the condition that the determinant of the coefficient matrix is zero. That can be accomplished in a straightforward manner on the digital computer and will result in the roots $k\ell^*$. The natural frequency is:

$$\omega_i^3 = (\frac{k\ell^*}{\ell})^2 \sqrt{\frac{EI}{\rho A}} \tag{16}$$

The mode shape $\phi_1(x) = \begin{cases} \bar{\phi}_1(x) & 0 \le x \le x_o \\ \bar{\phi}_2(x) & x_o < x \le \ell \end{cases}$

must be normalized by substituting $k\ell^*$ back into equation (15) and assuming $B_4 = 1$. Then A_1, A_2, B_1, B_2, B_3 may be calculated and normalized such that:

$$\int_0^\ell \phi_1^2(x)dx = \ell \ . \tag{17}$$

Then equation (12) must be checked to see if the original choice for X_o was correct. The appropriate value for X_o may be calculated using trial and error, or a constrained optimization procedure may be used. Equation (12) may be used to define an objective function:

$$G(x_o) = [\rho AL\omega_1\sqrt{2\xi_1} - k_s\phi_1^2(x_o)]^2 \qquad (18)$$

The minimum value of $G(X_o)$ will correspond to a solution to equation (12). The digital computer is to be used to find a solution to equation (15), which are eigenvalues and eigenfunctions. This procedure has been used in Reference [9] in a similar application, and an algebraic unconstrained optimization algorithm called the Variable Metric Method already exists in the IMSL Library. This procedure, although involving some computer programming, is straightforward and would be expected to yield the appropriate choice for X_o.

Practical considerations require further discussion of the model in Figure 7. Although it is possible to calculate X_o in this manner, the accuracy of the answer will depend on the accuracy of the model in Figure 7. The piezoelectric exciter was modeled as a concentrated load, but fabrication techniques would be simplified by epoxying a piezoelectric material between the tines as in Figure 6, which is more of a distributed load. A prototype must be built in the laboratory to check the accuracy of the model. Although the model could be modified to include a distributed load, the additional computational effort would not be worthwhile considering that a laboratory prototype must be constructed to verify any model.

It has been shown that a tapered tuning fork is better than one with uniform thickness. The procedure outlined above could be carried out for a tapered beam, since the exact solution form is known and given in Reference [8].

It is recommended that the correct choice for X_o be pursued for the tapered beam. Since the above outlined analysis has not yet been completed, no laboratory prototype exists for the tuning fork with a piezoelectric exciter.

SUMMARY

A new instrument for measuring angular vibration uses a tuning fork to amplitude modulate the angular velocity. This moves information upward in frequency where accelerometers are more sensitive. Only two design parameters define the sensitivity of the tuning fork velocimeter: the resonant frequency and displacement. It is demonstrated that by tapering the tines, the sensitivity is improved. Two prototype tuning forks are experimentally investigated with the result that a recommendation for a final prototype is given. First, the final prototype should be machined from a single piece of metal reducing the damping. Second, the prototype should be excited by a piezoelectric exciter optimally positioned for impedance matching. In this way it is expected that a new prototype sensor can be developed capable of measuring angles in the 10^{-6} radian range.

REFERENCES

1. Peters, Rex. B., and Paul H. Merritt, "A Precision Inertial Angular Vibration Measuring System," Shock and Vibration Bulletin, No. 50., Part 2, pp 1-10, Sept 1980.
2. Whaley, P. W., and M. W. Obal, "Angular Vibration Measurement Techniques," Shock and Vibration Bulletin, No. 48, Part 4, pp 83-93, Sept 1978.
3. Fearnside, K., and P. A. N. Briggs, "The Mathematical Theory of Vibratory Angular Tachometers," The Institution of Electrical Engineers, Monograph No. 264M, Nov 1957.
4. Lyman, J., "A New Space Rate Sensing Instrument," Aeronautical Engineering Review, Nov 1953, pp 24-30.
5. Barnday, R. E., J. B. Chatterton, and F. H. Gerring, "Gyratron Angular Rate Tachometer," Aeronautical Engineering Review, Nov 1953, pp 31-36.
6. Whaley, P. W., U. S. Patent Application No. 342,098, Feb 17, 1982.
7. Doeblin, E. O., Measurement Systems: Application and Design, McGraw-Hill, 1966, pp 161-174.
8. Timoshenko, S., D. H. Young, and W. Weaver, Jr., "Vibration Problems in Engineering," 4th Edition, Wiley & Sons, New York, 1974, pp 465-467.
9. Whaley, P. W., and J. Pearson, "Computer-Aided Design of Passive Vibration Isolators for Airborne Electro-Optical Systems," Shock & Vibration Bulletin, #49, Part 2, Sept 1979, pp 81-86.

AD P002683

AN EXTENDED RANGE PENDULOUS VELOCITY GAGE

BY: Laurence Starrh, LLNL and Roger Noyes, EG&G, Inc.

Abstract

This paper describes the modification of a transducer to extend its dynamic range. These transducers would be used to measure the response of geologic media to stress waves generated during and after underground tests performed by the Lawrence Livermore National Laboratory (LLNL) at the Department of Energy's Nevada Test Site . Included are descriptions of the previously used transducers as well as the modified transducers, their calibration and fielding.

The successful extension of range of these transducers will allow the existing measurements system to be a more valuable tool for the LLNL data analysts. The system will be used in the continuing effort to understand geologic phenomena of underground testing.

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INTRODUCTION

The development, implementation, and continued improvement of instrumentation and techniques for the measurement and analysis of ground motions have figured prominently in the underground nuclear testing program conducted at the Nevada Test Site. Under the aegis of the U. S. Department of Energy (DOE), scientists from the Lawrence Livermore Laboratory, assisted by instrumentation engineers at the Energy Measurements Group of EG&G, Inc., routinely field systems designed especially for measuring the response of geologic media to the stress waves generated during and after an underground nuclear explosion.

The measurement system described here (Figure 1) was, for the most part, developed in the early 1960's, and except for the implementation of improved variable-reluctance velocity transducers and accelerometers, as well as a solid-state carrier system, it remains basically unchanged. The velocity gage used today is a modified version of the Sandia DX velocity gage, which was an adaptation of a basic Stanford Research Institute

design. This gage is manufactured by Bell & Howell's CEC Division as Model No. 369719 per LLNL Specification No. LES 21988A. The present gage couplers use a smaller transformer and are overall much smaller than the originals.

Originally, a CEC System "D" Carrier system was used. This has been replaced with a Natel Engineering Company Model 2088 solid-state carrier system.

The transducer described in the paper is basically a velocity gage with a pendulum made from Heavymet instead of brass or aluminum previously used. The heavier pendulum extends the range of the gage down by a factor of 2.5 to 3.

EXTENDED VELOCITY GAGE DESCRIPTION

The velocity gage was constructed by taking a standard CEC velocity gage and installing a pendulum made from heavymetal (a C.M.W. product) Figure 2. Heavymetal is a sintered combination of tungsten with 5% or 10% alloys. The alloys make it easier to machine than pure tungsten, but keeps the mass nearly that of tungsten. The specific gravities of heavymetal, tungsten, brass, and aluminum are shown in Figure 3. The gage was filled with 2,000 CS silicone oil as would normally be done for a low range gage with a brass pendulum. There have been no tests conducted yet as to the maximum range this gage may be operated before there are shearing effects in the oil. The gage was then calibrated as a horizontal velocity gage. The results are shown in Figure 4.

An extra heavy gravity negating spring was made for this gage. The gage was emptied, this spring installed, the gage refilled. The gage was then calibrated as a vertical gage. These results are shown in Figure 5.

Another factor to be determined is the amount of iron core material needed in the pendulum that will allow the pendulum to be lifted magnetically and released for calibration purposes.

CALIBRATION

For calibration, variable-reluctance transducers are "married" to a gage coupler (Figure 6). The gage coupler contains two 402 ohm bridge completion resistors, input and output isolation transformers, two 28 V latching relays, and two externally mounted shunt resistors which are switched in and out with a 28V d.c. signal from the amplifier-demodulator. Mounting posts for two shunt resistors are on the top of each coupler. The relays are connected to form a four-state logic; zero, resistor 1, zero, resistor 2. Accelerometers and velocity gages use the same type coupler (Figure 7).

The velocity gage calibration procedure is somewhat complicated. The gage is checked for cleanliness, bearing fit, natural frequency, inductance, resistance, and insulation resistance before filling. A gage with the proper type pendulum material (brass or aluminum) and oil viscosity is selected for the system range of the measurement. In this case heavymetal and 2,000 cs oil. The gage is then filled under vacuum and sealed. If it is a vertical gage, the 1g negating spring must be adjusted for zero output in the normal operating position. The gage is then calibrated to determine its damping, which along with its natural frequency determines its useful frequency range. Finally, two linearity tests are made; one over the full range of the gage, the other only over that region that is to be used.

The dynamic output is recorded on an automated data system and static outputs are displayed on a DMM. The gage is driven by gravity in a 1g fall (2g if it is a vertical gage). Resistances are determined during the system linearity tests at points corresponding to the shunt steps required. The resistors are mounted on the gage coupler and the resulting shunt step outputs are obtained. A comparison with the required values is made by the automated data system. The ratios of the data points compared must agree to within 5% of the lower reading.

In addition to these measurements, a thermistor is mounted on each vertical gage so that temperature can be measured and a correction factor applied to the data to compensate for the thermally caused change in damping oil viscosity.

The Natel Carrier system used a 6 kHz sine wave for excitation and is adjusted to 5V rms at the gage input terminals. This system has phase and amplitude balance post to adjust for zero output, a reference phase control of 360°, and an adjustable attenuator and gain control to adjust the span. The system is set up for $\pm$2.5V d.c. output at system range.

The gages are usually calibrated so that with the calibration steps, the field setup will repeat the laboratory calibration to within $\pm$1%.

FIELDING

After being calibrated, the heavymetal gage was sent to the Nevada Test Site and mounted in an instrumentation trailer in a position parallel to the trailer vertical velocity gage. The comparisons made in Figure 8 support the estimated extended gage range of 2.5 to 3 with a factor of 2.76 brass.

The motion of the trailer during an event was recorded and the results are shown in Figure 9.

DATA REDUCTION

For those transducers measuring free-field ground motion, the device yield and the geology determine the upper limit of expected signal frequency content. For gages mounted on the emplacement pipe or other structures, the upper recorded frequency may be determined by the upper limit of the gage response. The total length of time the record is digitized also depends upon results of the observations of the oscillograph records. Velocity, of course, must return to zero at some late time. The digitizing time frame is set to capture enough of the data to allow this zero return to be analyzed.

The data are then analyzed via computer. The first step is the removal of noise and base line offsets. Each gage record is analyzed independently of all the others, noting again velocity and acceleration must return to zero if the records last long enough. The acceleration and velocity records are then integrated and all gages measuring the same quantity at the same location are compared. For example, the velocity and the integral of the acceleration are compared to ensure that they are indeed providing nearly the same record. Finally, all gages are taken as a whole to determine any systematic discrepancies. It must be pointed out that base line correcting of the gages is subjective and does not necessarily lead to the correct record. The investigator must rely on his experience for this.

At any step in the above analysis, the records may be converted from the raw A/D units (bits) to engineering units. The calibration steps referred to previously are part of each gage record and are digitized at the same time as are the motion data. Each calibration step corresponds to a known engineering unit level and digitizes as a raw A/D unit level. The ratio of these two provides the multiplicative factor for converting the gage data to engineering units.

The velocity gages are usually taken to be the most nearly correct measure of the ground motion, since a small drift in the base line can lead to a large error in the integral of the record. The displacement obtained as the double integral of the acceleration thus has the possibility of an extremely large error induced by the double integration.

Typical records are shown in Figure 10, where the records from a velocity gage and the integral of the associated accelerometer are compared. Figure 11 shows a comparison of the integral of the velocity and the second integral of the acceleration (displacement) for the two gages of Figure 10. Note that there is now a significant departure of the two records. It is assumed that the velocity gage, which is a lower frequency device and also subject to less error due to integration, is the more nearly correct representation of the true displacement. What is significant here is the close correlation attainable by this recording system for the velocities for the two gages.

SUMMARY

The nominal operating ranges of velocity gages with 2,000 cs oil and aluminum, brass and heavymetal pendulums are compared in Figure 12. The fielding of heavymetal pendulum gages has shown that this material will extend the range of these velocity gages down to a useful minimum range of 0.3 m/s, of course the investigations on the effect of oil shear and calibration techniques must be completed before the gage is ready to be produced on a production basis.

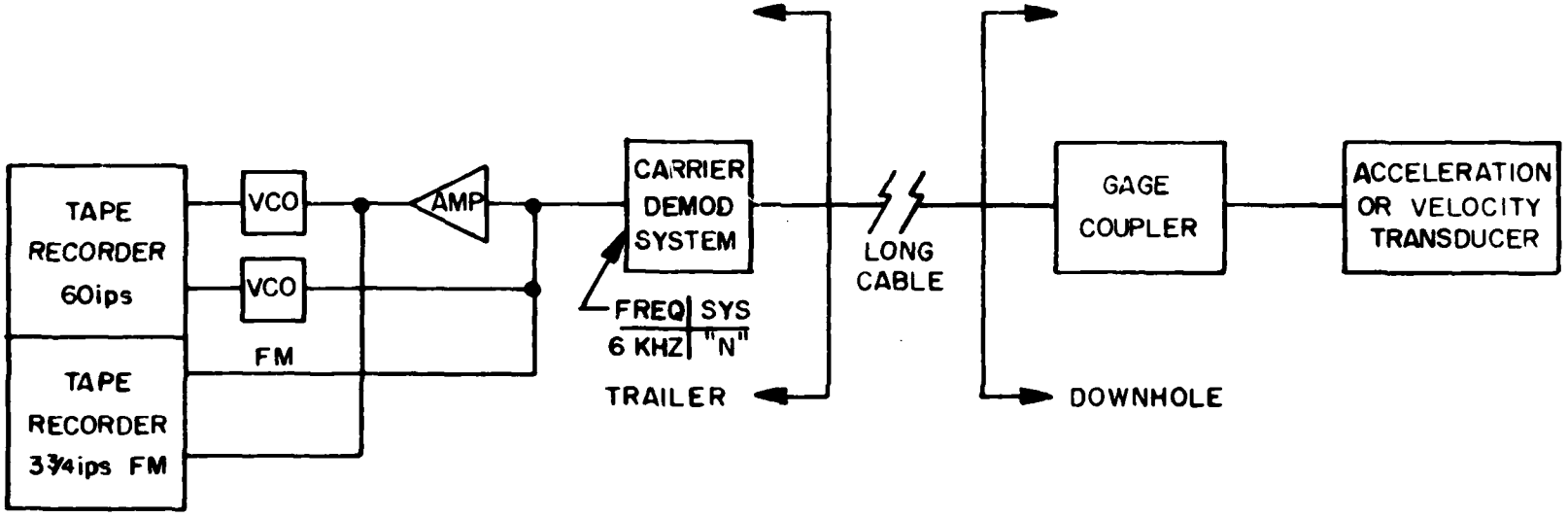

Figure 1.

SYSTEM BLOCK DIAGRAM

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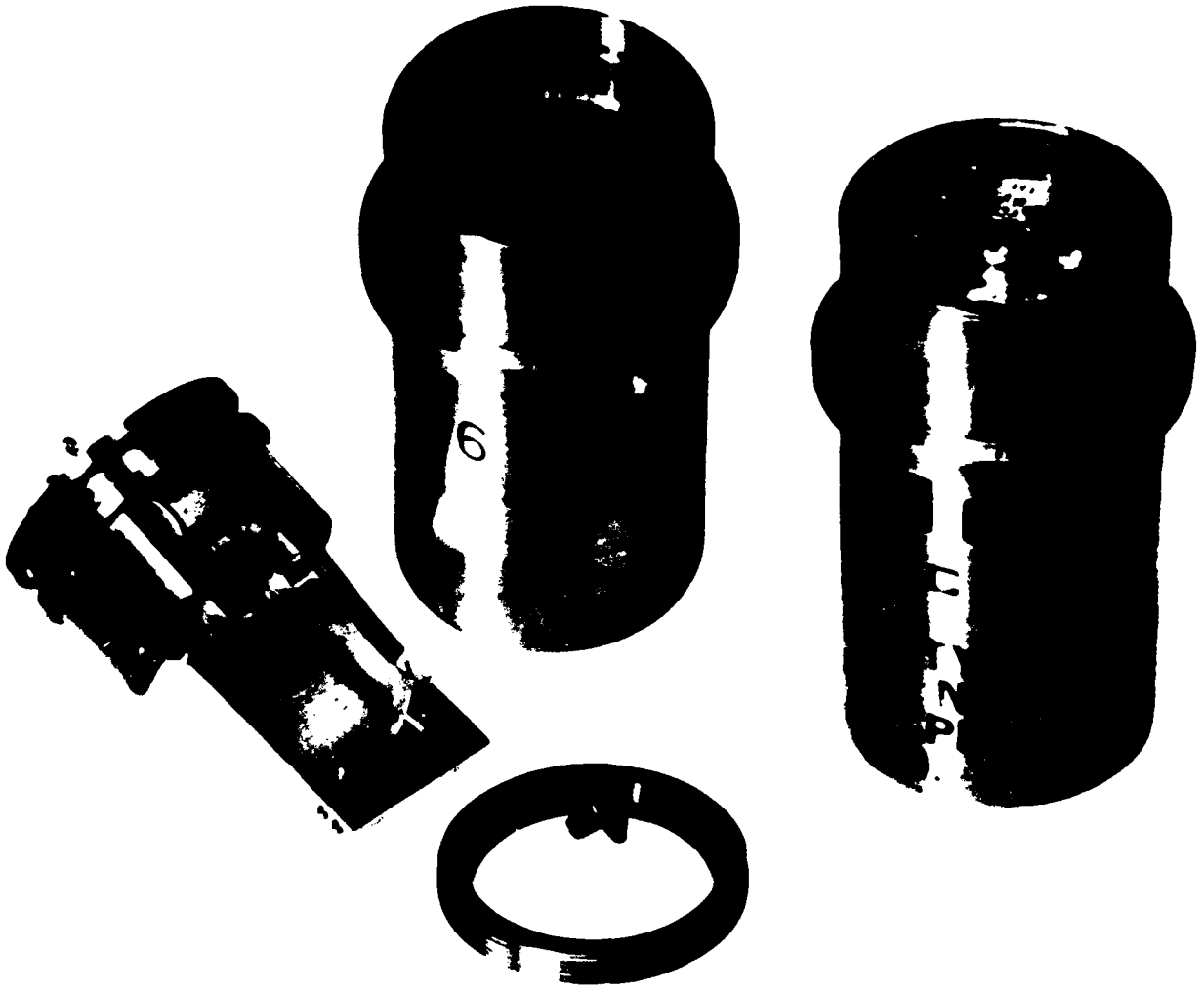


Gages Containing Brass Or Aluminum Pendulum Material

DENSITY (G/CC)

TUNGSTEN	HEAVYMETAL 95%/5%	BRASS	ALUMINUM
19.3	18	8.47	2.7

FIGURE 3

HEAVYMETAL HORIZONTAL CALIBRATION

FRICTION DAMPING	=	1	Hz
NATURAL FREQUENCY	=	3.05	Hz
LOG DELTA TIME	=	5.45	s
RANGE, STOP TO STOP	=	22.56	m/s
RANGE, LINEAR ±3%	=	18.15	m/s

FIGURE 4

HEAVYMETAL VERTICAL CALIBRATION

FRICTION DAMPING	=	2	Hz
NATURAL FREQUENCY	=	3.05	Hz
LOG DELTA TIME	=	1.54	δ
RANGE, STOP TO STOP	=	25.5	m/s
RANGE, LINEAR ±3%	=	19.5	m/s

FIGURE 5

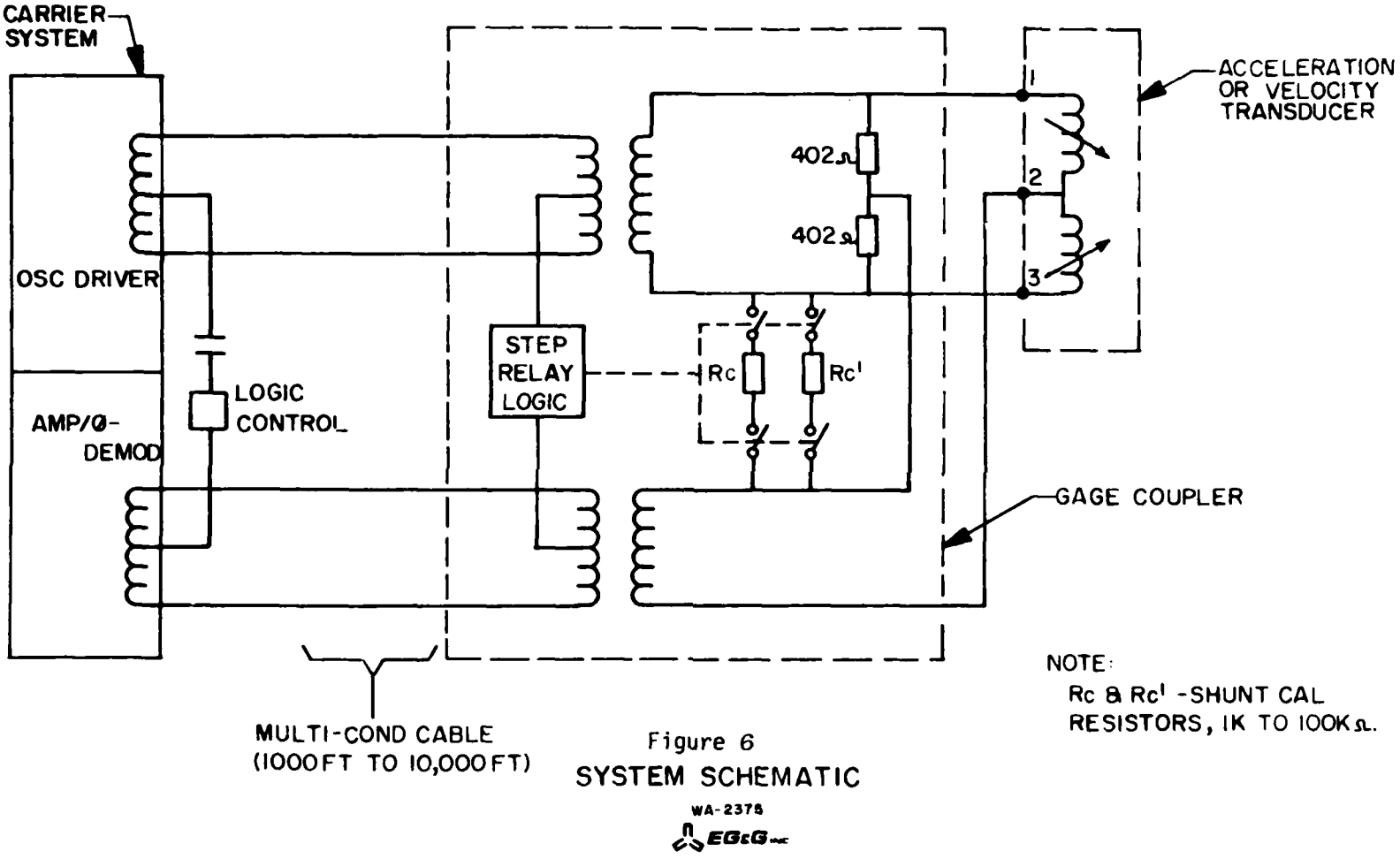
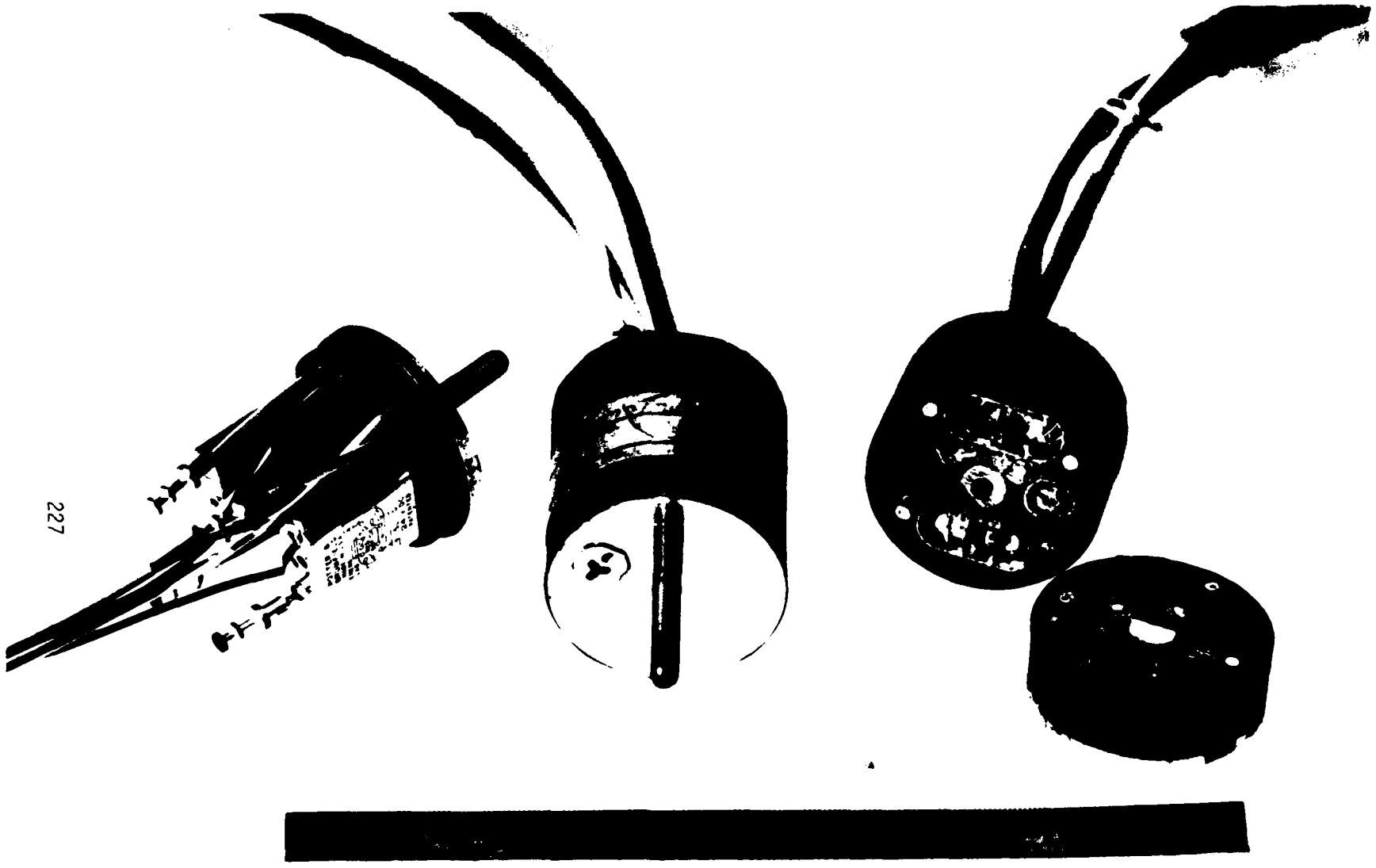


Figure 6
SYSTEM SCHEMATIC

WA-2378

EG&G Inc.



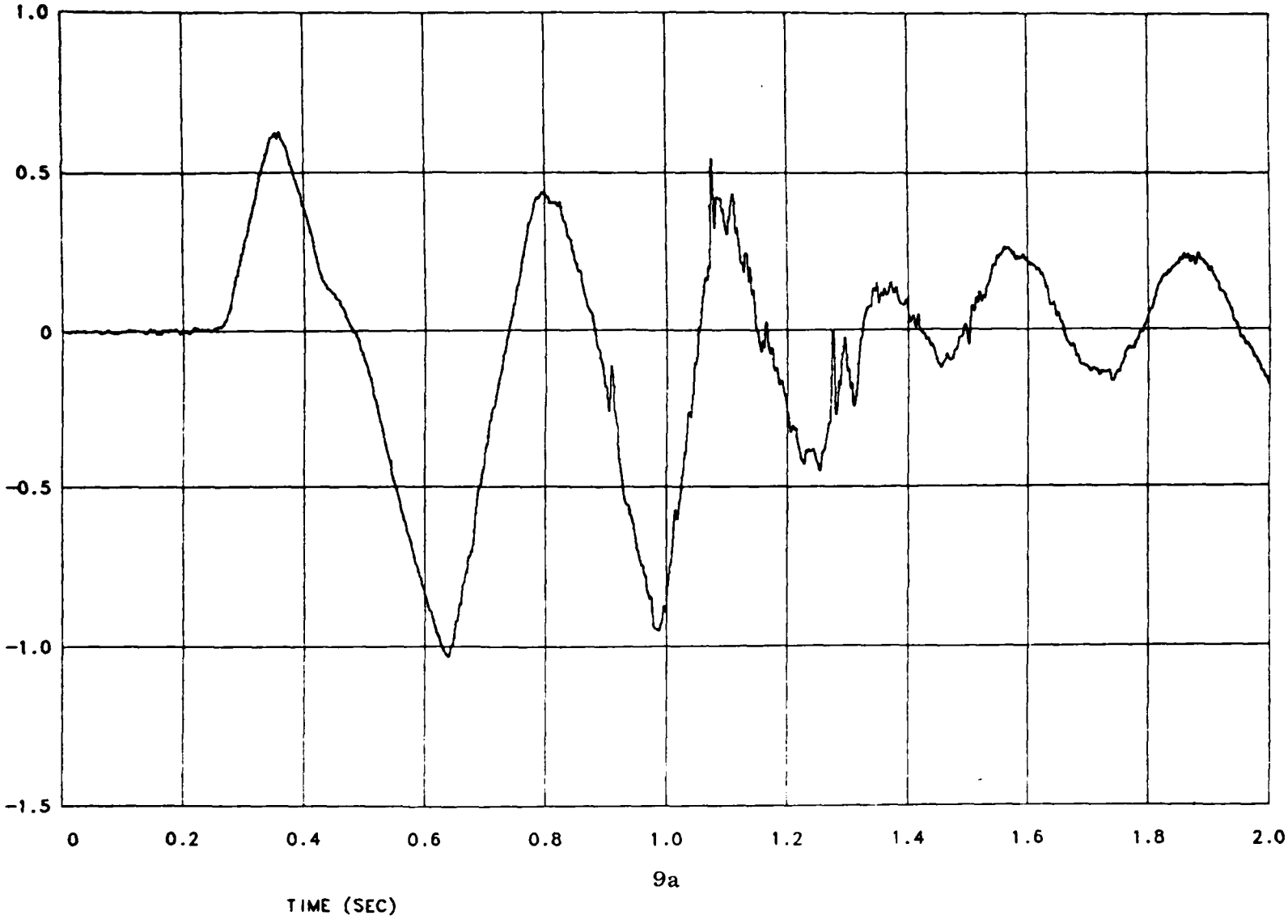
227

Accelerometer/Velocity Gage Coupler

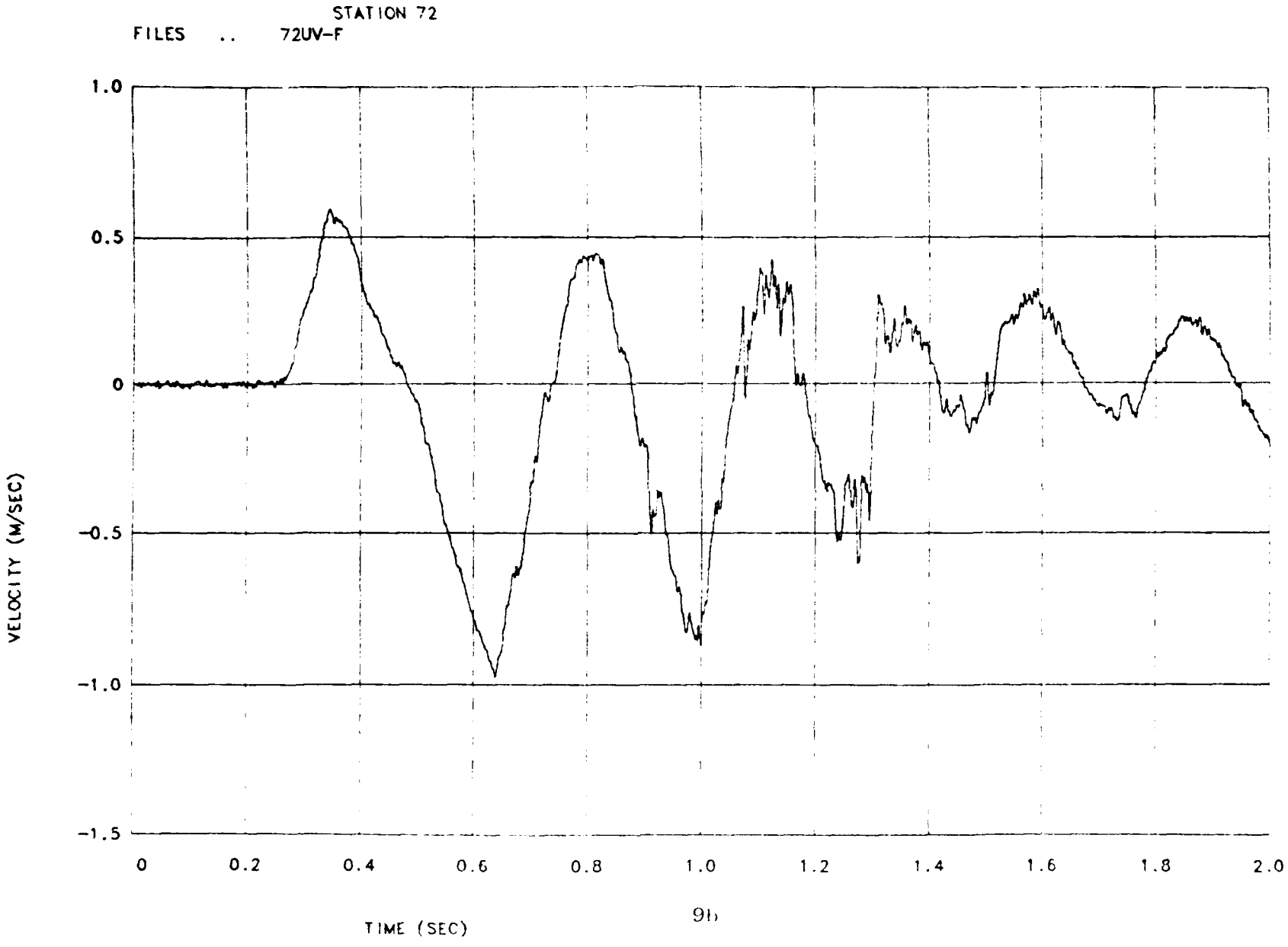
TYPE	SENSITIVITY	RANGE
HEAVYMETAL	0.1MV/V/M/S	25M/S
BRASS	0.04MV/V/M/S	50M/S

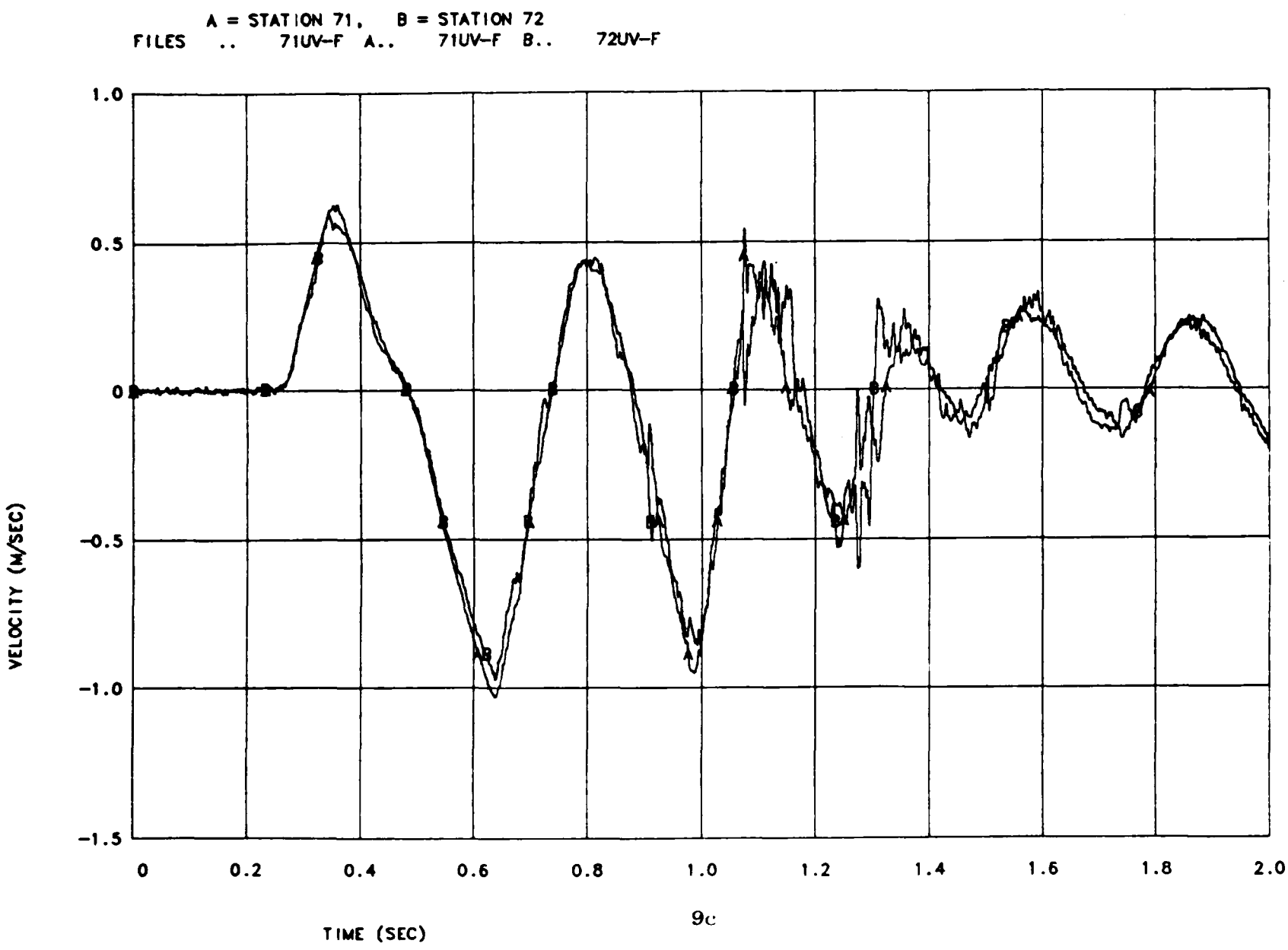
CHANNEL	TYPE	SUBSTITUTE INPUT	OUTPUT
71UV	BRASS	0.5MV/V	1V
72UV	HEAVYMETAL	0.5MV/V	2.76V

FIGURE 8


STATION 71
FILES .. 71UV-F
1.0
0.5
0
-0.5
-1.0
-1.5
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
VELOCITY (M/SEC)
TIME (SEC)

9a


STATION 72
FILES .. 72UV-F
1.0
0.5
0
-0.5
-1.0
-1.5
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
VELOCITY (M/SEC)
TIME (SEC)


A = STATION 71, B = STATION 72
FILES .. 71UV-F A.. 71UV-F B.. 72UV-F
1.0
0.5
0
-0.5
-1.0
-1.5
VELOCITY (M/SEC)
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
TIME (SEC)

9c

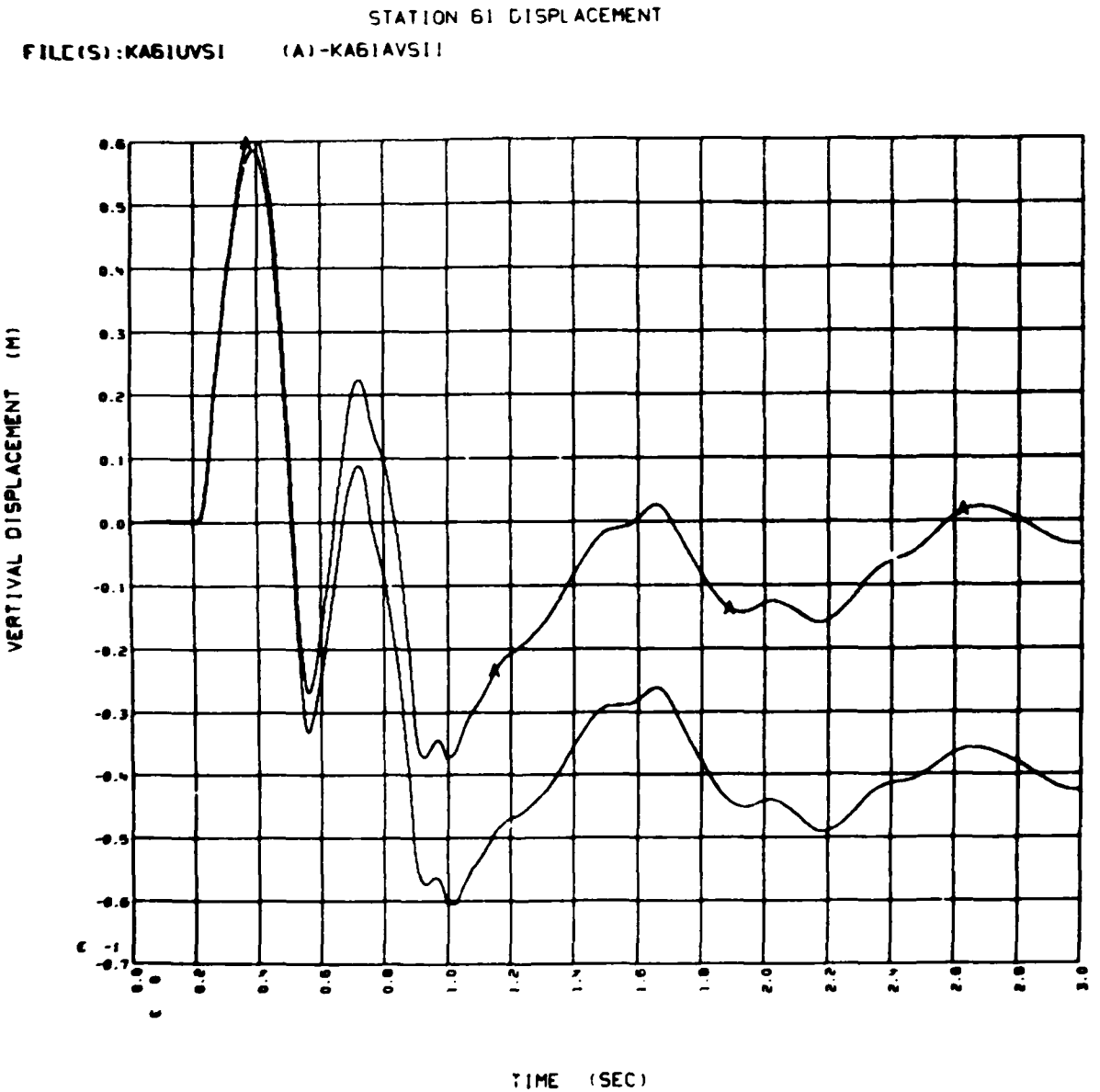


Figure 10
Comparison of velocity gage and associated accelerometer records

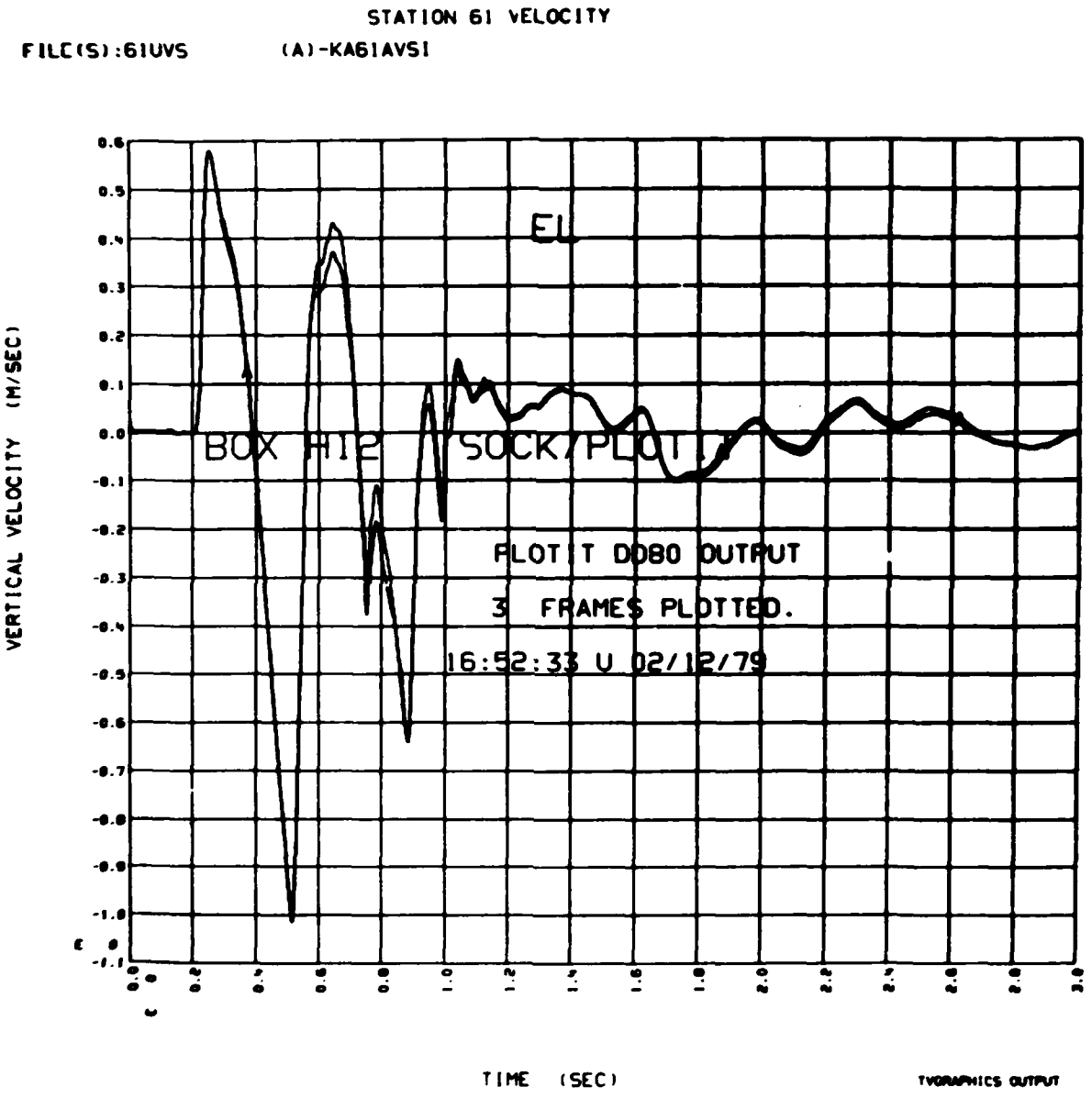


Figure 11
Comparison of the integral of velocity and the 2nd integral of acceleration

OPERATING RANGE

OIL	PENDULUM	USEFUL RANGE
2000 CS.	ALUMINUM	0 - 20 TO 0 - 60 m/s
2000 CS.	BRASS	0 - 1 TO 0 - 16 m/s
2000 CS.	HEAVYMETAL	0 - 0.3 TO 0 - 10 m/s

FIGURE 12

TUESDAY AFTERNOON Q&A SESSION

Q: PETER STEIN, STEIN ENGINEERING, TO DON GERIGK, LAWRENCE LIVERMORE LABORATORY

You used a pulsed power system. Was the temperature variation a problem?

A: DON GERIGK

We thought by using only 10 microamps we would eliminate or minimize that effect; however, we did not try to characterize it. The actual temperature of the comparison of surface temperature versus the temperature thermistor .... we didn't try that either. Well, we made one attempt at that by putting a bolt through the mounting plate with the thermistor buried in the bolt in the center of the plate which was attached, and the correlation there was very good. We did talk to some heat transfer people to give us an estimate of the effects of this plate on the actual temperature and they felt it would be minimal. They couldn't give any direct indication, however, because of the uncertainty in the heating mechanism, where there was convection, conduction through the plate down the length of the plate and so there are too many variables for them to really hang their hat on anything.

Q: PETER STEIN TO TOM MCGAUVRAN, BENTLY NEVADA CORP

You talked about the measurement of acceleration, velocity and displacement. I mentioned this morning a strain and deforce measurement on bearings and Tom Peterson talked about the strains due to the forces on the bearing. From your

paper it appeared that displacement seemed to be the neatest way. Do you have any physical argument as to why displacement should be more meaningful to discontinuity or problems in bearings as opposed to velocity and acceleration? Maybe there are other people in the group working on it. Not just because you make displacement transducers, but is there any physical reason why displacement should be a more meaningful quantity to measure?

A: TOM MCGAUVRAN

Well, actually I don't think displacement is any more preferential than any of the others, but it's really where the measurements are being taken. The traditional mounting locations for velocity and acceleration are one step removed from the bearing. Through the bearing casing is where you're getting your measurement; where the proximity measures half the bearing at the location. As far as displacement, I'm not convinced that has any superiority over velocity or acceleration if it could be made at the same point on the bearing.

Q: PETER STEIN TO TOM PETERSON, ROCKWELL INTERNATIONAL

You had a neat method of minimizing the temperature effects on your strain gages by using this rotated lot number selection. What kind of problems did you have with the copper lead wires down in that low temperature region?

A: TOM PETERSON

Essentially, Pete, we did it as part of our calibration. We did the calibration of the cartridge of this bearing supporter cartridge at ambient and then we did it

again at cryogenic type temperature, liquid nitrogen temperature. We did that both with support inside and out of the pump. We also had a little better feeling that when we mounted the pump in the engine and we dumped LOX to chill the pump itself we again got a base zero. We didn't see very many gradients and essentially with those two data points, ignored everything else that we might have gotten, or didn't see any great zero shifts due to that.

Q: KENNY COX, NWC, TO DON GERIGK

You mentioned one of the qualifications, one of the things you considered was portability. Looks to me like when you have a thing 8-ft in diameter and 100-ft long loaded on a flat bed truck that portability went out the window. I'm curious, did it give you any problems?

A: DON GERIGK

That's right, the portability here can be taken in two different contexts. The system, as I said, had to be available to be moved or had to be simple enough to move within the tower at the time of measurement. The portability I'm concerned with mostly is within the tower and not to and from the test site. There it was no problem. It was just the flexibility to move the machine, the data system, to accommodate the location at which we had to make the measurement.

Q: PAUL LEDERER, WILCOXON, TO DON GERIGK

I got the impression one of your error tables showed an overall system error at the same number of magnitude as the number of the individual error sources like the digital voltmeter and so on. Can you enlighten me on this please?

A: DON GERIGK

Well this, as I said, this is a mean error. It's not a root sum square and as a result, it could be less, it certainly was less, then the maximum errors. The maximum thermistor error was something like .28 degrees and yet the system error was only .011. This was a technique that was in favor with our statisticians in the lab to combine the error contributions in this manner.

Q: RAY REED, SANDIA NATIONAL LABS, TO DON GERIGK

In your paper I did not see addressed the average deviation of the set of 30 thermistors, from say a mean, as a set. The manufacturer apparently claims .1 degree C interchangeability. Do you have any information on that as a result of your test?

A: DON GERIGK

One, we did take one cycle and take the calculated published constants and calculated a set of constants from the published tables and converted them strictly from that information. I believe the worst one point was .13 degrees.

So of all the temperature points taken from one cycle, they were all less than .1 degree C except that one. So the manufacturer's information is pretty reliable.

Q: HENRY FREYNICK, LAWRENCE LIVERMORE LABS, TO TOM PETERSON

Could you just give some more information about the strain gages and liquid oxygen? What if they were not coated? And you indicated that they were coated with I believe a Refset. What kind of material is that? Is it thick, thin, does it need a heat cure, etc?

A: TOM PETERSON

I've got some data in my bag on its particular properties. It's like a coating, almost like the bearer B coating that BLH makes. This stuff is just a white coating that you spread over the gage and has a cure cycle at ambient for about 15 minutes, then elevated cure to about 150 degrees F for another 1/2 hour or hour. The problem with the LOX capability, apparently we discovered that the solder used - we were just using standard electrical type solder - is not compatible with liquid oxygen. We used Embond 610 adhesive and found that that was not compatible with liquid oxygen. Those two combined with the wire installation were not compatible so we coated the gage anywhere the apoxy was used and coated the solder joints also with the Refset.

Q: HENRY FREYNICK

When you say it's not compatible, how does its incompatibility show up? I mean does the solder shatter? Does it start a fire? What happens to the 610? Does it burn or does it just crack?

A: TOM PETERSON

The way we defined LOX compatibility was through some impact tests. In other words, would it provide a fuel for the oxidizer. In normal practices if you had the epoxy coating down and you poured liquid oxygen on it I don't know what it would do. But we were concerned with impact problems. If we had an impact would that start a reaction and ignite the liquid oxygen? Other than that we didn't have any degragation from it. We didn't have any trouble with the solder cracking or with the adhesive lifting or anything else. It wasn't an environmental coating for the gage, it was a coating against the liquid oxygen. It was a micromeasurements gage; an "SK type 13," 350 ohm with a 031 gage length.

Q: RICHARD PEPPIN, BRUEL & KJAER, TO TOM MCGAUVRAN

You say in your paper that the spectral content of the proximity probe system is less complex than that of an accelerometer and so on. You show in the figures, that appears to be the case, but I don't understand why. Why would you have such a noisy signal from the acceleration than you do from the displacement?

A: TOM MCGAUVRAN

Well, I'm not sure I can answer that from a technical standpoint. To my knowledge the accelerometer being a h'gh gain device will exhibit a number of frequencies just because of its amplification requirement. The proximity system does not have that inherent noise factor, does not have a noise floor anywhere near what acceleration is. I wish I had some other drawings and photographs of the spectral content. The ones I included were simple oscilloscope displays, but since the paper was completed we do have some that show the same information on the spectrum analyzer. There simply aren't that many components with the proximity system. As to why there are so many other ones with acceleration, I can't explain that beyond the high gain of the system.

C: PAT WALTER, SANDIA NATIONAL LABS

I was just going to explain why the accelerometer would have higher spectral content. The difference between displacement and acceleration, it's two derivatives away and any time you differentiate something you get noise. The analytical equivalent of that is in the frequency domain. Differentiating twice is just everytime you differentiate it's just a multiplication by J-omega. So until you differentiate twice, you just take the displacement spectrum and multiply it by omega^2, and that is going to ramp up all the high frequencies. So if you took the acceleration spectrum and multiplied it by over omega^2, it would just look like the displacement spectrum. It is just the physics associated with differentiation. And you take something integrative twice, the displacement is going to look pretty and the acceleration is going to look noisy.

C: RICHARD PEPPIN

But those are regular signals.

C: TOM MCGAUVRAN

That's true, but they are pure signals. They are not being integrated.

C: PAT WALTER

But they are still two derivatives away. You're looking at them. Even though they are coming from different instruments, one's the displacement and the other one is the second derivative of the displacement.

C: TOM MCGAUVRAN

One other possible explanation is the high frequency nature of the roller element bearing. Acceleration forces tend to thrive on high frequencies. They show up much easier than displacement does. Displacement at very high frequencies is essentially out of the range of the capability of the transducer to measure. So it might be a combination of the high gain and the immeasurability of the small displacements at those very high frequencies where the accelerometer can give you a measurable output.

Q: PAT WALTER TO DR. WAYNE WHALEY, UNIVERSITY OF NEBRASKA

What was the thing that drove you to look at the vibrating fork? If you want to measure angular rates - we talked about constrain gyros and open loop gyros and laser gyros and that - and you looked for an alternative technique to measure angular rates. What was the application at Wright-Patterson that you couldn't satisfy with commercial?

A: WAYNE WHALEY

What did the Weapons Lab say? A microradian up to a kilohertz in space, something like that. You know, real broad band, real low level and something thats tiny. The size of a pencil eraser. That's my motivation.

PAT WALTER TO TERRI COLLOM, NAVAL AIR TEST CENTER

What were you striving for in this system that you couldn't get with a commercial altimeter?

A: TERRI COLLOM

Well I'm not sure you can really do the job with a commercial altimeter. You have to tie into the aircraft pitostatic system and you're trying to measure displacements on the order of 15 or 20 feet. With the position you get there, we just didn't really feel that was a viable approach.

C: PAUL LEDERER

I have another theory in addition to Pat's. Your proximity probe basically is a modulated RF device isn't it? And the price of demodulating it, you essentially introduce a low pass filter don't you? This may explain why the spectrum from that looks a lot cleaner than that of the accelerometer.

C: PETER STEIN, STEIN ENGINEERING

I think we've made the round. The displacement and the velocity in the acceleration may have exactly the same basic frequency components, but by the time you differentiate twice, you take the higher frequencies and give them a lot greater amplitude. I'm back to the question that I asked originally. If you're trying to measure the rotating unbalance and a rotating unit then mils displacement is the key? The people might measure acceleration but the real answer is in the displacement. If you're studying the damage to bearings, is the real answer in the higher frequency components that might be diagnostic of bearing damage, in which case an accelerometer would be better, or is the real information to the bearing damage of the rolling elements in the displacement? This has nothing now to do with the measuring system but what's doing the damage to the bearings? Does anyone here know?

C: TOM MCGAUVRAN

In response to that I think we are in the process of making those evaluations right now. That's why we have the instrumentation at two dozen different plant

sites and are working with all the major manufacturers of the rolling element bearings. I don't think anyone has a clear cut answer. Obviously the rolling elements will contribute very high frequencies and there is acoustic emission studies and things like that. But the frequencies are very broad band and very complex. We're just trying to see whether there is a simpler way to make those determinations.

C: DENNIS REED, EG&G

My past experience is in the diesel engine industry. We did some of the work. And I think in regard to the question on this bearing acceleration, what we found is in the accelerations every time a ball comes around on the race it raps it so you get a sharp banging. That's why you get all your sharp acceleration pulses in the hash, essentially, you are looking at. Whereas, all of these jarring motions end up causing the bearing race and the housing to move back and forth gradually and that's why you are picking up the nice, clean traces on the displacement and also in the velocity. So I think the fact is that the accelerations are just the rapping from the bearing coming around or the balls coming around, and all of those things get damped out through the bulk of the bearing housing and the race itself, and it ends up in just a gradual motion moving. Same thing you have with a sleeve type bearing, say in a diesel engine. It's the sharp rapping that is causing the problems and you do see that in a displacement, say in the crank shaft or the block of an engine where you actually see movement. And typically what's been done is to measure the displacement of the engine block itself as it's flexing due to those bearing loads.

C: DAVE MILLER, SUNDSTRAND AVIATION

Most of our measurements of this type are done on small high-speed turbines. And by small, they are 4 to 6 inches in diameter and 120,000 rpm. One comment I would make is that we are usually interested in what the shaft itself is actually doing. And if we put accelerometers on bearing housings or the external housings, we are seeing symptoms of what's going on inside, but we don't actually know what the shaft is doing. So we're interested in things like critical speed and actual shaft motion so we try to go to proximity type probes. The problem we have with this is finding any probes that are small enough to get into a 1/4- to 1/2-inch diameter shaft.

Q: HANK HEGNER, MANTECH INTERNATIONAL CORP, TO TOM MCGAUVRAN

Why did you go to an eddy current over a fiber optic? It looks like you're using the same approach that Jerry Phillips used at David Taylor and you went to an eddy current for this application. I was just wondering why your decision was to go in that direction rather than fiber optic type?

A: TOM MCGAUVRAN

I'm going to have to rely on information from other people on the fiber optics. Both of them can accomplish the measurement. The proximity device has proven itself in an industrial environment. It's easier to set up and calibrate and has a longer life expectancy. Besides that, we already manufacture proximity probes. It was a matter of creating a much higher gain than what is normally

used for shaft monitoring. We normally used 200 millivolts per mil. To measure the outer race, we are going to 2000 millivolts per mil. So we had to make some modifications to the proximeter, the oscillator demodulator, but the probe is essentially a standard probe. We're using standard products and modifying the proximeter to make the same measurement.

Q: DAVE MILLER, SUNDSTRAND AVIATION, TO DON GERIGK

I'd be interested in some details on where you got your data for your accuracy statements on the stability of your calibration bath and platinum probe?

A: DON GERIGK

They are essentially information furnished by the manufacturer. The probe was just recently calibrated. We got that information on the bath and Mueller Bridge directly from the manufacturer.

Q: DAVE MILLER

Can you refresh my memory on what the readout device is on your standard probe?

A: DON GERIGK

That's a Legion Northrup Mueller Bridge.

C: PETER STEIN

Would it be fair to ask the speakers if they had any second thoughts about what they would have wanted to say in their speech if they had had another minute?

C: TOM PETERSON

We got into a bearing discussion here; one gentleman asked why not use the optic type device instead of the Bently. From one person that is currently involved in a test using an optic device to measure bearing race deflection, they're a pain in the neck. I'm sure the state of the art is going to come along a little way. But, they're a problem calibrating. We developed some problems in extreme environments, cryogenic type environments, and they are cumbersome. Also have some experience with Nevada Bentleys, and not in this application but in others. At least our lab is a little more adapted to a proximity type device instead of an optic type device.

Q: KENNY COX, NAVAL WEAPONS CENTER, TO TOM PETERSON

These strain gages you put on, maybe I missed something there. Were they put on to test the item, or were they put there and left there and they go into space and come back and are reused, or are they taken off when you go into space?

A: TOM PETERSON

The strain gages mounted on the cartridge were in a specific instrumented pump that was only put in rocket engines that were on test stands. In fact we have

very little flight instrumentation on the engines themselves compared to what they have on test stands. I guess what I'm saying is no, we just isolated this particular pump and instrumented it, and it only saw sea level type tests and none of it flew. To back that up, with just the few shuttle flights, that is roughly about 3,000 seconds of time. We've got development time just on the engines themselves of over 100,000 seconds. So we spent all our time on a test stand and very little of it actually boosting the shuttle.

Q: RICHARD PEPPIN, BRUEL AND KJAER, TO TOM MCGAUVRAN

I guess we're talking about this bearing analysis and I'm not sure, somebody brought up an interesting point there about what the bearing faults are doing to the outer race. If you have a fault on the outer race diametrically opposed to the proximity probe, then the question is how does that displacement, when the roller hits that flan, get translated into motion near the proximity probe? That's what I don't understand. See, I can understand with measuring the forces because the force will be transmitted around the bearing race, but I don't understand how it would work for displacements. That seems like a complex solid mechanics problem.

A: TOM MCGAUVRAN

I don't understand it either. The one thing that I might say is you probably picked the worst case situation. However, as I indicated in the paper, if you have one mechanical flaw in the bearing, it's just a matter of time before you have many more. So if it does not pick up that one, it will certainly pick up

other ones that are passing by the observed point. Worse case. I agree you're probably going to be hard pressed for much of an indication across the outer race.

Q: BOB WHITTIER, ENDEVCO, TO TOM MCGAUVRAN

I kind of gathered that you were actually measuring the harmonics of the rotating frequency, which is what I call the resultant motion or vibration caused by bearing wear, but not a direct measurement of the bearing wear, where bearing wear in creation of the wear process for developing a spall start to the micro crack. This is where your acoustic emmision type comes in. Once you have a spall then you set up the resident vibrations of the bearing system itself, which are the spikes you talked about. Or, back into the lower frequency domain again, what you call the unbalance of the system caused by the wear itself. So I think you have all those motions taking place, and from a wear standpoint it depends at what point you want to detect. If you want to detect the very smallest wear process, I think you're in the high frequency.

A: TOM MCGAUVRAN

We didn't talk about the monitor portion of this because we specifically wanted to talk about the transducer end of it. The monitor that we coupled to this transducer system is actually what we call a dual path monitor and it has low-pass and high-pass frequency filters in there so that you can look at rotor related problems as a separate situation from the bearing related problems. That's kind of a departure from previous monitoring and in the past got an indication when the bearing was bad and that was time to change

it. We are trying to take that one step further to detecting a rotor related problem and perhaps correcting that before it becomes a bearing related problem.

Q: BOB WHITTIER

If you analyze the frequency, the data that you're reporting, are they harmonics of the rotating frequency?

A: TOM MCGAUVRAN

Well, everything seems to be hinged around the roller passage frequency which is a direct relation to the rpm. It seems to be a break point at three times the roller passage frequency. Three times and above tends to be a bearing related problem. Three time and below happens to work out to be a rotor related problem.

Q: JOHN BURNS, NAVAL OCEAN R&D ACTIVITY, TO TOM PETERSON

On your strain gages that you have inserted in your instrument, do you shock them all at one time with this LOX or do you bring them down to temperature gradually before you start your pumps?

A: TOM PETERSON

On the engine test stands, I'm pretty sure it's the same thing on the shuttle itself, they've got some prevalves just before the engine and these prevalves

are just dumped open. So what you get is just liquid oxygen just forming down into t' . pump. It just flows down and chills the pump, and you might say it's shocked.

Q: JOHN BURNS

I was wondering about compatibility and thermal effects on your adhesives and mounting system that you were using for these and it doesn't come loose on you?

A: TOM PETERSON

Part of the preliminary test before we used this Refset compound is that we went through some thermal shock type tests. We went from ambient down to liquid nitrogen temperature, shocked it several times. Also, shocked it and then had the coating on a strain test bar and strained it. We did this repetitively and then after four shock tests we went back and looked for cracks, disbonding, tried to see if the coating would lift on us through the shocks, and we didn't see anything through those tests nor did we see any disbonding after the pump was disassembled that had the strain gage cartridge in it.

Q: LAWRENCE MERTAUGH, NATC, TO TOM MCGAUVRAN

For the good bearing is the dominant frequency, is that the ball passing frequency that you are seeing? In other words you have a dominant frequency showing up, what is that frequency? It seems to me that it's sort of interesting that the displacement transducer seems to be dominated by that

frequency for most of the failures. It's not quite as clear on the inner race but on the outter race and the ball. That frequency, whatever it is, seems to dominate the picture. Whereas the velocity and accelerometers, that doesn't seem to be the case, and therefore, it would seem to me that might represent a problem in terms of diagnostics. The clearness of the signal would seem, since it always contains that one frequency or at least for the most part, might actually represent a hinderance rather than a help.

A: TOM MCGAUVRAN

I have not gotten into the diagnostic end of this that extensively to really address whether that will be a hinderance or a help. The people that are doing the diagnostics in our mechanical engineering services group, or division, feel that it is not. In fact, it's very positive.

Q: LAWRENCE MERTAUGH

Do you know whether that is the ball passing?

A: TOM MCGAUVRAN

To my understanding it is.

Q: SCOTT WALTON, ABERDEEN PROVING GROUND, TO TERRY COLLOM

On your inertial platform, you were very careful. You had two perpendicular accelerometers so when the plane pitches up and that vertical component shifts

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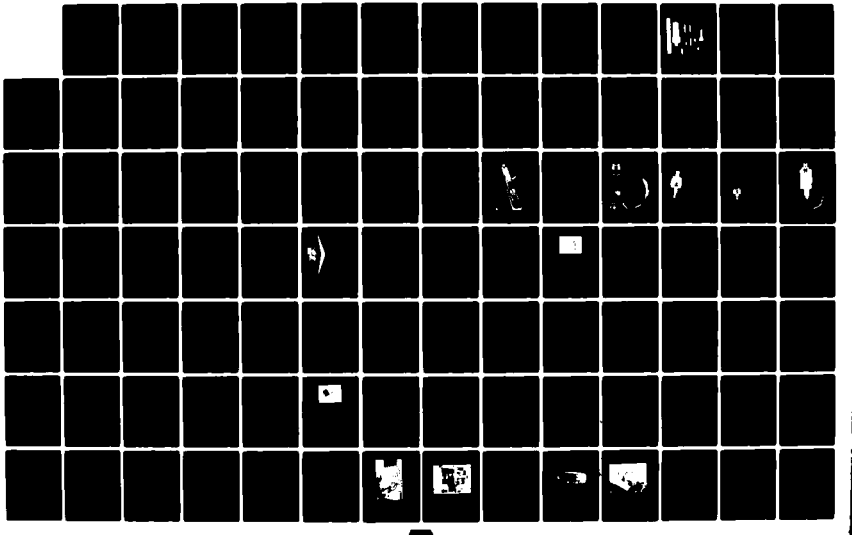
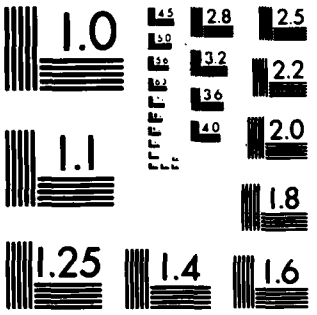




MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

you can correct for that. How come you don't have a roll component? Are you really sure that the aircraft does not roll from left to right or that doesn't worry you?

A: TERRY COLLOM

It turns out there are two components that have actually been neglected in this analysis, and that's to make the hardware reasonably practical. You could look at both the roll latitude and yaw angle and you come up with the equation that's in the paper that has about five terms. And if you assume the roll angle and the yaw angle are fairly small, those five terms reduce down to what I've shown on the viewgraph and what not. These are considered reasonably small in practice and they were eliminated just to make the hardware less complex.

SESSION III

PRESSURE

Bill Xavier, Chairman

ADP002684

WEAPON CHAMBER PRESSURE MEASUREMENT

W. Scott Walton
Materiel Testing Directorate
Aberdeen Proving Ground, MD

Extensive testing, at pressure levels from 34 to 758 MPa (5,000 to 110,000 PSI) was done at Aberdeen Proving Ground to evaluate 15 different types of electrical pressure transducers used in large caliber weapons. When using a given type of transducer, the ability to consistently distinguish dynamic pressure variations as small as 0.2% was demonstrated. Yet different models of pressure transducers disagree by as much as 2%.

I. BACKGROUND

Measurements of pressure inside large caliber weapons are critical for establishing the balance between crew safety and combat effectiveness. A 2% error in chamber pressure measurement can result in a 3% change in weight, a 4% change in effective range, and a 6% change in fatigue life.

A study of electrical pressure transducers used to measure large caliber weapon chamber pressure was conducted at Aberdeen Proving Ground from January 1979 to March 1982. Extensive testing, at pressure levels from 34 to 758 MPa (5,000 to 110,000 PSI) was done to evaluate 15 different types of pressure transducers.

Tests to evaluate bias between readings from different types of transducers as well as the variability of readings produced by a single type of transducer were conducted. In the laboratory, both dynamic and static pressure readings were made. In the field, a 175mm gun was used to evaluate differences in transducer performance.

II. CHAMBER PRESSURE INSTRUMENTATION

Peak chamber pressure can be measured mechanically with "crusher gages" or electrically with electrical pressure transducers. Although this paper does not address mechanical measurement, M-11 copper crusher gages were used in conjunction with electrical transducers in many of the dynamic tests.

In this study, 2 to 4 samples each of 10 types of piezoelectric and 5 strain type transducers were obtained. Figure 1 shows several of the different transducers. Of the 15 types tested, 8 were commercially manufactured and 7 were fabricated by various US Army proving grounds or laboratories.

To facilitate changing from one type of transducer to another, all transducers were housed in an adapter 3.2cm in diameter and 8cm long. This procedure not only made changing transducers practical, it allowed

recognition of a discrepancy between the static and dynamic performance of a miniature transducer caused by an installation problem.

A technique to be avoided if at all possible, is the installation of a miniature transducer directly into a large caliber gun tube. This practice presents two problems. First, a workpiece as big as a large caliber gun tube presents a number of challenges to the machinist, which can lead to dimensional, alignment, or surface finish errors. Second, there is no way to test the transducer in place to see if an installation problem has occurred.

It is preferable to mount the transducer in a small adapter that can be accurately machined. Then the transducer-adapter assembly can be checked both dynamically and statically before field testing begins.

For many years, the typical instrument used to record chamber pressure measurements has been the FM analog tape recorder. These instruments typically have a frequency response of 40 to 80 kHz, which is well above the 5 to 10 kHz response normally required for large caliber chamber pressure waveforms. Analog tape recorders usually have a signal to noise ratio of 100:1 and 1% linearity. The digital data acquisition system and computer controlled signal conditioning used in this study has an absolute accuracy of better than 0.3% and resolution to better than 0.1%.

III. LINEARITY TESTING

Linearity testing was done by measuring transducer output from 34.5 MPa to 483 MPa (5,000 to 70,000 PSI) in steps of 34.5 MPa. At each pressure level, three readings were made. Pressure was supplied by a dead weight pressure balance accurate to better than 0.1%.

The worst case results are shown in Figure 2. Note that this is a plot of peak nonlinearity. For the 11 most promising transducers, the mean, nonlinearity is only 0.3% of full scale over the entire range. This error can be further reduced by limiting analysis to only the expected pressure range of a particular test (e.g., 350 to 450 MPa only).

IV. TESTING FOR VARIATION

It is important that a transducer read consistently from shot to shot, since variability of the transducer cannot normally be distinguished from variability of the ammunition being tested. During the testing for variation phase, estimates of the within-gage variation (WGV) and gage-to-gage variation (GGV) were obtained.

Assume that the output of a given pressure transducer follows the mathematical model:

$$X = P_A + \beta + \Delta + \varepsilon$$

where

X = Reading obtained from transducer
P_A = Actual pressure
β = Bias of transducer (constant for all readings)
Δ = Variability of transducer (random variable)
ε = Experimental error (random variable)

It is assumed that β is a property that varies from one transducer to another (i.e., from one serial number to another) and also varies from one model of transducer to another (e.g., from model A to model B). For any one transducer, however, β is assumed to be constant.

Tests were conducted in this study to find the following quantities:

Within-gage variation (WGV). This quantity is a measure of the variation that would be observed if the same transducer is subjected to the exact same pressure over and over. It is the standard deviation of the random variable Δ of a single gage in the mathematical model above.

Gage-to-gage variation (GGV). This quantity is a measure of the variation that would be observed when changing from one transducer to another of the same type (i.e., same model, different serial number). It is a measure of the difference between the β's of two gages.

Gage model bias. This quantity is the systematic bias that is observed when changing from one model of transducer to another (e.g., from model A to model B).

Comparison of the transducers under dynamic conditions was done using the hydrodynamic pressure generator shown in Figure 3. A large mass or slug is driven by compressed air and strikes a piston in the high pressure hydraulic system. When the slug strikes the piston, a high pressure pulse ($\sim$6 milliseconds duration) is produced in an oil filled chamber. This chamber can accommodate four electrical transducers and four M-11 copper crusher gages. This device is used to develop the relationship between copper sphere deflection and pressure level that is presented in copper crusher gage tarage tables.

For each type of transducer, 4 samples were placed in the ports of the hydrodynamic generator. Ten shots were fired at a pressure level of approximately 379 MPa (55,000 PSI). The static test for variation was done using a dead weight pressure balance with 4 ports at a pressure level of 310 MPa (45,000 PSI).

The results are presented graphically in Figures 4 and 5. In each figure a ratio is shown (1.38 for WGV and 3.05 for GGV). This ratio represents a difference that is significant at the .05 level.

Consider the WGV data presented in Figure 4. This characteristic is relatively small (typically 0.05%) for all transducers and essentially the same value under both dynamic and static conditions.

GGV appears to be the larger component of transducer variability. Note that GGV is generally greater than WGV and dynamic GGV is generally larger than static GGV. The mean static GGV observed was 0.25%. The mean dynamic GGV observed was .41%.

V. TESTING FOR BIAS

This phase of testing was conducted to see if one type of transducer consistently read higher than another. It should be noted that there is no technique known that will produce a calibrated dynamic pressure pulse with whose amplitude is both accurate and traceable to the National Bureau of Standards. The only type of pressure that is accurate and traceable is static pressure.

Because of this problem a "majority rules" kind of logic is required when analyzing differences between transducer measurements under dynamic conditions. That is, if most transducers read one pressure level, and one or two read significantly different, it is assumed that the majority reading is the "correct" value and the outliers are "wrong". In fact, there is no way of determining which reading is "correct" and which reading is "wrong" unless the differences are very large.

The first test for bias was conducted using a 175mm gun. The gun tube was drilled for installation of pressure transducers at four locations as shown in Figure 6.

Testing for bias was conducted using only the 11 most promising transducers. Because all 11 types of transducers could not be tested at once, a balanced incomplete block test plan was used. An 11 by 2 plan requires 55 shots to permit each transducer to be tested with every other type of transducer. Two replications of this plan, for a total of 110 shots were conducted. The sequence of shots was randomized.

In shots 1 and 2, for example, two Model D transducers are placed in one set of forward and rear positions, and two Model K transducers are placed in the other set of forward and rear positions. This arrangement permits comparison of the transducers in two rear positions and comparison of the two forward positions.

Because the pressure level of each shot is slightly different and a given transducer is only used on certain shots, it is not appropriate to compare the simple mean output of the various types of transducers. Reference 1 describes the technique used to correct for shot-to-shot pressure variations by calculation of the "treatment effect" of each transducer. These "treatment effects" are estimates of the means which would have been observed if all transducers had been used in every shot.

To contrast static effects with dynamic effects, the same 110 shot sequence was repeated using the dead weight pressure balance at 50,000 PSI (344.75 MPa). Four transducers are tested at a time, two of one model versus two of another model. Ideally, all four transducers should agree with one another and indicate 50,000 PSI.

The final test for bias was conducted using the hydrodynamic pressure generator. Once again, the randomized 110 shot sequence was followed.

In the hydrodynamic generator, all four electrical transducers should agree with one another. In addition to the electrical transducers, four M-11 mechanical copper crusher gages were used in each shot. Because the hydrodynamic generator is used to develop the tarage tables for the M-11, the mechanical readings should agree very well with the electrical readings.

Figure 7 is a comparison of the three different tests for bias. All tests were conducted in the 275 to 350 MPa region (40,000 to 50,000 PSI) and are plotted on roughly the same scale. The quantity W represents a difference that is significant at the .05 level.

Note that the quantity W (which can also be considered as an indicator of experimental error) and the extreme spread (ignoring outliers) of the results essentially double when moving from static conditions to dynamic conditions. Error and extreme spread essentially double again when moving from laboratory conditions (hydrodynamic generator) to field conditions (175mm gun). Finally, note that the extreme spread (ignoring outliers) of estimated treatment effects differ by more than 2%.

These observations illustrate the need for both laboratory and field testing of pressure transducers. Laboratory testing is important for establishing suitability of transducers and identifying outliers. It is also usually more accurate than field testing.

The acceleration and thermal characteristics of the hydrodynamic generator, however, are not the same as those of a large caliber weapon. Field testing, therefore, is and always will be the final determining factor for establishing the suitability of a transducer. Because field testing is almost an order of magnitude more expensive than laboratory testing, it would seem prudent that transducers used on critical tests should be tested both statically and dynamically in the laboratory before being used in the field.

VI. HIGH PRESSURE TESTING

The effort to increase firepower and improve weapon performance has resulted in increasing levels of chamber pressure. These higher levels present a variety of new measurement challenges. A limited amount of testing was conducted at the 700 MPa (102,000 PSI) pressure level.

Static testing was done using a controlled clearance dead weight pressure balance at 689 MPa (100,000 PSI). Dynamic testing was done using a newly acquired dynamic pressure generator which produced pulses of approximately 3 milliseconds duration. No field testing was done because of the extreme expense of the ammunition required ($2000 per round).

Both the static and dynamic facilities were limited to 2 transducers per shot. Balanced incomplete block tests for bias were conducted using the 7 transducers capable of operating at this pressure level.

The static test required 21 static pressure readings. The results are shown in Figure 8. Only 5 electrical transducers performed satisfactorily during the dynamic test. The analysis of the 10 shots using those 5 transducers is shown in Figure 8 also.

Note that the extreme spread of electrical transducer treatment effects is approximately 0.5% both statically and dynamically. A difference of ∿0.5% between static treatment effects is significant at the .05 level. Yet a difference of more than 2% between dynamic treatment effects is required to obtain the same level of significance.

VII. LATIN SQUARE TESTING

A Latin square test was conducted to determine if any bias existed between the four electrical transducer locations in the hydrodynamic pressure generator. An enhancement of a classical Latin square test plan was used to obtain additional precision through replication.

In a classical Latin square test of four locations (ref. 1), four shots would be required, using a different configuration for each shot. The enhanced plan uses three shots in each configuration, as shown in Figure 9, for a total of 12 shots.

This entire sequence was conducted once using four tourmaline transducers and a second time using four miniature quartz transducers for a grand total of 24 shots. Analysis of all 24 shots as well as analysis of the quartz transducer data in groups of 4 shots each indicated that the difference between the four positions was not significant at the .05 level.

Analysis of the 12 shots done with the tourmaline transducer produced an interesting observation of the precision of dynamic pressure measurements. These shots were analyzed as three separate tests of four shots each as shown in Figure 10. Note that the difference between the top positions (A & D) and the bottom positions becomes more pronounced as one moves from the first shot in each configuration to the last shot in that same configuration.

Note that by the third shot in a given configuration (i.e., shots 3, 6, 9, and 12) a small, but clearly significant difference exists between the top positions and the bottom positions. It is assumed that this small effect (0.16% of reading) is caused by the packing grease flowing out of the transducers in the top positions. While conducting the test, it was observed that after three shots, the original packing grease remained in the bottom tourmaline transducers, but was gone from the top transducers.

The important fact to be remembered is not the observation that "grease runs downhill"! The important observation is that a significant difference as small as 0.16% can be discerned from dynamic pressure measurements.

Such precision is only possible when a powerful analytical approach, such as the Latin square test, is used. The Latin square analysis removes transducer model bias (2%), shot-to-shot variation (3%), and gage-to-gage variation (.4%) to obtain high precision.

Hence, this level of precision (0.16%) should not be confused with absolute accuracy. It should, however, serve as a goal for future improvement of measurement accuracy.

VIII. CONCLUSIONS

The results of this study present the science of chamber pressure measurement with a dilemma. When using a given type of transducer, the ability to distinguish variations of dynamic pressure as small as 0.2% from experimental error was demonstrated. Yet different models of pressure transducers disagree in field testing by as much as 2%. Before any dramatic improvement in the accuracy of chamber pressure measurement can be made, the transducer model bias problem must be solved.

As mentioned previously, there is no way of knowing which type of transducer is "correct" and a "majority rules" kind of logic has been used in this study. A technique for developing a calibrated (traceable to the National Bureau of Standards $\pm$ 0.5%) pressure pulse with an appropriate magnitude, rise time, and duration is needed.

REFERENCE

Natrella, Mary Gibbons; Experimental Statistics; National Bureau of Standards Handbook 91, Issued 1 August 1963; US Government Printing Office, Washington, DC.

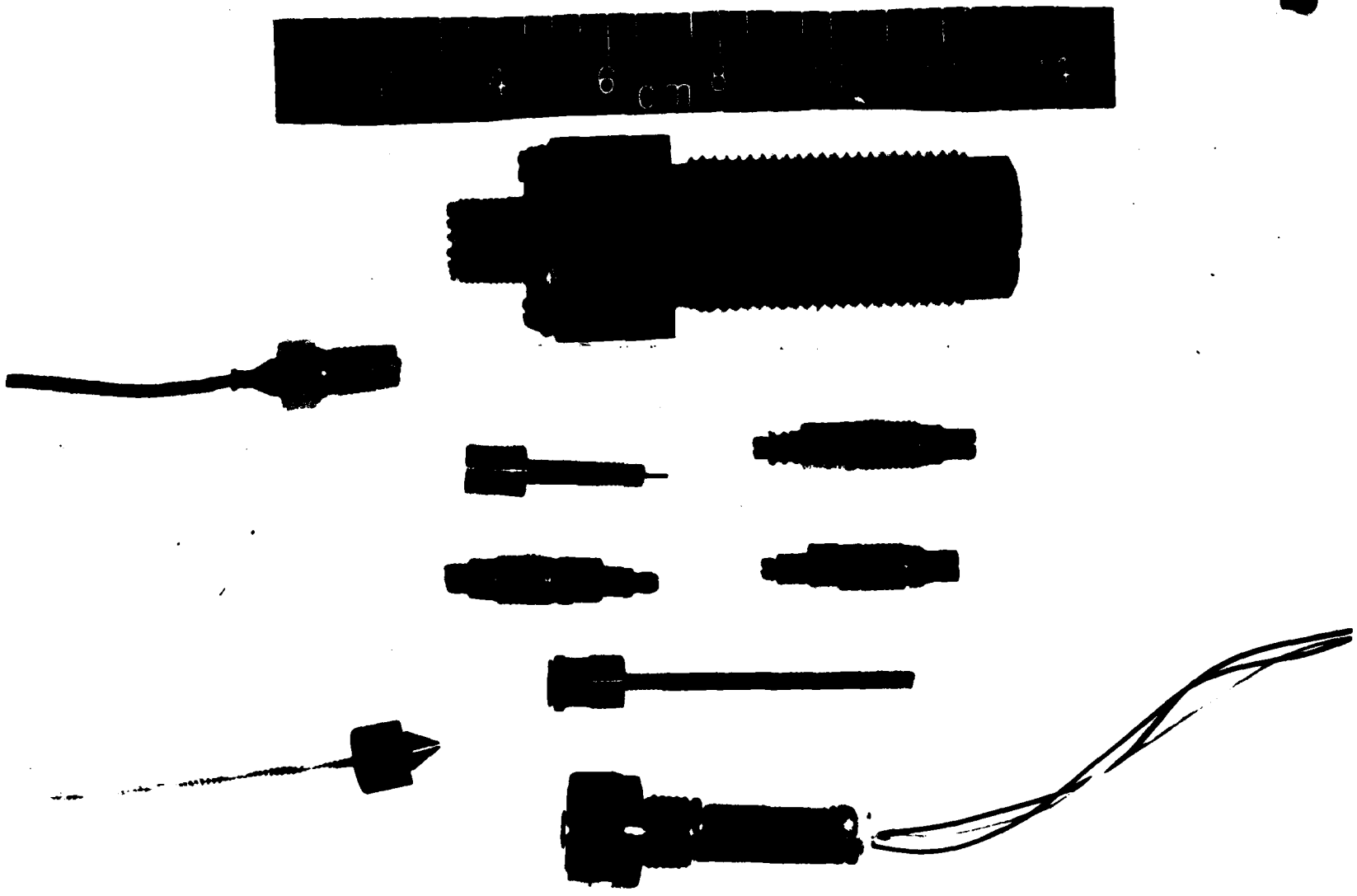


Figure 1. Photograph of several different types of pressure transducers used in this study.

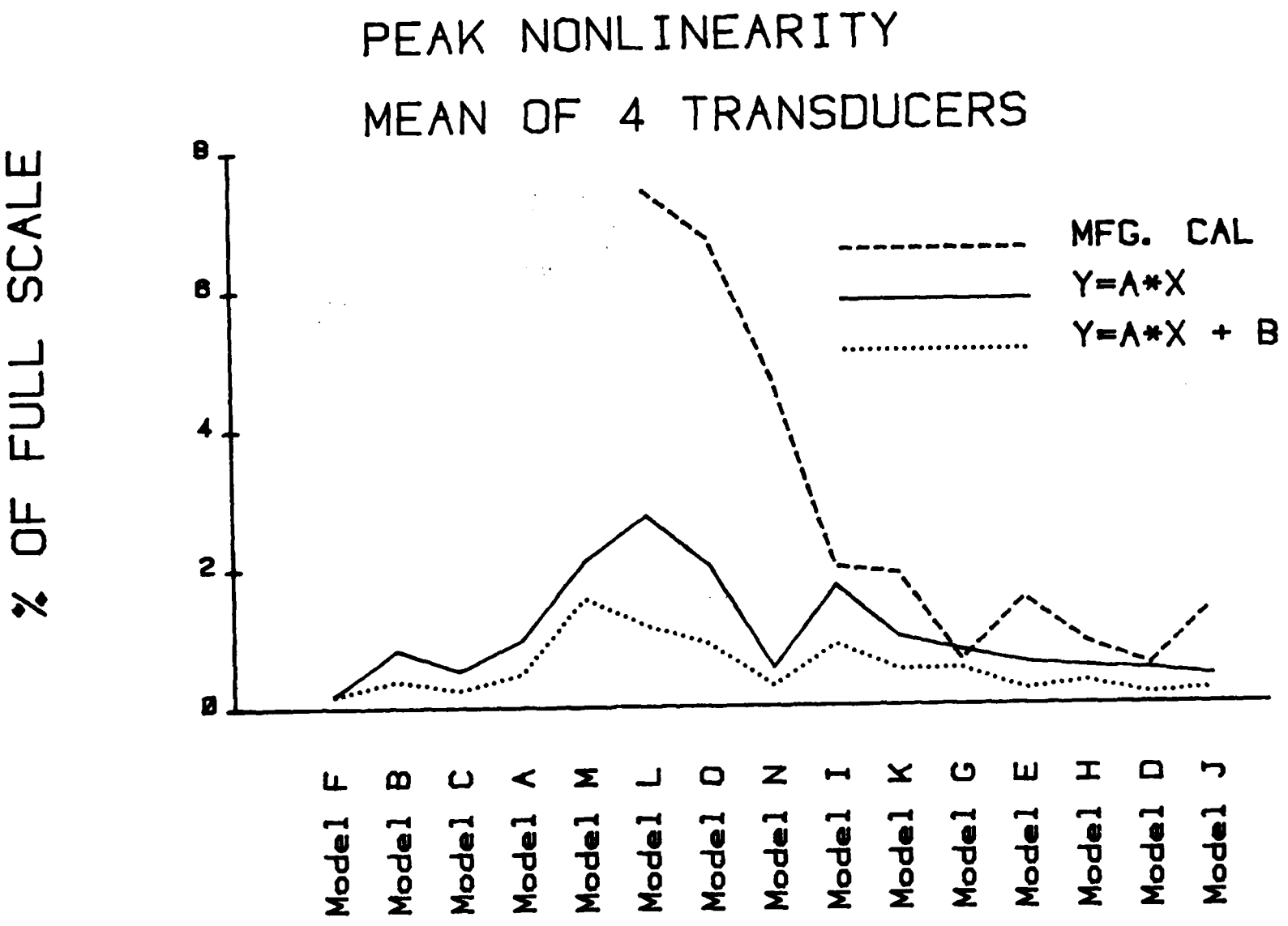
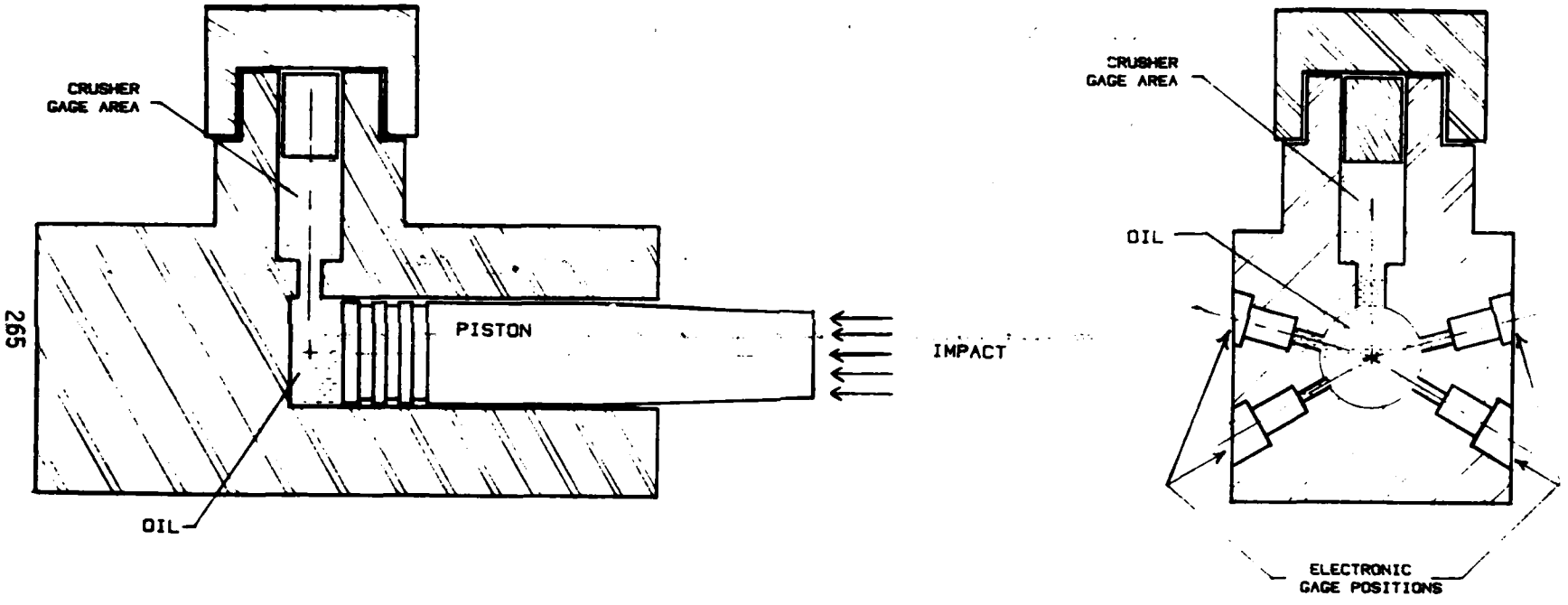


Figure 2. Comparison of several measures of linearity performance of 15 types of pressure transducers.



HYDRODYNAMIC
PRESSURE GENERATOR

Figure 3. Schematic diagram of hydrodynamic pressure generator.

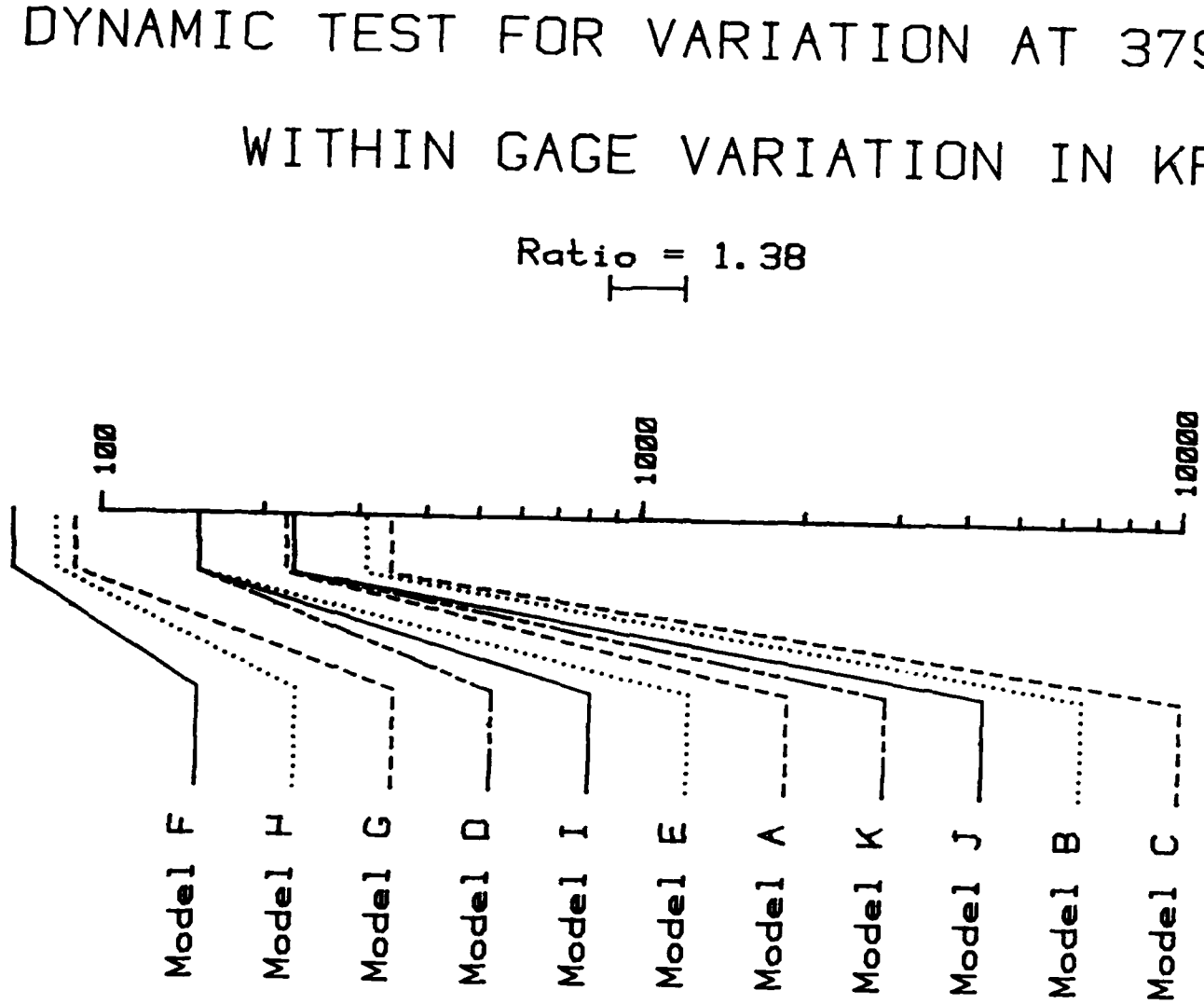


Figure 4A. Comparison of static to dynamic WGV.

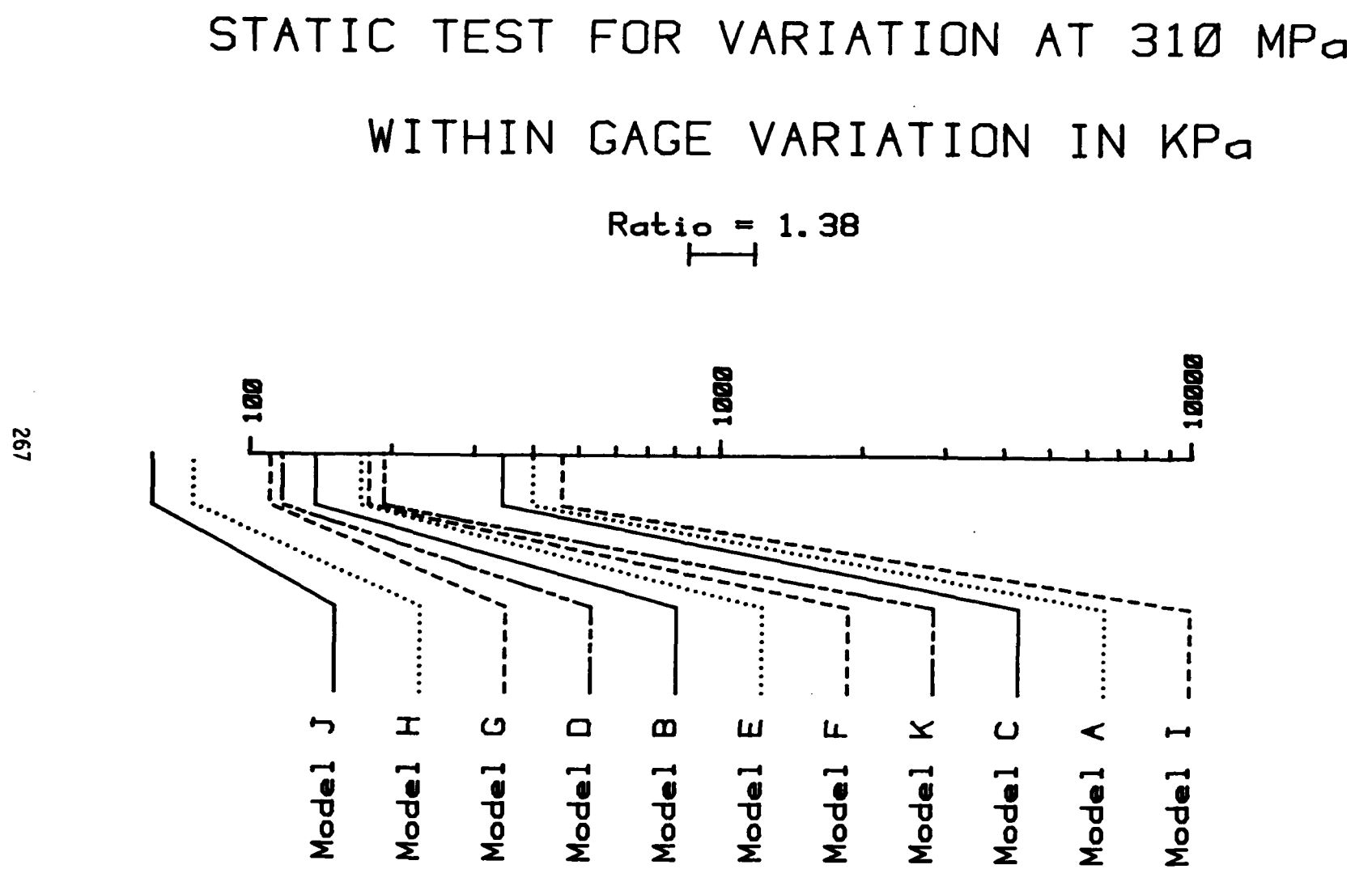


Figure 4B. Comparison of dynamic to static WGV.

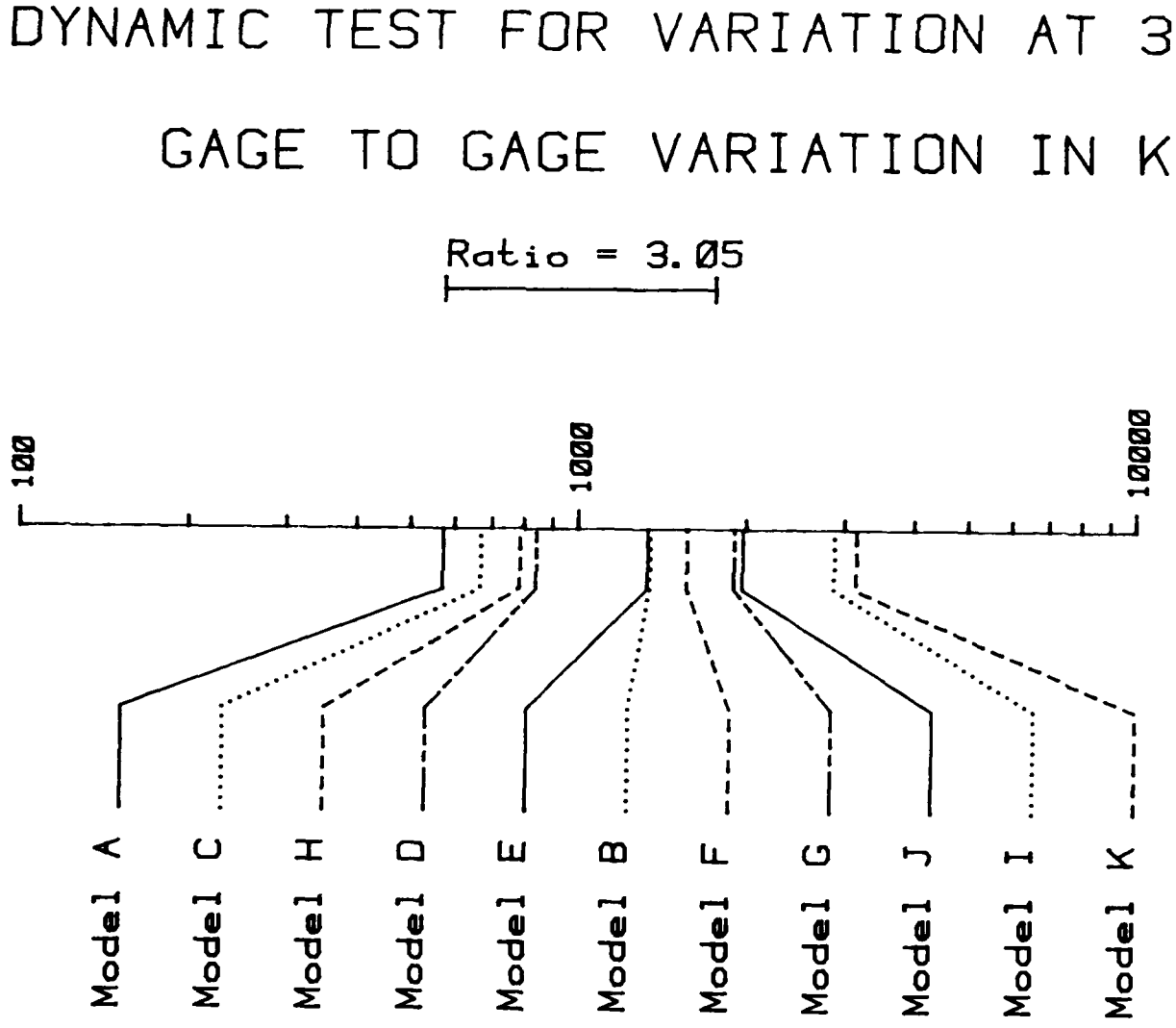


Figure 5A. Comparison of static to dynamic GGV.

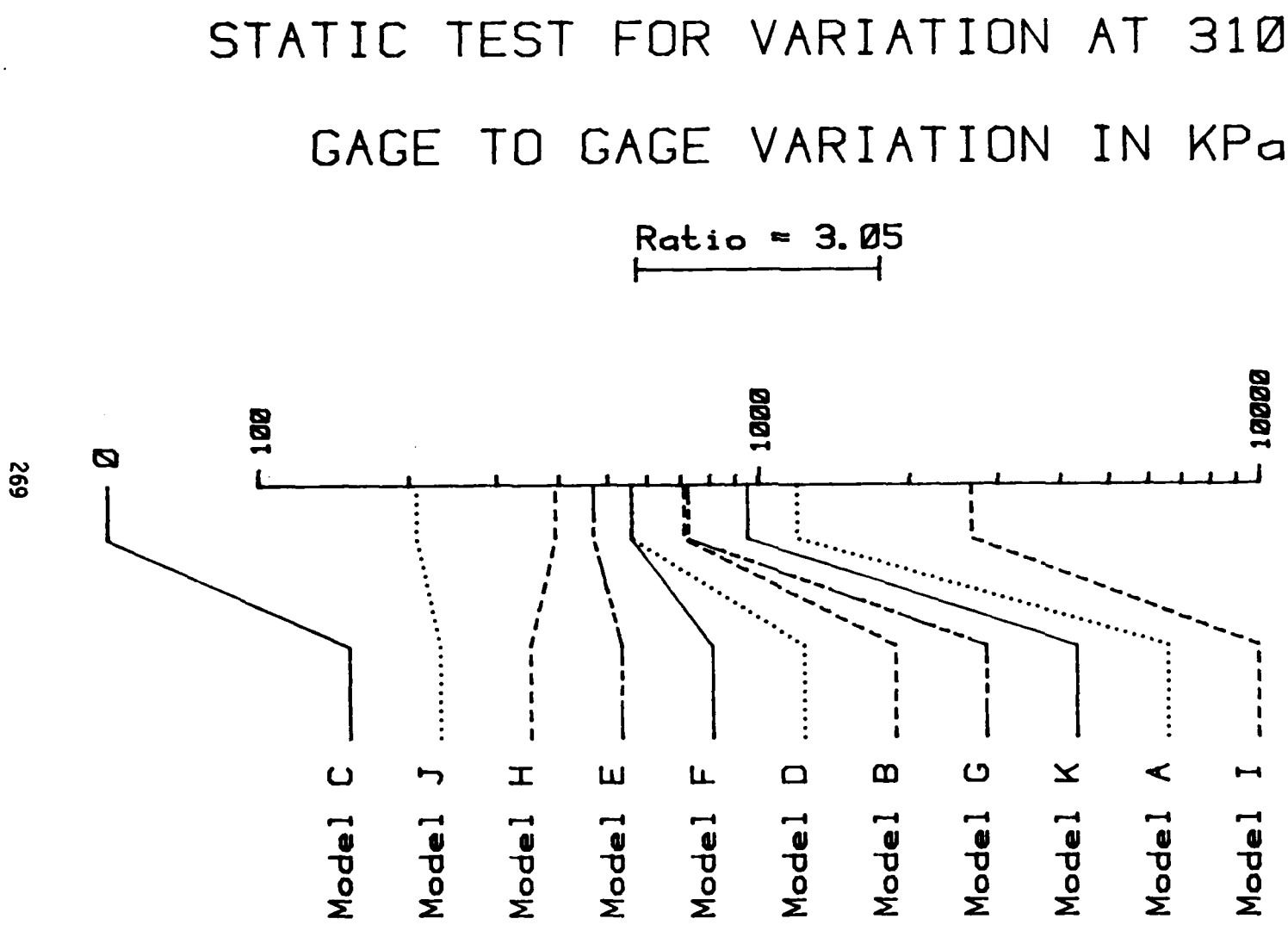
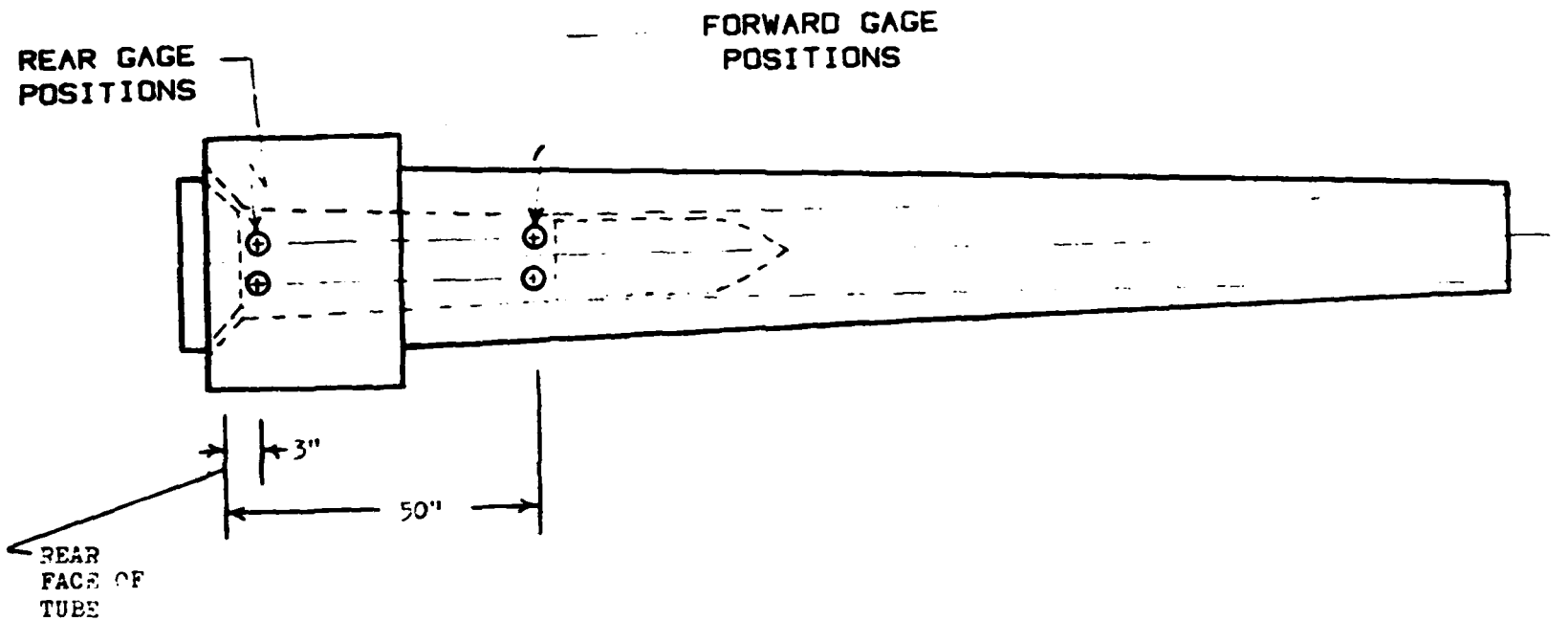


Figure 5B. Comparison of dynamic to static GGV.



GAGE LOCATIONS
ON 175mm GUN

Figure 6. Location of transducers for field testing.

HYDRODYNAMIC GENERATOR TEST FOR BIAS

TREATMENT EFFECT IN MPa

W = 1.54

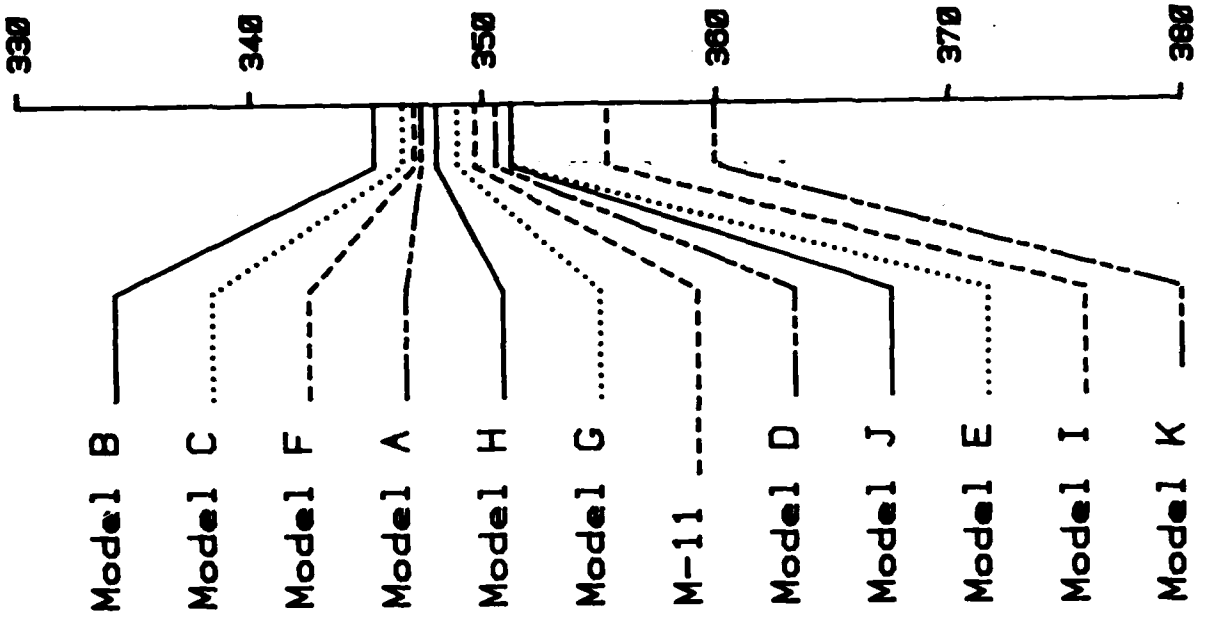


Figure 7A. Graphical summary of bias test data.

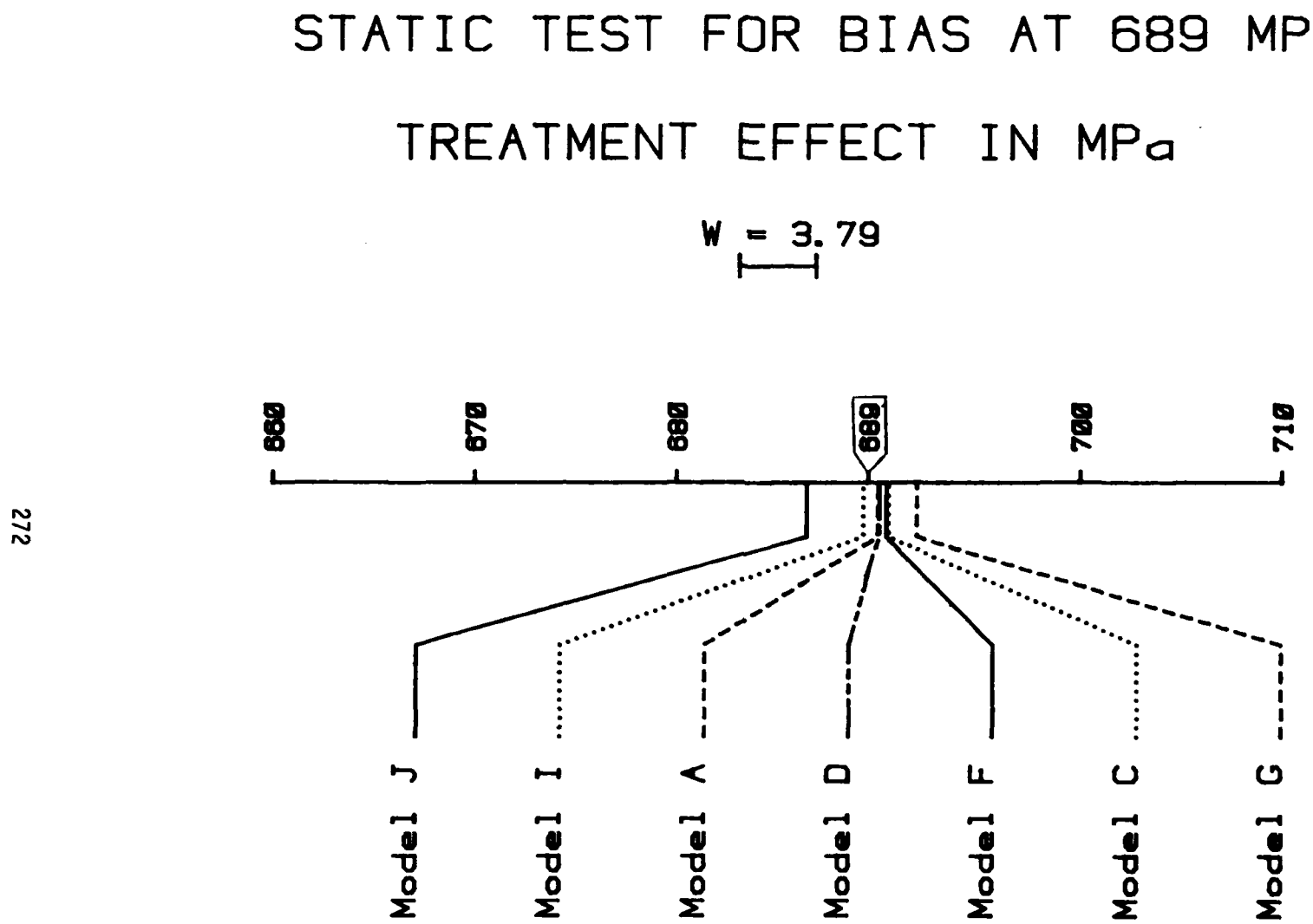


Figure 7B. Graphical summary of bias test data.

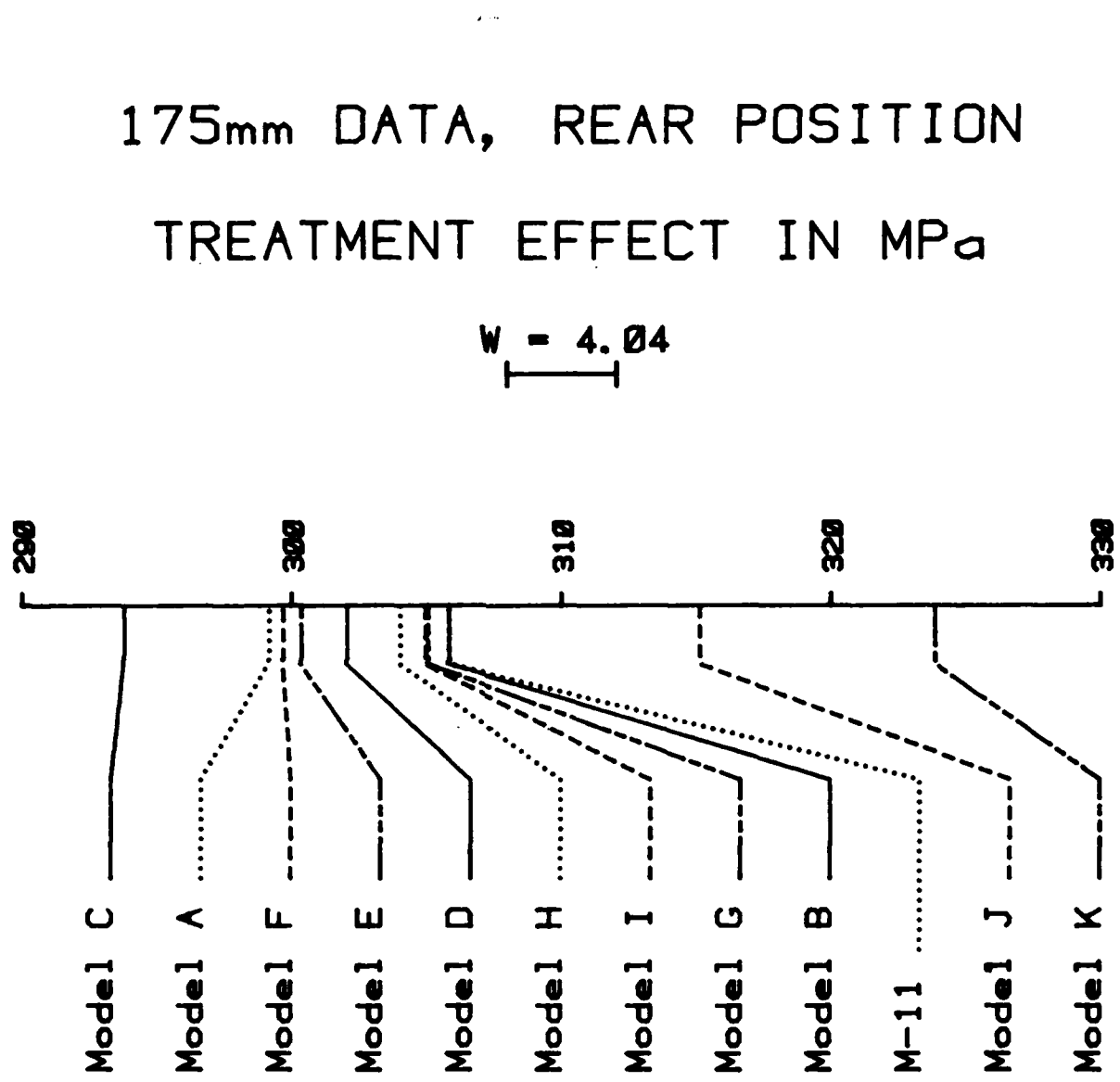


Figure 7C. Graphical summary of bias test data.

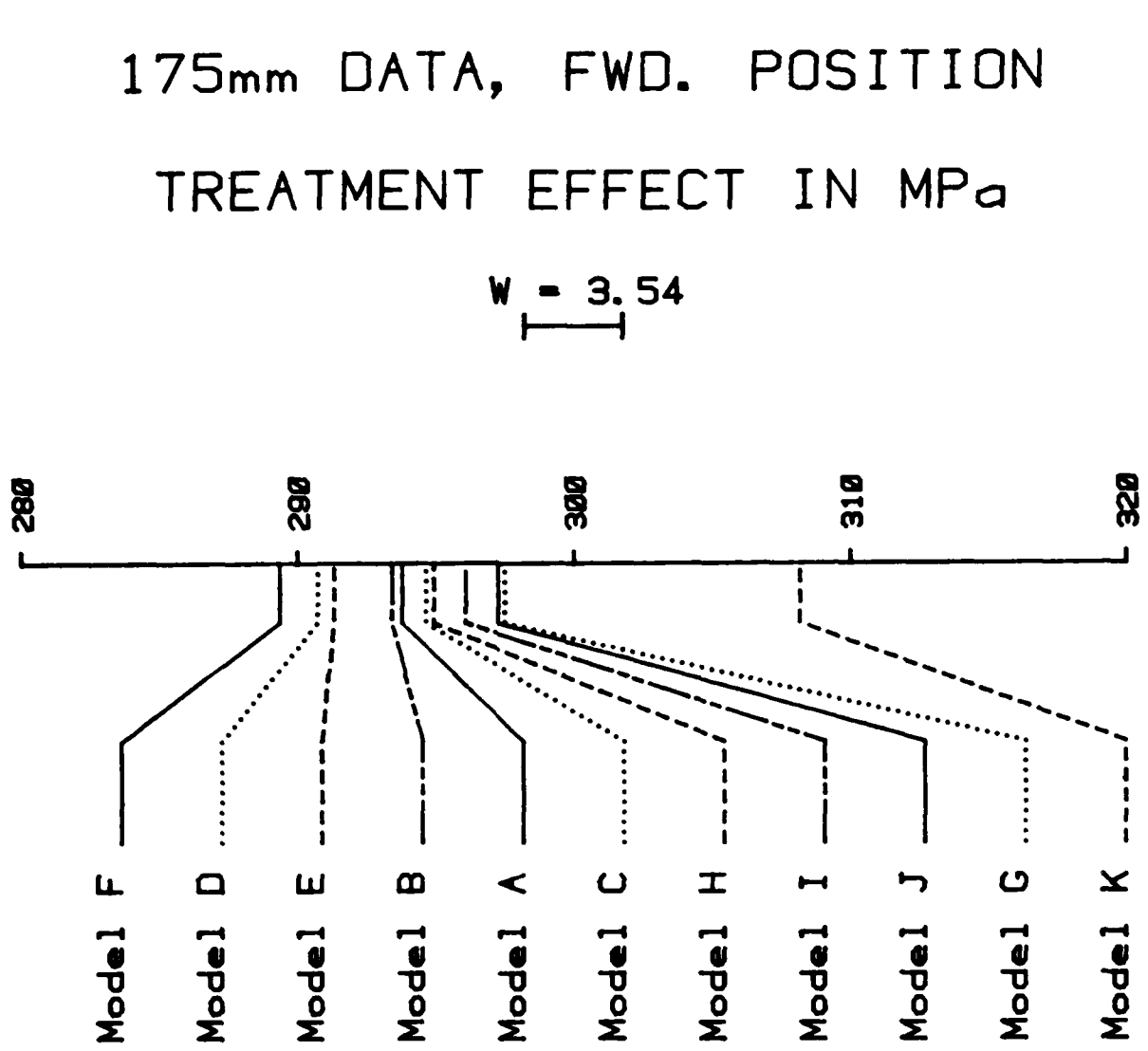


Figure 7D. Graphical summary of bias test data.

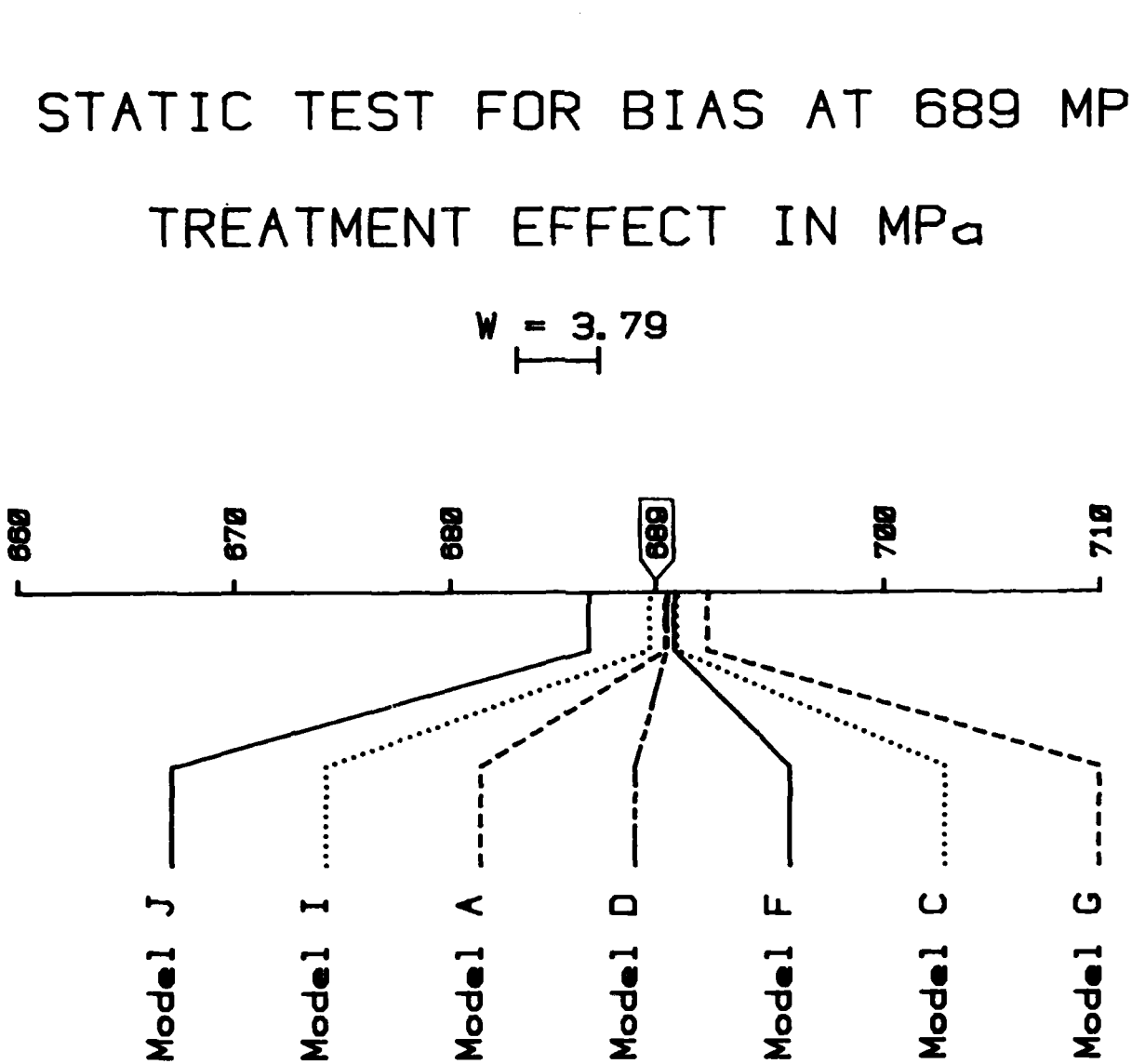


Figure 8A. Graphical summary of high pressure test for bias.

DYNAMIC TEST FOR BIAS

TREATMENT EFFECT IN MPa

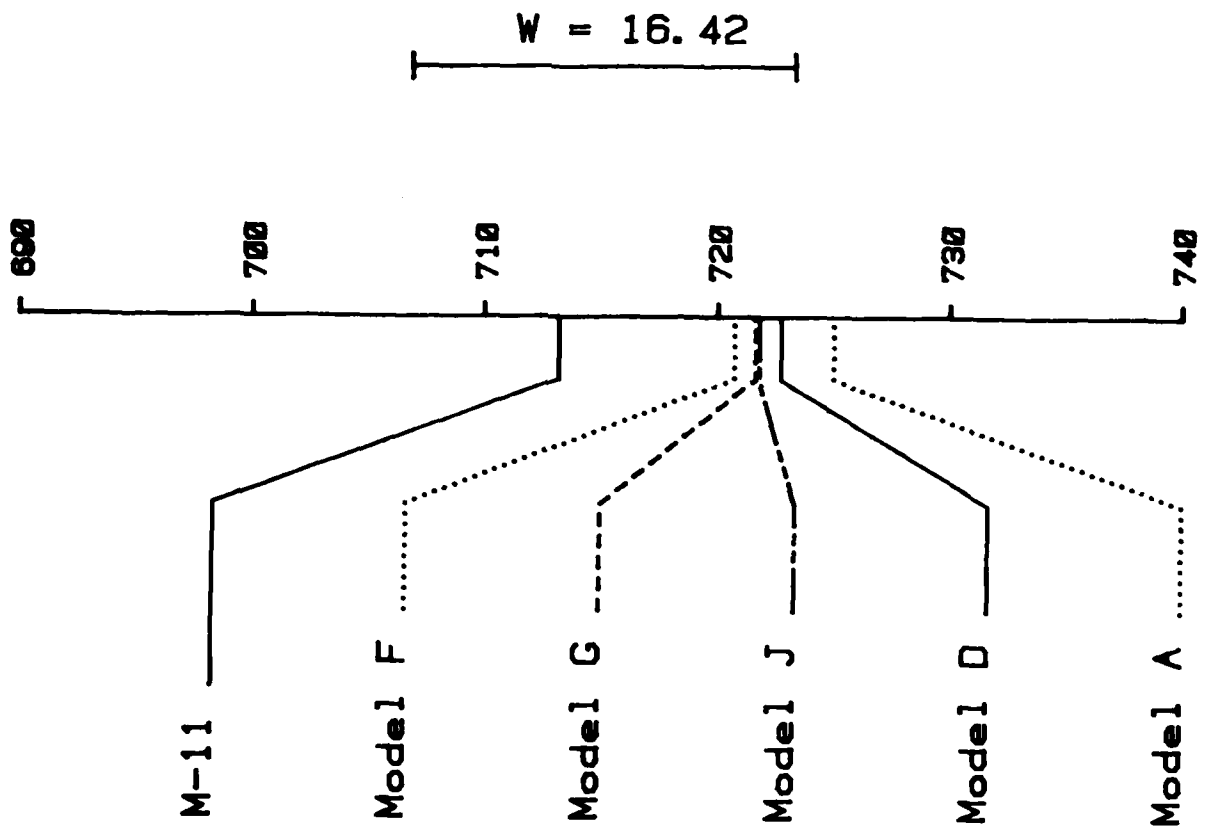


Figure 8B. Graphical summary of high pressure test for bias.

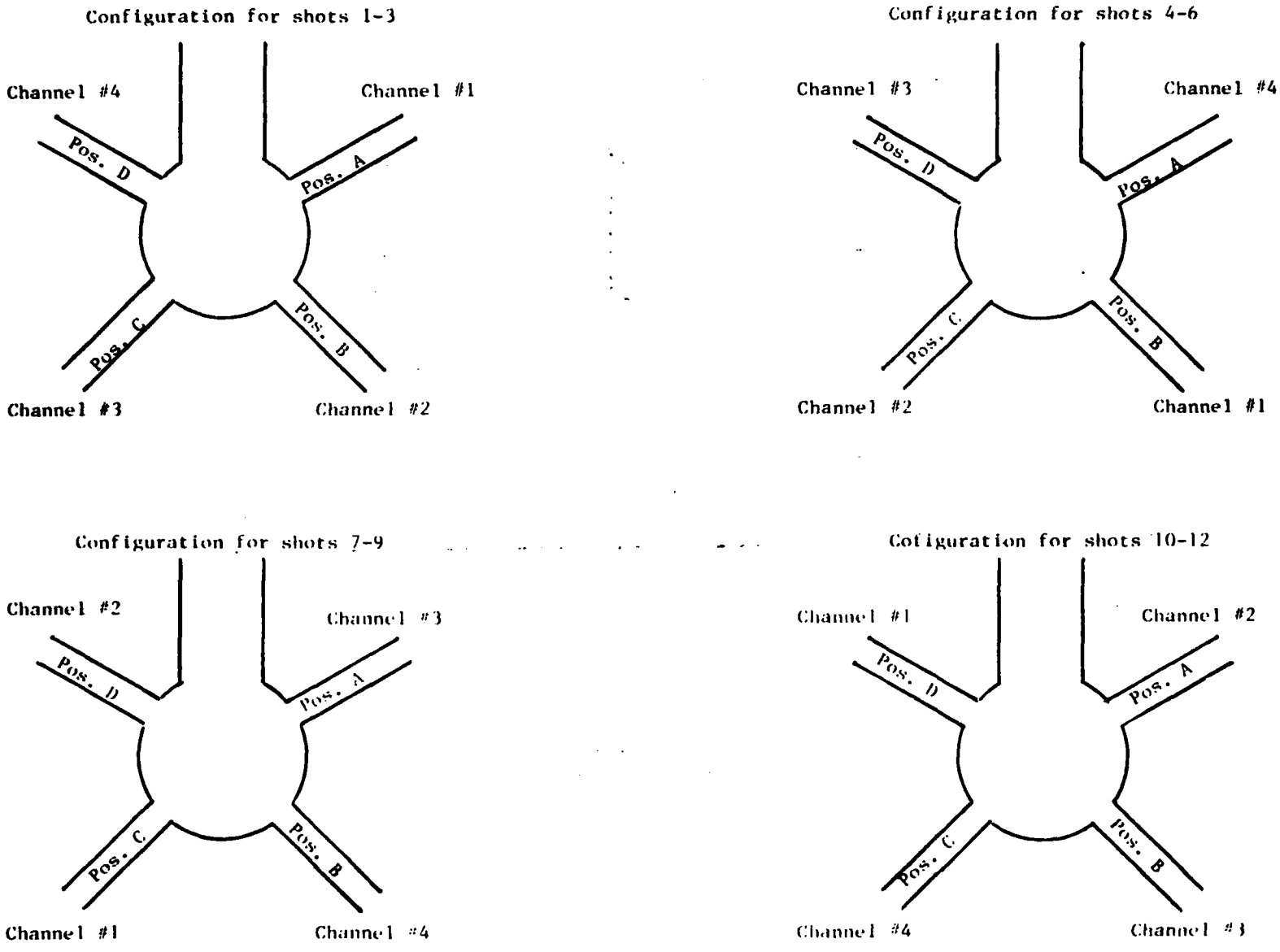


Figure 9. Diagram of the four different mounting configurations used in Latin square test.

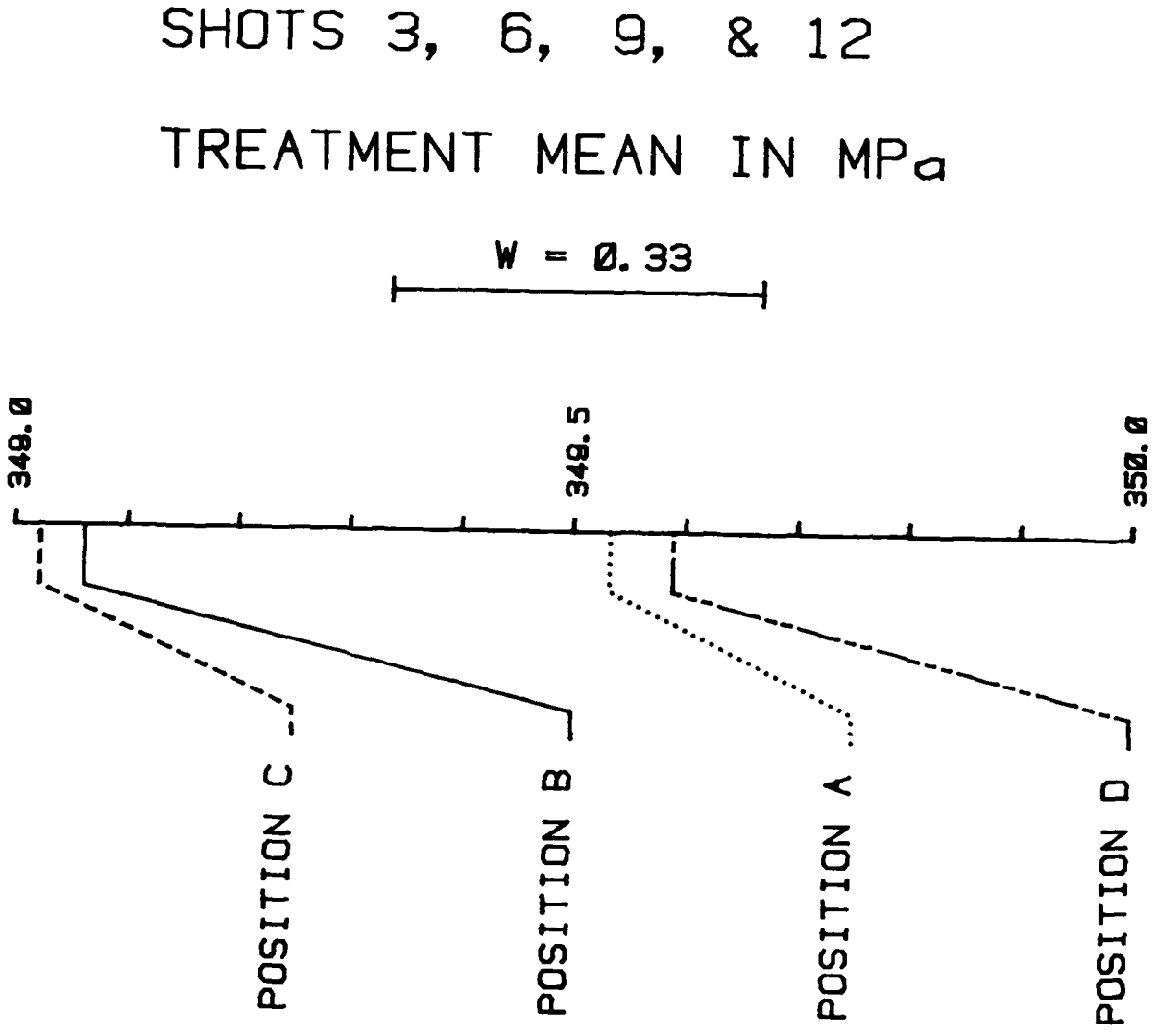


Figure 10A. Comparison of selected groups of shots of the Latin square test.

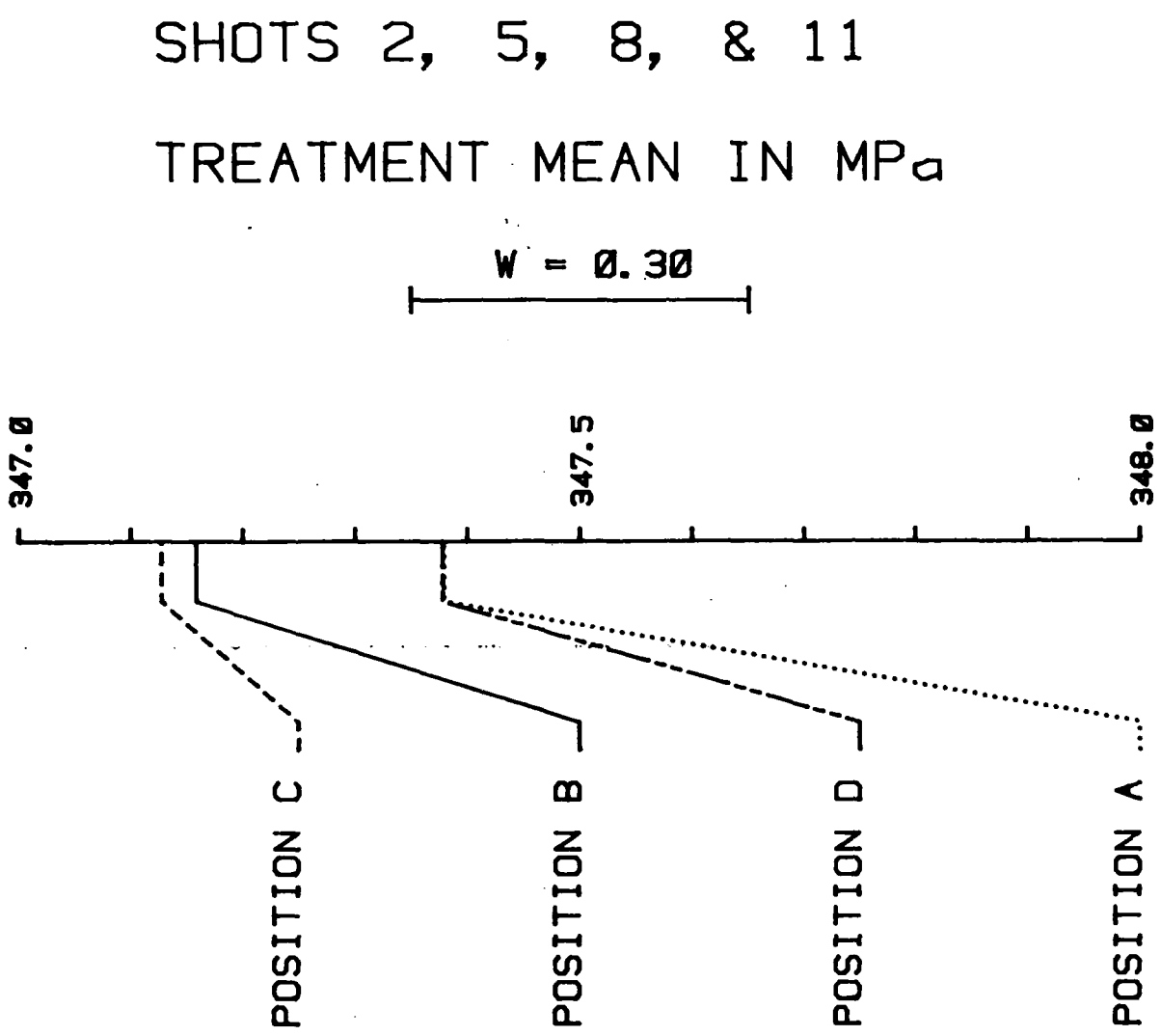


Figure 10B. Comparison of selected groups of shots of the Latin square test.

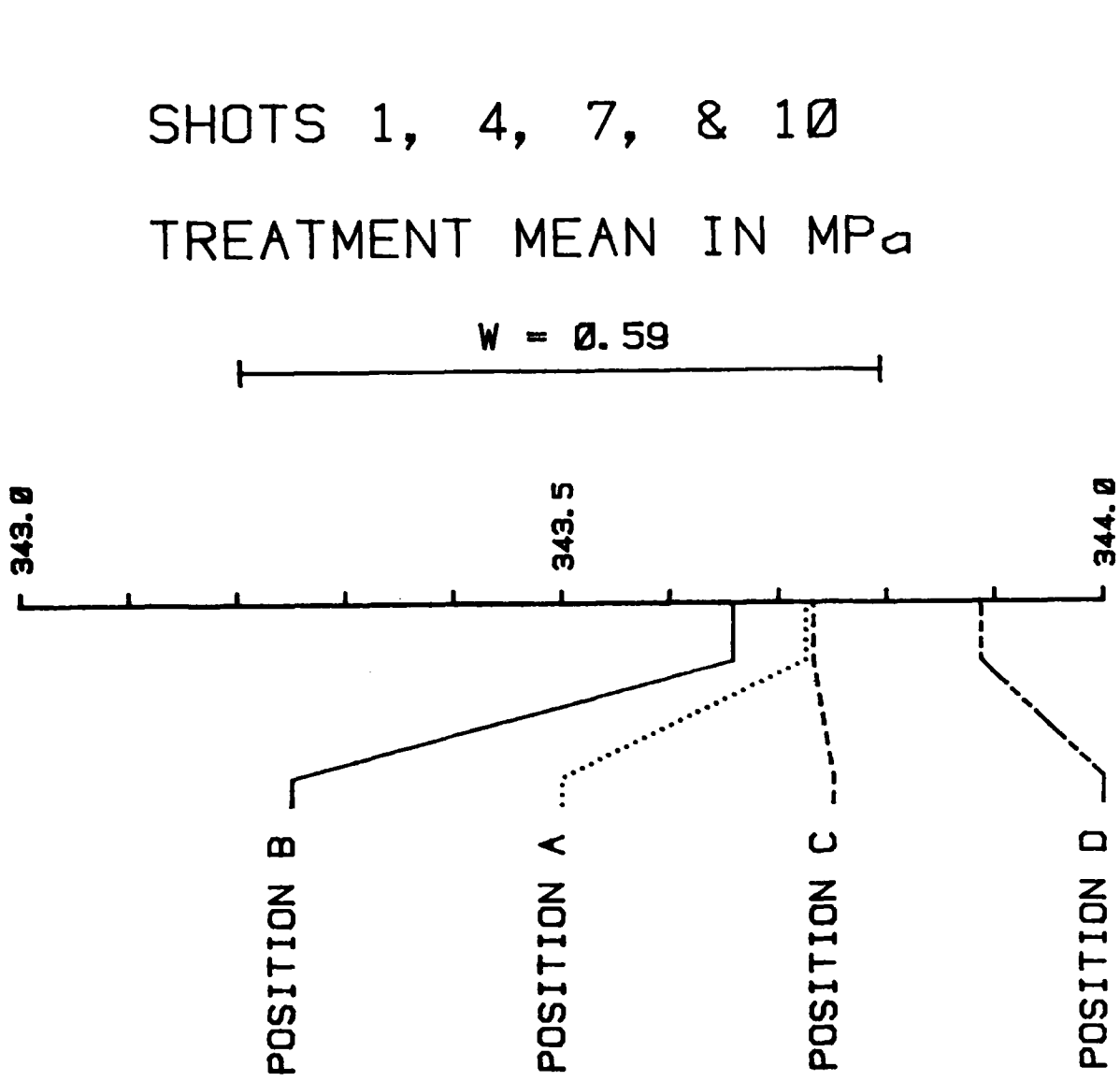


Figure 10C. Comparison of selected groups of shots of the Latin square test.

ACKNOWLEDGEMENT

FOR

"WEAPON CHAMBER PRESSURE MEASUREMENT"

BY

W. SCOTT WALTON

The work described in this report has been accomplished as part of the U.S. Army Materials Testing Technology Program, which has for its objective the timely establishment of testing techniques, procedures, or prototype equipment (in mechanical, chemical, or nondestructive testing) to insure efficient inspection methods for materiel/material procured or maintained by the U.S. Army Materiel Development and Readiness Command.

ADP002685

SOIL PORE GAS PRESSURE MEASUREMENTS AT THE NEVADA TEST SITE

BY: Lee Davies and Roger Noyes, EG&G, Inc., Las Vegas, Nevada
John Kalinowski and Ted Stubbs, EG&G, Inc., San Ramon, Calif.

ABSTRACT

This paper describes a system that monitors soil pore pressure in dry reconstituted soil, serving as the tamping and containing medium for experimental explosions. This system has proven to be reliable and stable over the several years that it has been maintained and operated. It yields information on compression of the soil due to the initial shock wave, rarefactions due to settling and variations that correlate well with variations in atmospheric pressure. The burial depth of sensing systems ranges from a few feet to over 1,000 feet in alluvium-like material. The primary sensing device is a pressure transducer in a protective structure sometimes referred to as a "cowbell" or a "rocket." The why, when and where of the measurements is given along with the system calibration, instrument installation, recording and data reduction.
Examples of data and their analysis are presented.

INTRODUCTION

A system will be described here that is used to monitor the pore pressure in the material used to backfill a drill hole in which a nuclear explosive is being tested, (see Figure 1). This system incorporates a transducer, canister, cable, signal conditioner, power source, recording instrument, transducer calibration, and data reduction. Each component is vital to the final analysis and understanding of the phenomena that occurred.

The usual method of backfilling a nuclear test emplacement hole is with alternate layers of fine and coarse earthen material and two or more epoxy plugs, (see Figure 2). The instrument cables are spread apart to prevent open channels between cables, multipair cables are internally gas blocked with epoxy. Good geologic siting, proper burial depths and care in the backfill design provide for the containment of nuclear debris and escape of gases carrying radioactive substances.

The pressures of interest, in most cases, are those pressures that are not supposed to be present. Occasionally these pressures are quite large and occur quickly but mostly the pressures are low, a few psi, and occur as seeps. The system monitors these long term and low pressure seeps.

HARDWARE

The system is composed of four major components: downhole hardware and transducers, signal conditioning and recording, calibration, and data reduction. The downhole component is composed of a transducer, canister, cable, and emplacement device. The emplacement device is a wire cable lowered from the surface. Several canisters may be attached to this cable. The canister has been positioned with more complex hardware such as extension arms but survivability decreases with such hardware. The canister, which encloses the transducer, is a strong metal bottle, (see Figure 3). It is to protect the transducer from the backfill material and compressive shocks and other dynamic effects, except pressure surges, caused by the explosion and also provide a Faraday type cage for protecting the system from the electromagnetic pulse (EMP), (see Figure 4). A filtered channel at the bottom of the canister is provided so that the diaphragm of the transducer can view the gas pressure in the backfill. This method of construction allows for the sensing of only the "pore" pressure and not pressures from impinging rock. The cable is attached to the canister by a connector. A strain relief on the connector is provided by means of a Kellum grip that grips the cable and fastens to the canister. A small quasi loop is formed in the cable from the connector to the gripped cable section to provide the relief. A four pair, twisted, individually shielded pair cable with overall shield is used.

TRANSDUCERS

Transducers used are of the unbonded strain gage or bonded semiconductor type, (see Figures 5, 6, 7, & 8). The transducer accuracy claimed is ±0.3% full scale output as defined from a best-fit straight line, including non-linearity, repeatability and hysteresis, operating over a temperature range of -65° F to +200°F. Temperature range and effects are +30°F to +130°F and 0.005% fullrange per °F over the limited compensated range. Gage stability is claimed as 0.5% per year. Several manufacturers produce transducers that meet these requirements. The long term stability is important not only in terms of the measurement time but also because of the inaccessibility of the gage once it is placed downhole and covered up. These times may be from a week to three months. Emplaced gages have been used two years after their event use to measure in-situ permeability using barometric pressure fluctuations and have performed very well (see Figure 9). (These measurements were for a study on coal mine tunnel stresses.) Temperature, although tightly specified, is not much of a problem because soon after the backfill operation is completed a temperature equilibrium is obtained which varies very little over the period of measurement and longer. This constant temperature environment aids in acquiring better data.

CALIBRATION

The pressure transducers previously described are calibrated with constant current, or dual constant current excitation. The typical four arm wheatstone bridge type utilizes constant voltage or single constant current. The two gage (quasi-two arm) type use dual constant current. The transducers are physically connected to a pressure/vacuum source which is monitored with a precision pressure gage or dead weight tester, (see Figure 10). They are connected electrically to a signal conditioner which emulates the type used in the field. The signal conditioner provides the excitation sources, balance circuit and the voltage monitor points. An accurate digital voltmeter is used to monitor the output during calibrations, (see Figure 11).

A known pressure is applied to the transducer. The excitation and balance control are adjusted to fix the output end points. The pressure source is then stepped through a series of points while the output of the signal conditioner is recorded. The excitation voltages are monitored and recorded. Current is monitored as a voltage drop across a 10 Ohm resistor. A computer will be used in the near future to gather the calibration data and provide feedback/servo control to the pressure source. Prior to the pressure calibration several resistance measurements are made on each transducer. These are used in the field to verify transducer and circuit integrity.

The calibration data is supplied to the field for setup and to the data center for data reduction.

SIGNAL CONDITIONING AND RECORDING

Signal conditioning utilized is normally dual constant current for the two-arm pressure transducers. This method of excitation is preferential due to the lengths of cable run from the transducer to the recording trailer which exceed several thousand feet. The output of the pressure transducer is amplified and then F.M. multiplexed onto magnetic recorders which are remotely controlled. Tape speed is 7-1/2 ips which provides four hours of recording time. The typical signal to noise ratio of a channel is in excess of 40 db. Field event channel calibration is accomplished by a microwave signal activating a six step voltage substitution calibration sequence which is recorded on magnetic tape. This calibrator is then powered down prior to zero time to preclude the system going into a calibration mode after zero time. When the trailer is re-entered the magnetic tapes are played back and "quick-look" oscillograph recordings are made and evaluated. At this time the tapes are shipped to LLNL for detailed evaluation and analysis.

DATA REDUCTION

Data reduction begins with the review of oscillograph traces made from the event analog tapes. This allows for a plan of attacking those measurements which may contain data of immediate interest and for pointing out possible equipment or instrumentation problems. The event analog data tapes are then digitized so that the data may be operated on with a computer. The calibration data is combined with the field calibration steps and with the digitized calibration steps so that the engineering units are determined for each data channel. Baseline shifts, instrumentation offsets, timing adjustments, and other perturbations are then corrected in the data. Finally, hard copy plots of the data are made so that the analytic review and analysis of the data can begin. Pressure changes of a tenth of a psi or more are routinely analyzed, (see Figures 12 and 13).

EG&G

PORE PRESSURE MONITERING SYSTEM

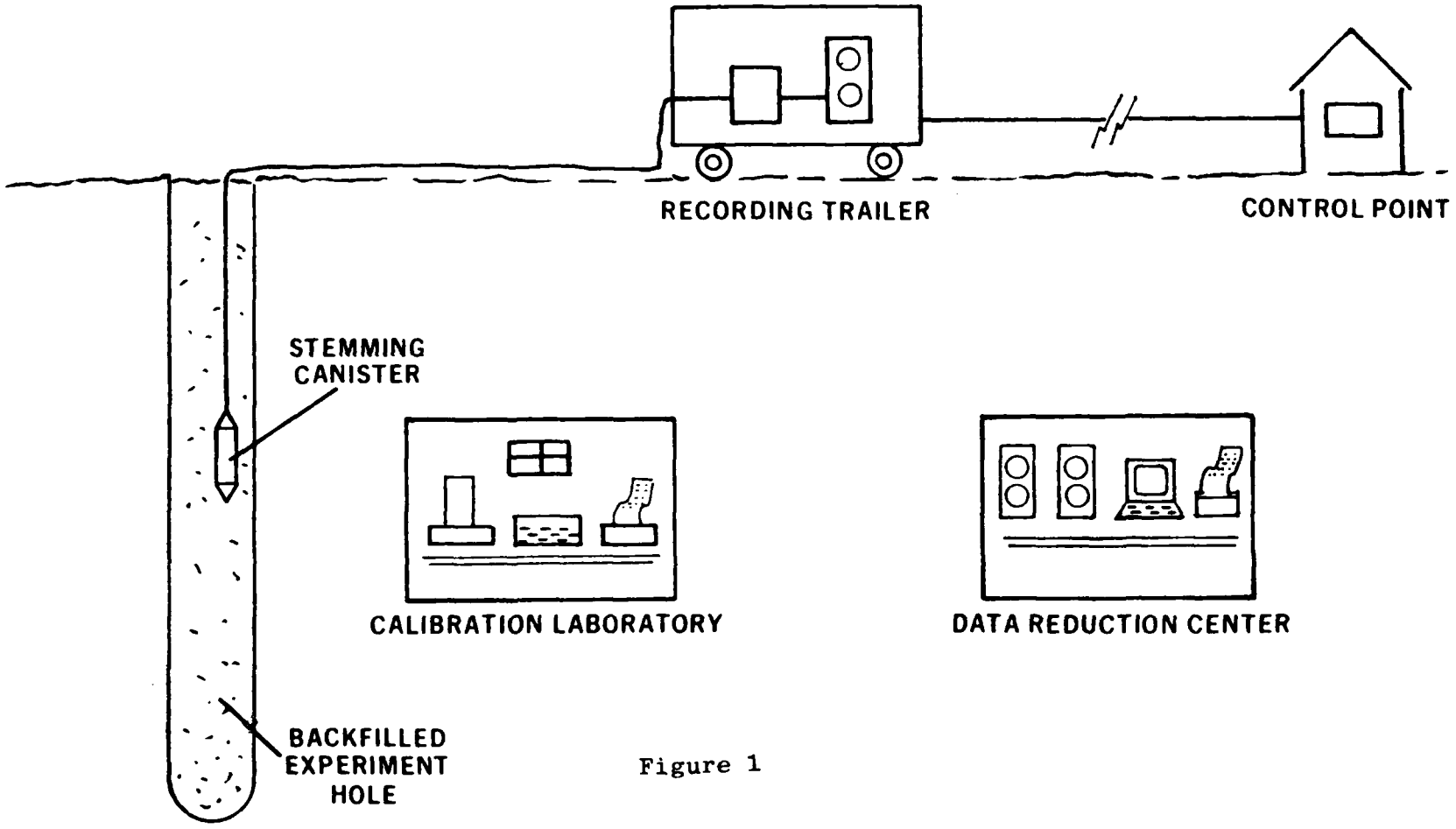
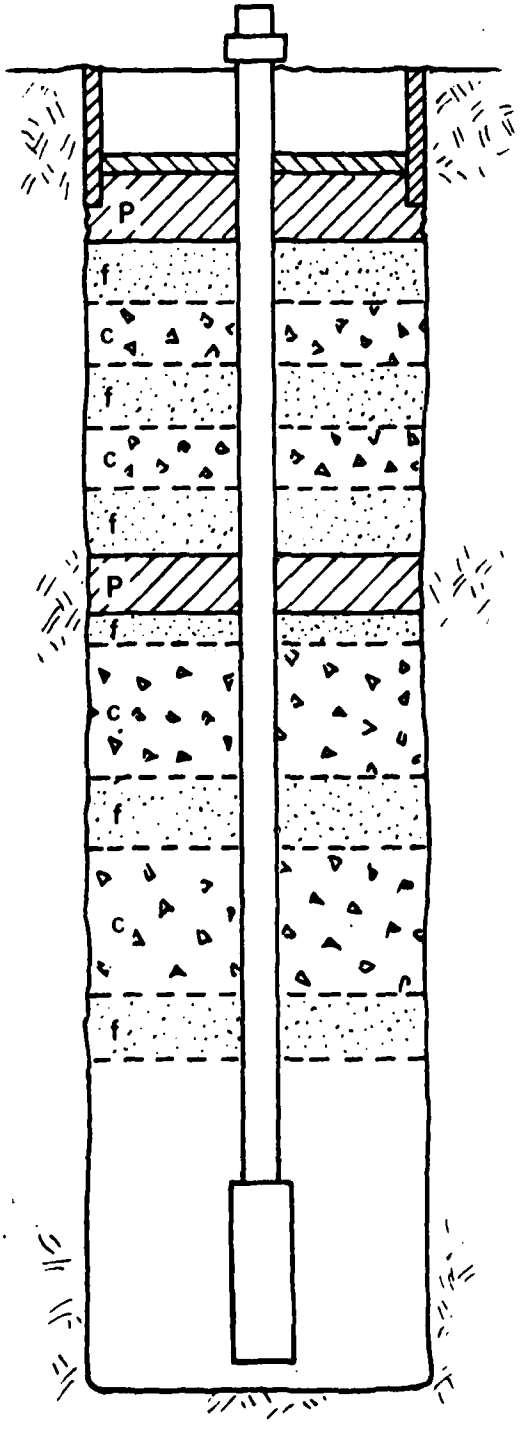


Figure 1

EG&G

BACKFILLED EXPERIMENT HOLE



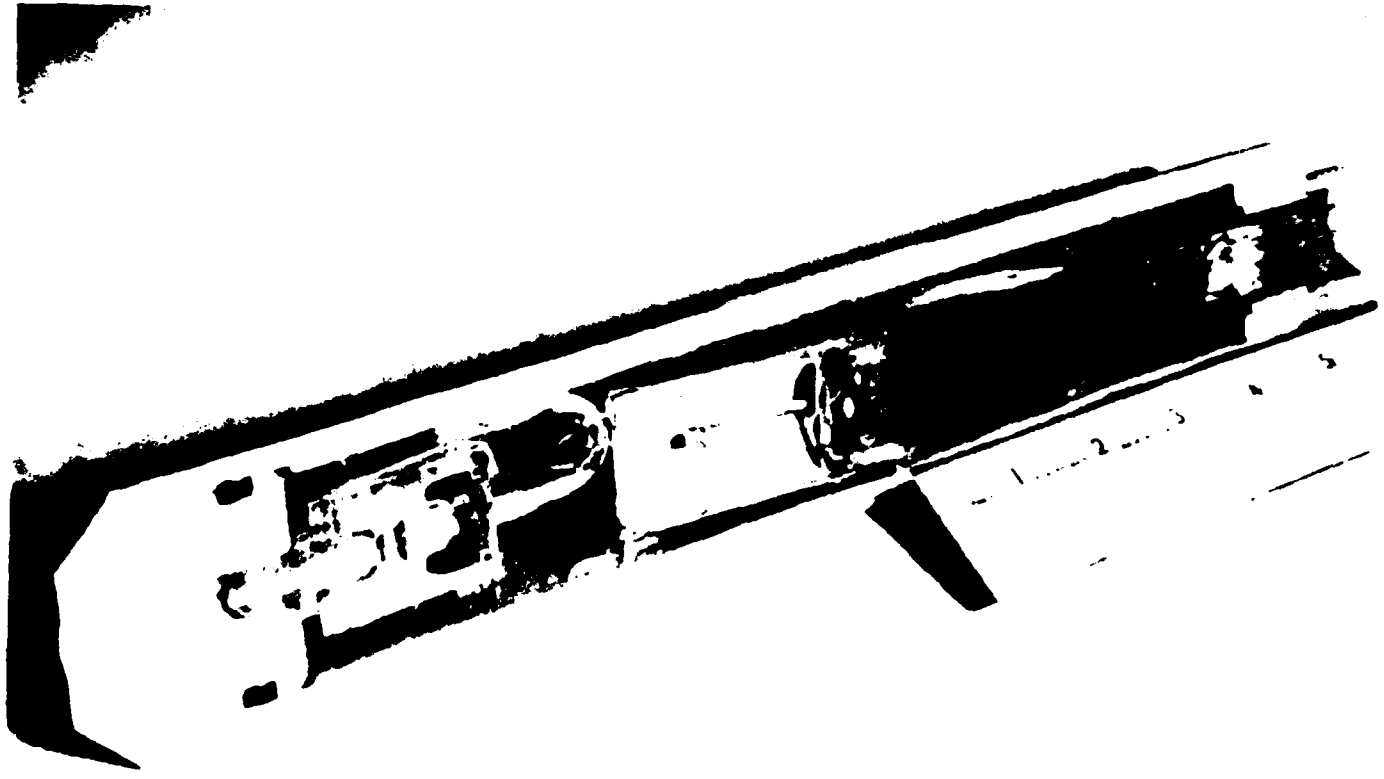
f-Denotes fine material

c-Denotes course material

P-Denotes rigid plug

Figure 2

EG&G



STEMMING CANISTER

Figure 3

EG&G

STEMMING CANISTER

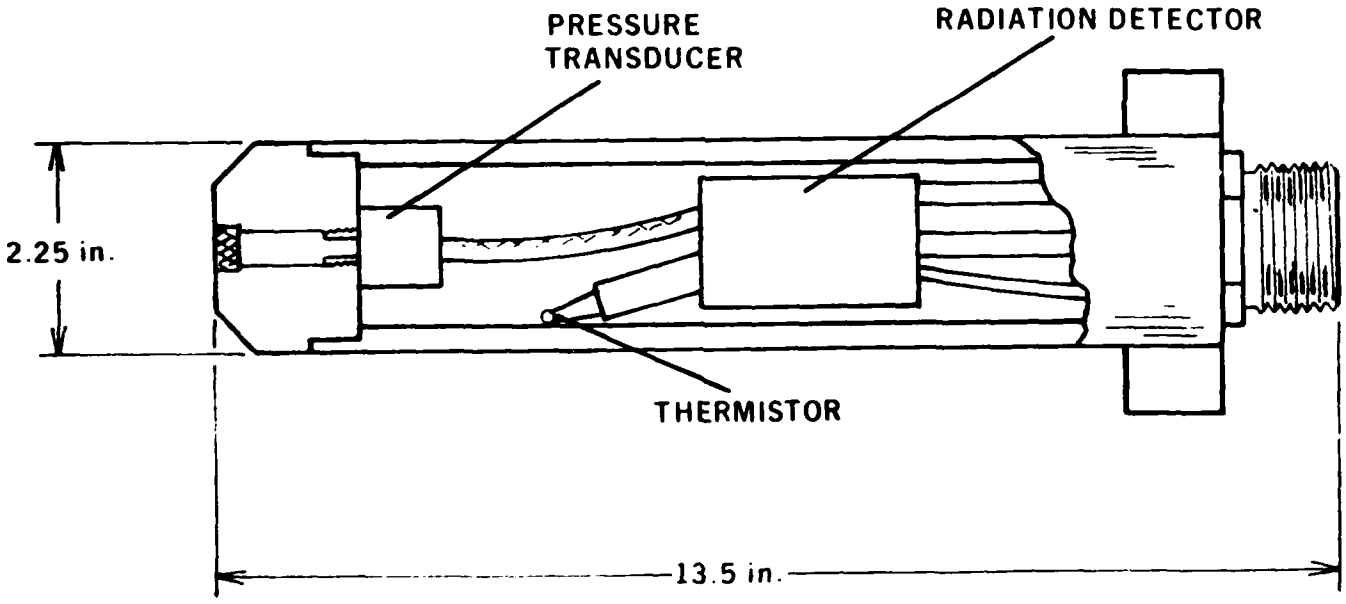


Figure 4

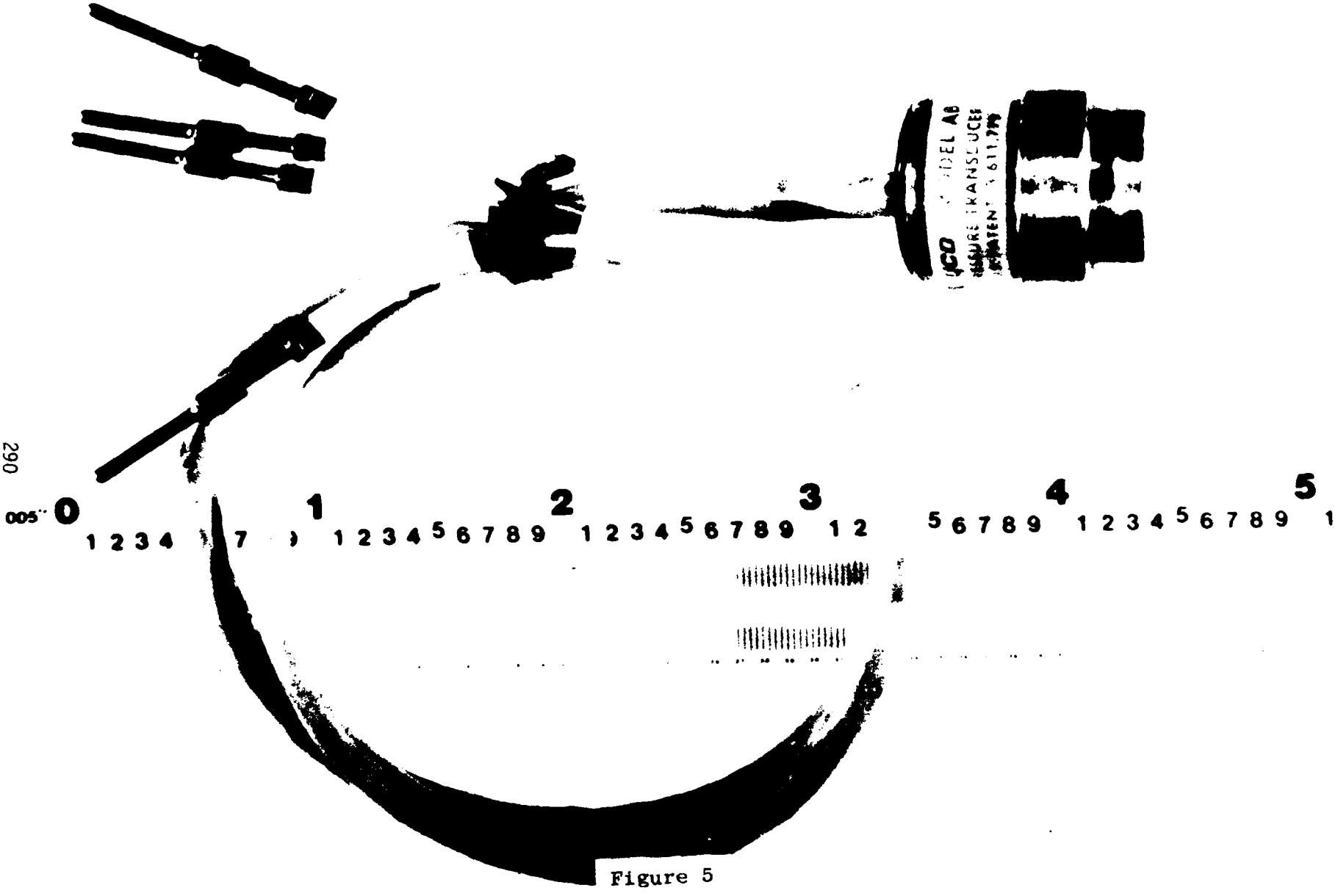
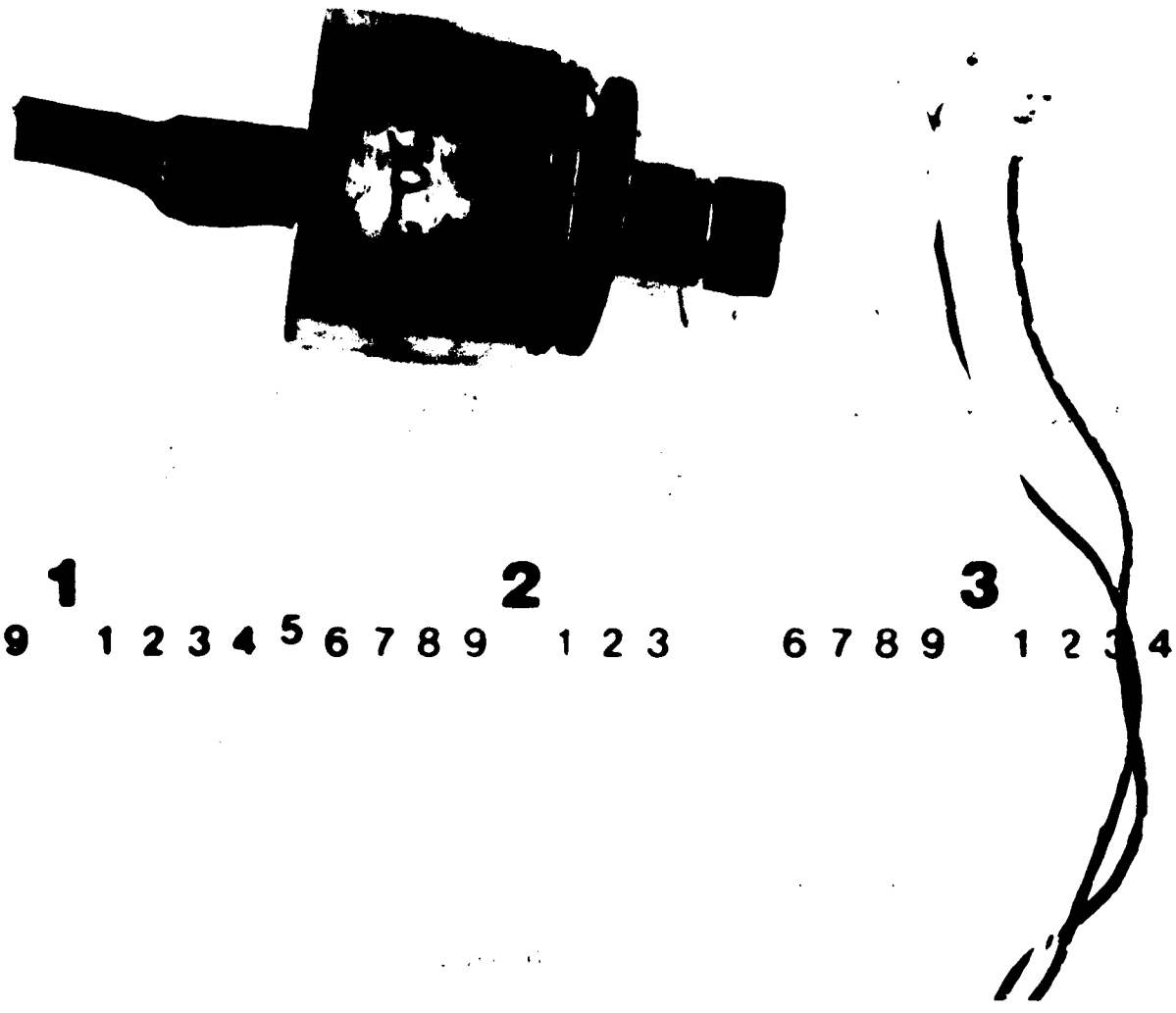


Figure 5


291
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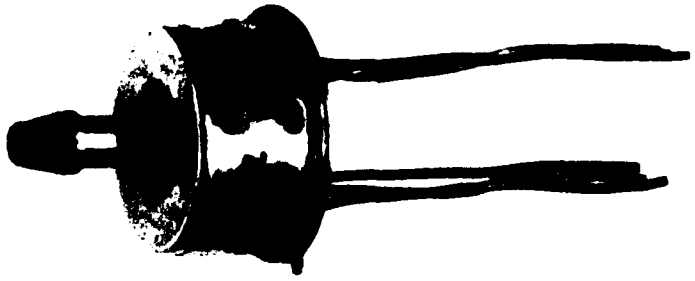
2
3
1 2 3 4 5 6 7 8 9 1 2 3 4 5 6 7 8 9 1 2 3 6 7 8 9 1 2 3 4



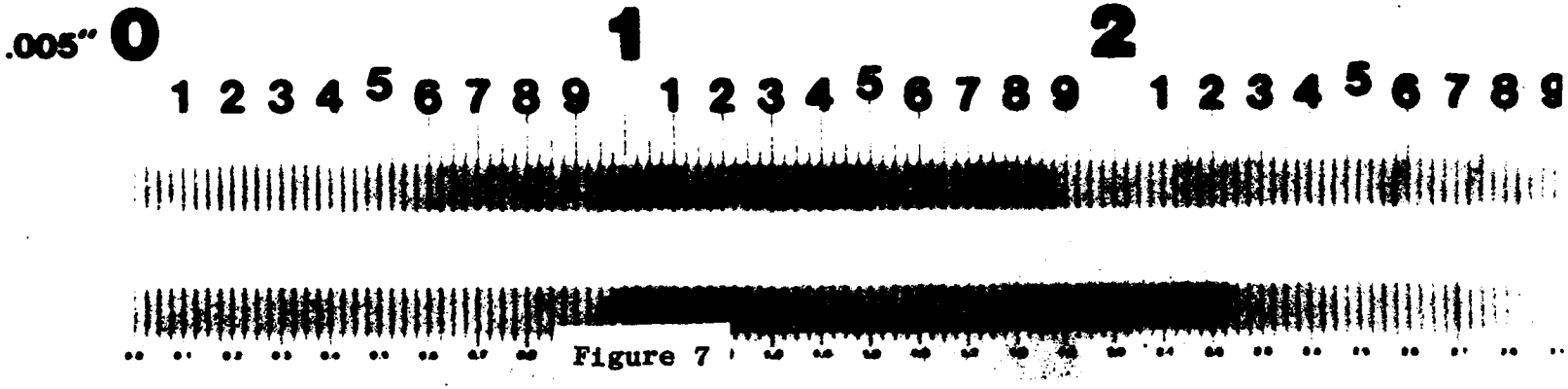


Figure 7

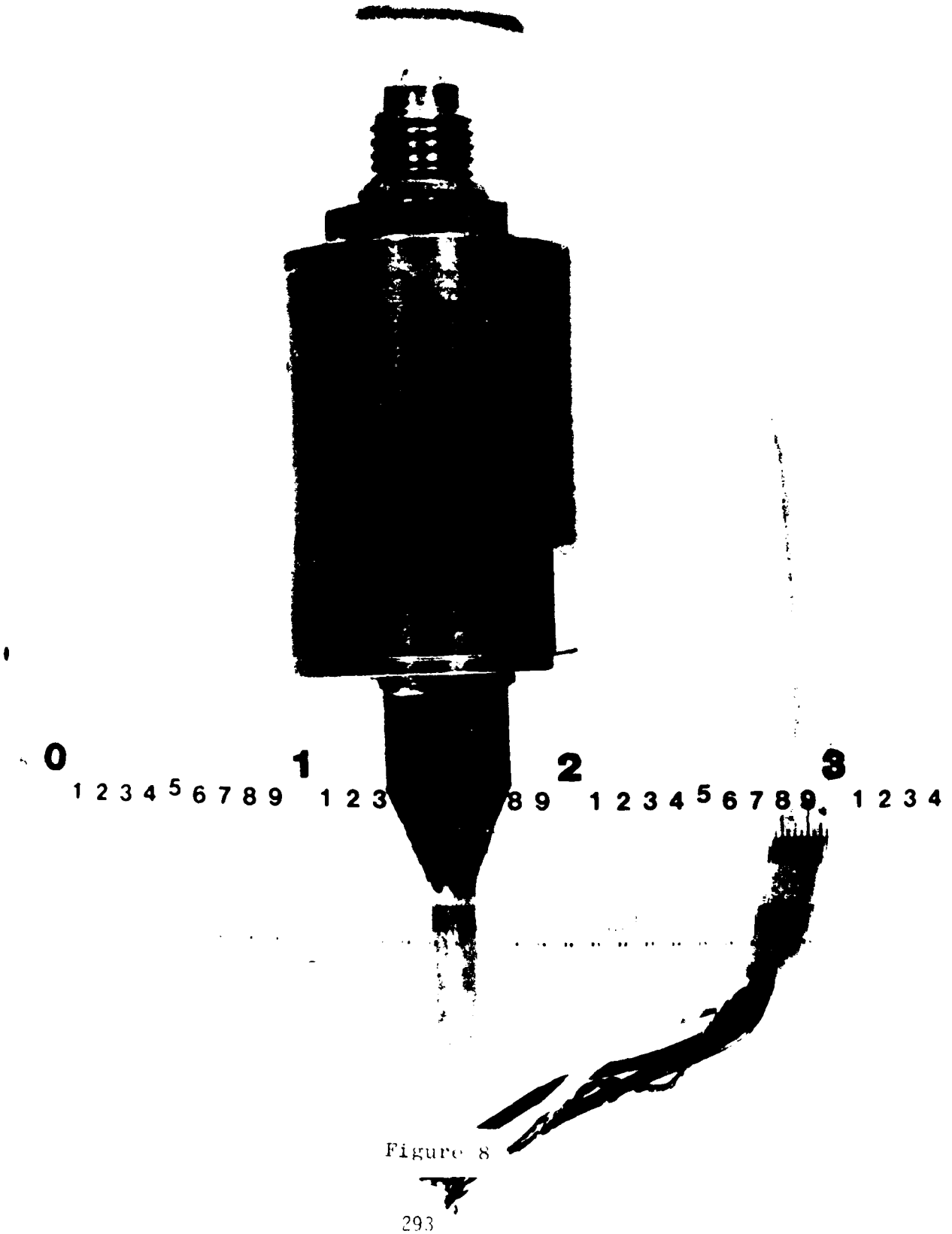


Figure 8

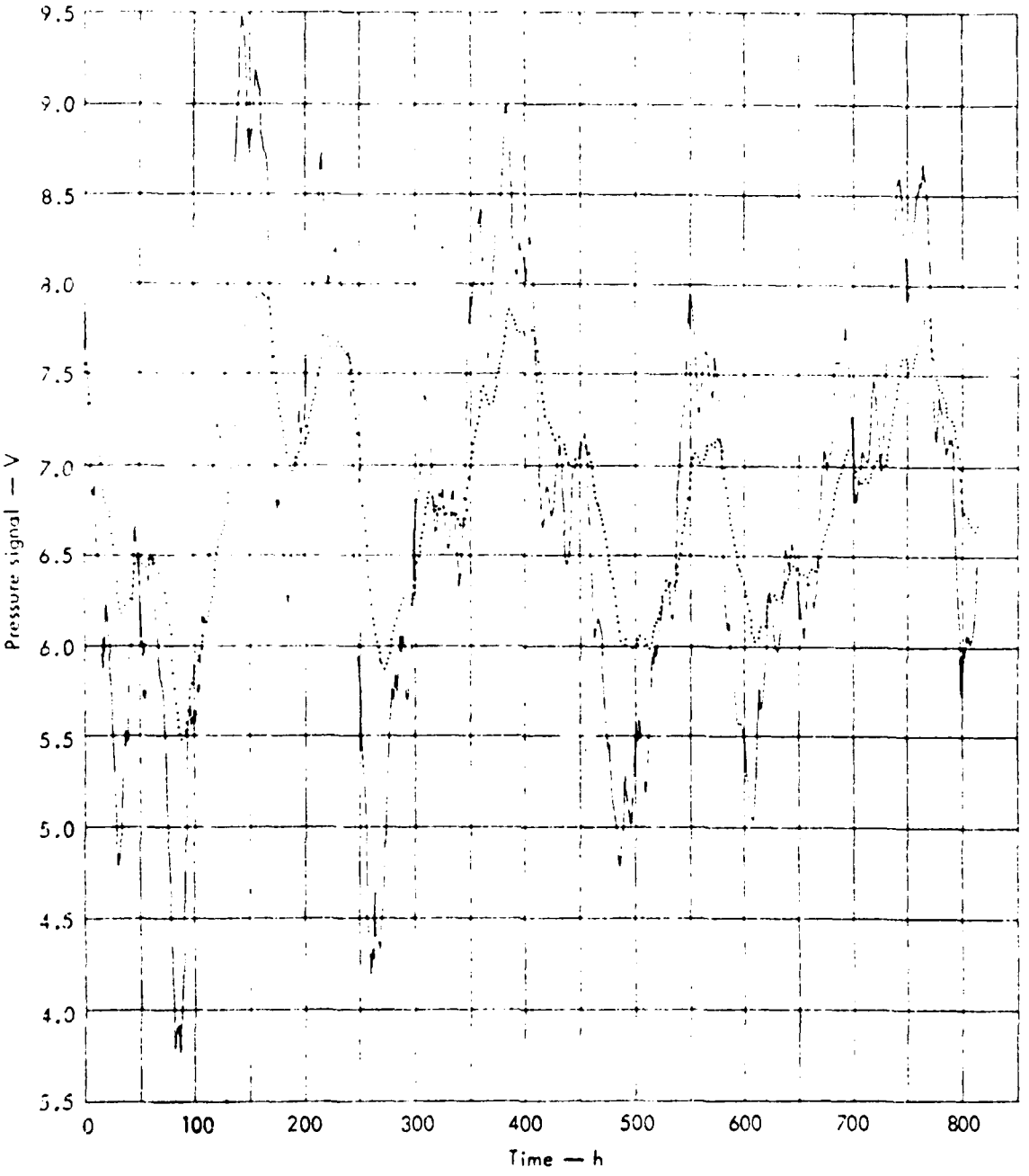


Fig. 2. Pressure versus time. The solid line indicates atmospheric pressure and the dotted line the pressure in UeU29-2.

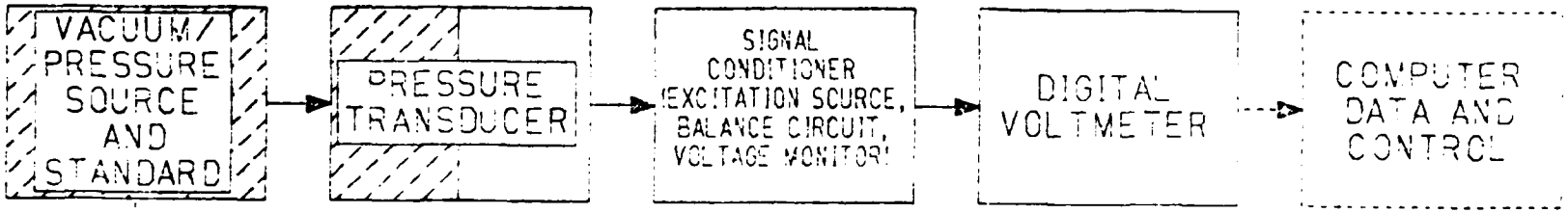
Figure 9

PRESSURE STANDARDS AND/OR GENERATORS

1. MANOMETER, 0 TO 8 INCHES WATER
2. D.W.T.* 0.3-50 PSIA OR G
3. D.W.T.* 15-500 PSIA OR G
4. D.W.T.* 30-12140 PSIG
5. D.W.T.* 1-100 PSIG
6. D.W.T.* 10-1000 PSIG
7. D.W.T.* 750-30000 PSIG
8. LEAK TESTER 0-20,000 PSIA
9. QUARTZ GAGE 0-16 PSIA
10. QUARTZ GAGE 0-100 PSIA, G OR D
11. QUARTZ GAGE 0-500 PSIA, G OR D

*DEAD WEIGHT TESTER

Figure 10



PRESSURE CALIBRATION SYSTEM

LEGEND

ELECTRICAL

PRESSURIZED

FUTURE SYSTEM

Figure 11

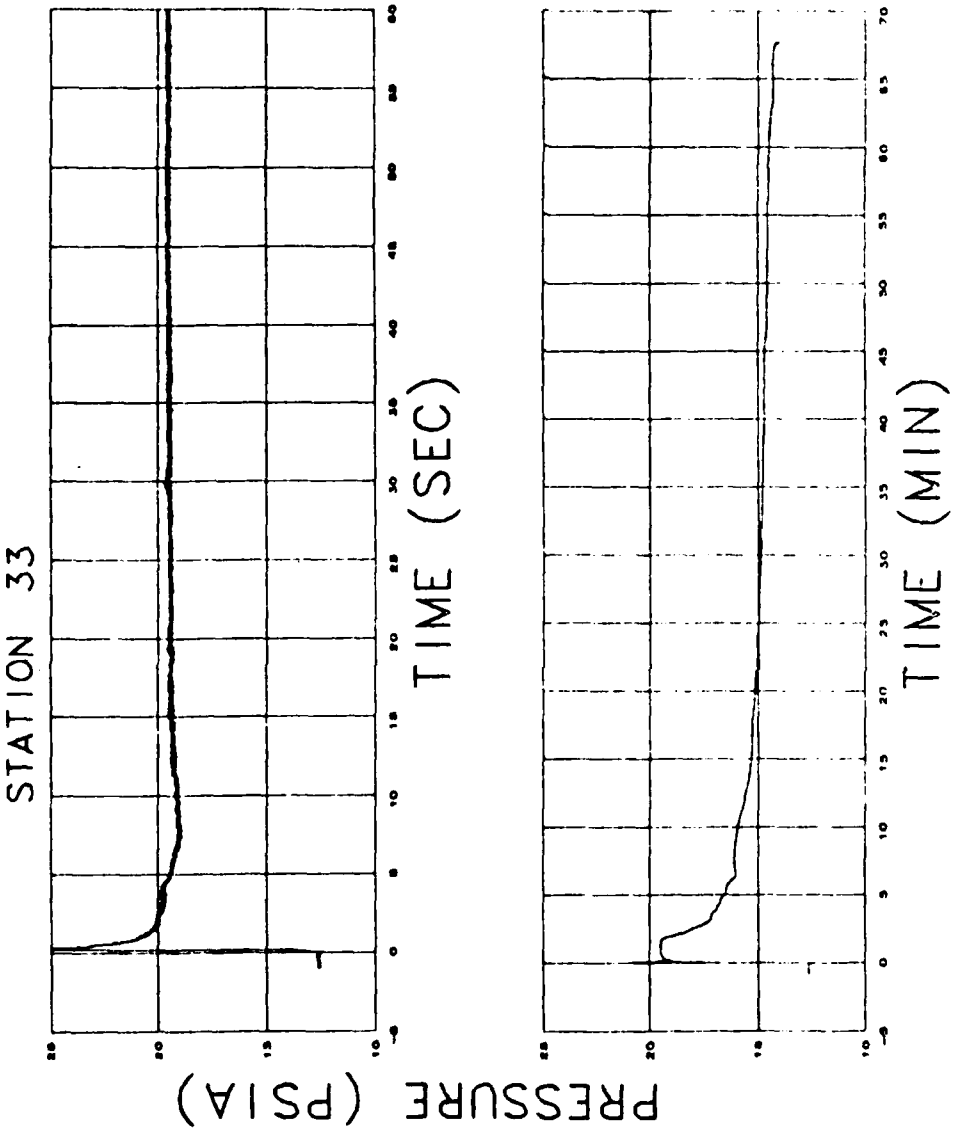


FIGURE Figure 12

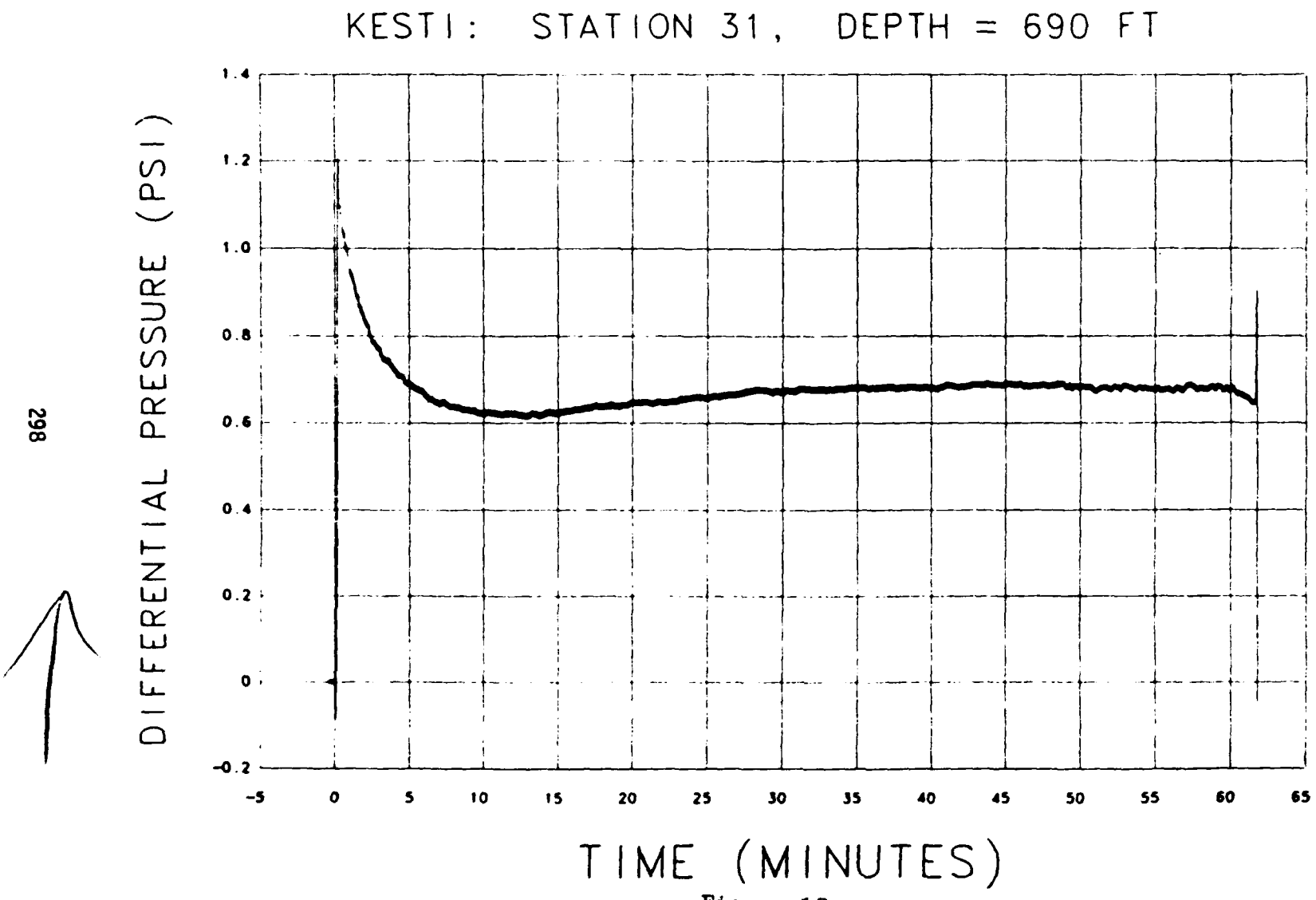

KESTI: STATION 31, DEPTH = 690 FT
DIFFERENTIAL PRESSURE (PSI)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
-0.2
-5
0
5
10
15
20
25
30
35
40
45
50
55
60
65
TIME (MINUTES)

Figure 13

AD P002686

TEMPERATURE COMPENSATION AND SHUNT CALIBRATION OF SEMICONDUCTOR PRESSURE TRANSDUCERS

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KULITE SEMICONDUCTOR PRODUCTS

Presented at The Twelfth Transducer Workshop
June 1983 Melbourne, Fla.

ABSTRACT

Silicon integrated sensor transducers are conventionally temperature compensated by the use of simple passive resistor networks. These networks serve to trim the bridge temperature coefficients to achieve the desired performance. This paper presents several techniques commonly used for this type of transducer. These circuits are presented to allow full understanding by the user of the operation of such transducers and to provide a basis for the thermal compensation of custom flexures and transducer structures employing semiconductor sensors. A novel integrated sensor employing on-chip compensation is presented.

INTRODUCTION

Silicon integrated sensor technology has emerged over the last thirty years from the laboratory and developed into a remarkably successful research and commercial enterprise. The term silicon integrated sensor (ref 1) refers to a structure in which the sensors (typically 'p' type diffused piezoresistive elements) are formed integrally with a force-collector or flexure (typically an 'n' type silicon pressure sensing diaphragm). This technology has proven to be the technique of choice for the manufacture of a broad range of measuring instruments accounting for one-fifth of the dollar

volume and three-fifths of the unit volume of all pressure transducers manufactured currently in the U.S. (ref 2).

A representative state of the art structure is shown in figure 1. Single crystal 'n' type silicon is formed into a cup shaped diaphragm structure onto which have been diffused 'p' type piezoresistive elements in a wheatstone bridge configuration with an open node for the addition of an external zero balance resistor. The .108" diameter sensor shown is mounted by a solid state bonding process (ref 3) onto a thick borosilicate glass pedestal which serves to stress isolate the diaphragm from its mounting surface. This pedestal is particularly important in providing effective isolation from stresses due to the mismatch of thermal expansion coefficients between the silicon and the stainless steel transducer housing generally employed.

The technology employed for the manufacture of these devices has been discussed extensively (ref 4-12) elsewhere and will not be repeated here. This class of devices was first used in the mid-sixties to produce miniature dynamic pressure sensors which provided a tool not previously available to the test community and opened up the possibility of dynamic measurements in the range of DC to 20 KHz with transducers one-tenth the diameter of previously available instruments. Particularly successful for flight and wind tunnel

test, these transducers contributed substantively to the development of today's generation of turbine aircraft. Integrated sensor transducers are currently manufactured in a variety of packages which cover the spectrum from low cost consumer products through aerospace, medical and military production and test hardware to industrial applications.

Among other considerations, two major questions faced early investigators:

1) Was silicon a suitable rugged force collecting element?
2) Could the relatively high temperature coefficients of silicon piezoresistive transducers be effectively reduced by practical temperature compensation methods?

Both problems were, in fact, very adequately solved as the technology developed.

Silicon is an excellent spring material entirely suitable for transducer flexural applications. For a review of the mechanical properties of silicon, see refs 13 & 14. Silicon has a low density with an anisotropic elastic modulus whose maximum value is close to steel (approx. 30×10^6 psi). This combination of high stiffness and low density, combined with the ability to be formed into very small, low mass flexural

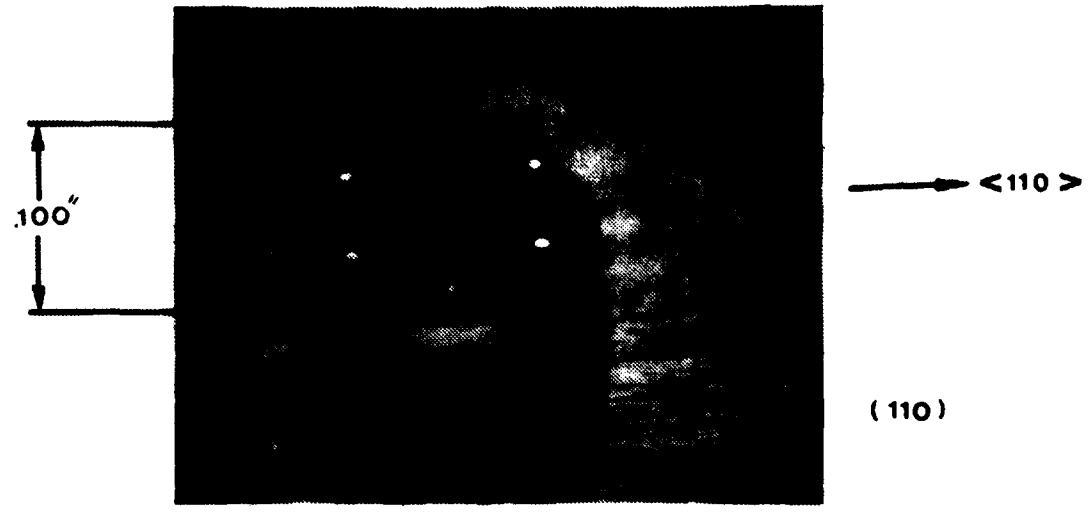

FIGURE 1 SILICON INTEGRATED SENSOR PRESSURE TRANSDUCER CAPSULE

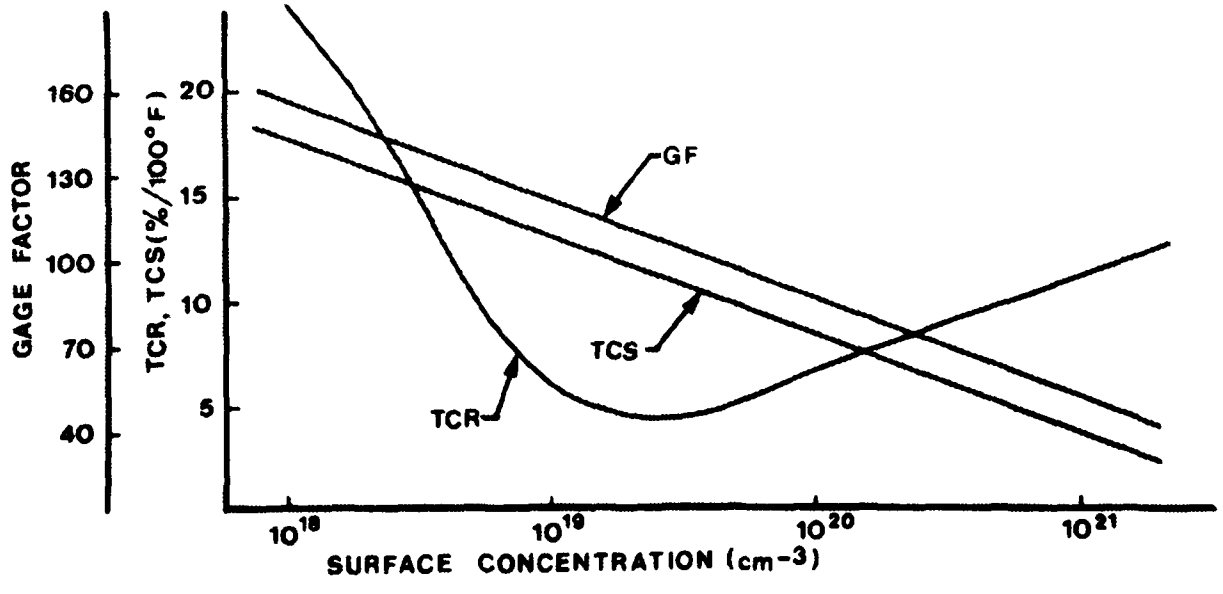

FIGURE 2 PIEZRORESISTIVE PROPERTIES OF DIFFUSED LAYERS

elements allows the fabrication of very high resonant frequency devices. Brosh (ref 15) has shown that for a specified sensitivity, frequency response is inversely proportional to the diaphragm diameter. The small sizes achievable with integrated circuit technology is important in achieving high frequency devices.

Silicon is a near perfect, single crystal readily available with dislocation densities of less than $100/cm^2$. It exhibits negligible mechanical creep or hysteresis, long the bane of metallic and especially epoxy bonded transducers. Integrated sensor transducers typically exhibit hysteresis below the range of convenient measurement (.01% full scale).

Silicon is remarkably strong with typical transducer flexural members exhibiting failure limits in excess of 140,000 psi. Silicon shows no plastic deformation prior to yield, and burst and proof pressures are identical for this class of transducers.

The second problem of the relatively high thermal coefficients of this class of devices was also solved successfully by the use of simple circuit techniques employing passive, low temperature coefficient balancing, and temperature trimming resistive networks. By using such techniques with the current state of the art, it is entirely feasible to produce a .093"

diameter, 5 psi transducer with static and thermal errors equal to or better than the best commercially available transducers. Thermal errors of .5% per 100 °F, a static error band of .25%, a repeatability of .05%, and long term stability of .25%, are readily achievable.

This paper discusses the common methods employed for the thermal compensation and shunt calibration of integrated sensor transducers.

The measurement technologist depends on his instrument for reliable data. All transducers respond to a variety of inputs besides the sought after parameter. In order to obtain precise measurements, a detailed knowledge of the operation of the measuring instruments employed is desirable. This paper presents the techniques employed for temperature compensation of this class of devices in order to help achieve this goal.

ERRORS ASSOCIATED WITH UNCOMPENSATED INTEGRATED SENSORS

An integrated sensor structure, as shown in figure 1, is essentially a complete pressure transducer requiring only packaging, cable attachment, and the addition of a resistive network which serves to normalize sensitivity and offset and to trim by means of a passive shunting technique, the thermal coefficients of offset and span.

In order to fully understand this compensation technique, it is necessary to define a number of performance parameters and error terms associated with transducers.

A transducer exhibits room temperature performance defined by the following parameter:

V_o is the offset at zero applied pressure in mv

V_{fs} is the reading at full scale pressure in mv

V_{fso} is the difference $(V_{fs} - V_o)$

V_e is the applied excitation in volts

V_s is the sensitivity (V_{fs}/V_e) in mv/V

G.F. is the gage factor of the bridge elements

The performance over an extended temperature range is defined by the following parameters,

TCS is the temperature coefficient of sensitivity of V_s expressed in %/100 °F

B is *TCS* expressed as a fractional change in V_s per °F (this is a more convenient form for us in mathematical expressions)

TCR is the temperature coefficient of resistance in %/100 °F

α is *TCR* expressed as a fraction per ^{o}F

TCV_o is the temperature coefficient of bridge offset (V_o) in %/100 ^{o}F

In order to fully compensate the device, the following must be achieved,

1) The offset V_o must be made close to zero, typically, less than 3% V_{fs}.

2) The sensitivity V_s must be set to a desired value for a given excitation (V_e), typically 10 to 30 mv/v.

3) The change in offset with temperature TCV_o must be reduced to near zero, typically less than 1% per 100 ^{o}F.

4) The change in sensitivity TCV_s must be reduced to near zero, typically less than 1% per 100 ^{o}F.

Figure 2 shows the change in the basic parameters of integrated sensors as a function of impurity concentration. The device technologist is free to vary impurity concentration in order to achieve a compromise in the three parameters shown resulting in a device which can be compensated for the best overall performance.

Figure 3 shows typical uncompensated and compensated temperature coefficients for a diffused diaphragm type integrated sensor. The compensated values are achieved by the use of the circuit techniques described in the following sections.

COMPENSATION OF V_o AND TCV_o

Both half active and fully active bridges are often employed in the manufacture of piezoresistive type transducers. Figures 4 & 5, respectively, show typical, well-proven and effective compensation circuits for the normalization of initial offset V_o and temperature coefficient of offset TCV_o.

Since two parameters are to be adjusted, it is necessary to provide at least two trimming elements. As seen from figure 3, the as-manufactured value of TCV_o is quite low. If the offset were balanced to zero by the addition of a simple series balance resistor R_s, then this low value of TCV_o would be adversely affected. This is because it is most convenient and provides minimum thermal gradient error if a stable near-zero *TCR* balance resistor is employed. Since this resistor is placed in series with a single bridge arm, it effectively reduces the *TCR* of that bridge arm and thus adversely affects the TCV_o. A rule of thumb for the magnitude of this effect is that it is

	UNCOMPENSATED	COMPENSATED
V_E	10 VDC	10 VDC
V_{FS}	100 mv	100 mv ±20 %
TCR	9.5 %/100° F	——
TCS	-4.5 %/100° F	1.0%/100° F
TCVo	-.75 %/100° F	.5 %/100° F
Vo	±50 mv	±3mv

FIGURE 3 PERFORMANCE PARAMETERS FOR TYPICAL INTEGRATED SENSOR

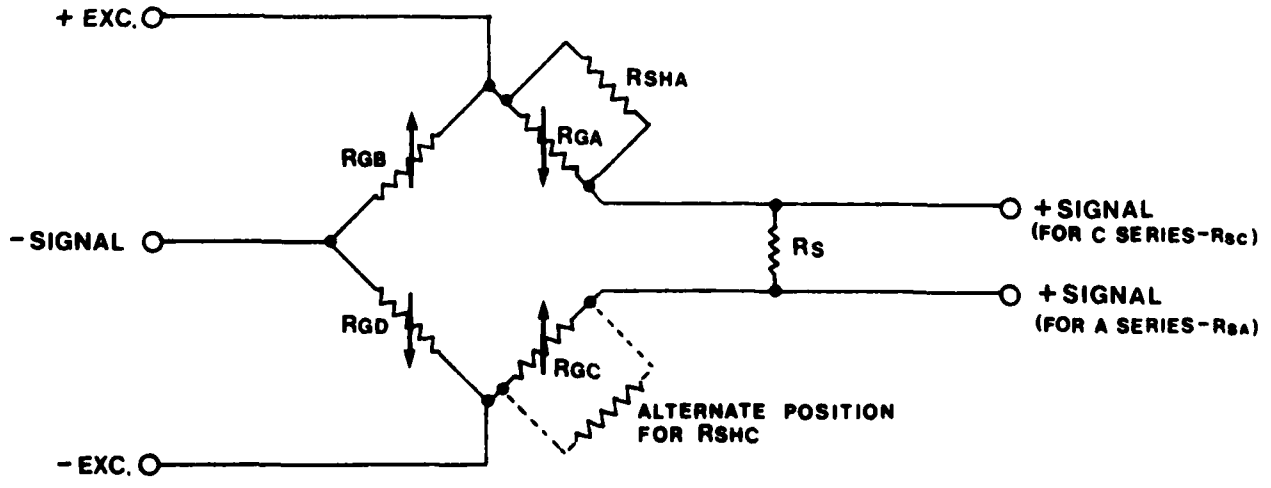

FIGURE 4 5 WIRE ZERO BALANCE AND ZERO COMPENSATION SCHEME FOR FULLY ACTIVE BRIDGE

approximately $V_o \alpha \Delta t$. That is a 50 mv zero offset adjustment applied to a bridge with TCR of 10%/100 °F, causes a TCV_o of 5 mv/100 °F.

If a shunt resistor R_{sh} is employed along with the series resistor, this undesirable effect can be avoided.

Consider the case of a negative offset - this can be corrected with a series in the 'c' leg (as shown in fig 4, active bridge resistors are designated R_g with legs indicated 'a' through 'd', direction of resistance change with applied pressure is designated with arrows); however, this series resistor will reduce the TCR of R_{gc} inducing a negative TCV_o. This may be corrected by balancing one-half the offset with R_{sc} and one-half the offset with R_{sha}. It is seen that R_{sha} also adjusts the offset positively. However, the effect on TCV_o is positive since the TCR of the 'a' leg is reduced. Thus, it is seen that the offset is adjusted without affecting TCV_o. In general, ignoring nonlinearities of parameters and the compensation circuit, two unique values and positions of R_{sh} and R_s can be found such that, V_o is reduced to zero, and TCV_o is made near zero.

The above can be described mathematically as follows:

Consider the strain gage bridge of figure 4 which has an open node between gage legs 'a' and 'c'. When the node is

closed, and an excitation voltage V_e is applied to the input terminals, any unbalance among the four gage legs will produce an offset V_o. When the temperature changes, the unbalance will, in general, also change to produce a shift in offset ΔV_o.

If two resistors R_s and R_{sh} are added to the bridge, the new offset V_o' is given approximately by,

$$V_o' = V_o + P \frac{V_e R_g}{4R_{sh}} - S \frac{V_e R_s}{4R_g} \qquad (1)$$

where, R_g is the average gage resistance for a symmetrical bridge and S and P are location parameters for the compensation resistors. When S or P is +1, the resistor is in the 'a' leg; when S or P is -1, the resistor is in the 'c' leg. At temperatures, other than room temperature, there is a shift in output $\Delta V_o'$ and an associated change in resistance ΔR_g such that,

$$\Delta V_o' = \Delta V_o + P \frac{V_e \Delta R_g}{4R_{sh}} + S \frac{V_o R_s \Delta R_g}{4R_g(R_g + R_s)} \qquad (2)$$

If equations (1) and (2) are now solved for R_s and R_{sh} with the conditions that $V_o' = 0$ and $\Delta V_o' = 0$ then,

$$R_s = \frac{4 S R_g(1+\alpha \Delta t) \left(V_o - \frac{\Delta V_o}{\alpha \Delta t}\right)}{(2+\alpha \Delta t) V_e} \qquad (3)$$

$$R_{sh} = \frac{P\, R_g\, V_e\, (2+\alpha\,\Delta t)}{4\left[V_o + \dfrac{(1+\alpha\,\Delta t)\,\Delta V_o}{\alpha\,\Delta t}\right]} \qquad (4)$$

In these equations $\alpha\,\Delta t = \Delta R_g/R_g$ is the average fractional resistance change with temperature of all gages and S and P are chosen to make R_s and R_{sh} positive. A typical procedure is to first measure V_o and R_g, or more conveniently, the output impedance at some reference temperature (usually room temperature), then raise the temperature to the highest value of the temperature range of interest and measure ΔR_g and ΔV_o. These four quantities, together with V_o, are sufficient to pin the offset to zero at the two temperature points. There will be, in general, some residual or uncompensated null at all other temperatures due to the nonlinearities of the compensation circuit and the temperature coefficients of resistance and offset. However, this offset is typically on the order of .25 mv or less.

To illustrate the computation let,

V_e = 5 V

V_o = +50 mv @ rt

R_g = 350 Ω @ rt

$$V_o = +48 \text{ mv } @ 175\ ^{\circ}F$$

$$R_g = 385\ \Omega\ @ 175\ ^{\circ}F$$

Consequently,

$$\Delta V_o = 48 - 50 = -2 \text{ mv}$$

$$\alpha = \frac{385 - 350}{350(100\ ^{\circ}F)} = .001$$

$$R_s = 10.3\ \Omega$$

$$R_{sh} = 32.8\ \Omega$$

In this example, S is +1 which means that the element R_s is placed in series, with gage 'a' and P is -1, which requires that the shunt element R_{sh} be placed in parallel with gage 'c'. In general, the above ignores the temperature nonlinearity of the parameters TCR and TCV_o and the temperature nonlinearity of the compensation circuit. Since only two values are used to correct these two parameters only an approximation is possible. However, this approximation is found to be quite good and sufficiently accurate for most purposes. If higher degrees of accuracy are required, this can be achieved by the addition of additional passive or active resistive elements.

It is noted that the above compensation is achieved with the use of zero TCR compensation resistors. Compensation

is effected by adjusting the bridge *TCR*, thus the bridge is the only temperature sensitive element in the network. This is known as passive compensation and is an important concept. It is seen that it is unnecessary for the compensation resistors to be at the same temperature as the bridge. Since these resistors are, in general, placed at a different location in the transducer package than the bridge, the use of this technique avoids errors associated with thermal gradients between the compensation module and the transducer pressure sensitive diaphragm.

One half active bridge networks are often used in integrated sensor transducers. It is important for proper temperature performance that such a bridge be made up of two gages, one of which has a positive response to applied pressure, and one of which has a negative response, for instance, R_{ga} and R_{gc}. Such a bridge is readily compensated by the circuit shown in fig 5. This circuit has the significant advantage that the shunt balance resistors R_{shb} and R_{shd} effect offset adjustment independent of adverse effects on TCV_o. This is because the offset is adjusted by shunting the inactive legs R_{cb} or R_{cd} which are low *TCR* bridge completion resistors. Otherwise, the technique is similar in concept and execution to the 5 wire compensation technique described above. The temperature compensation for zero offset change of a half

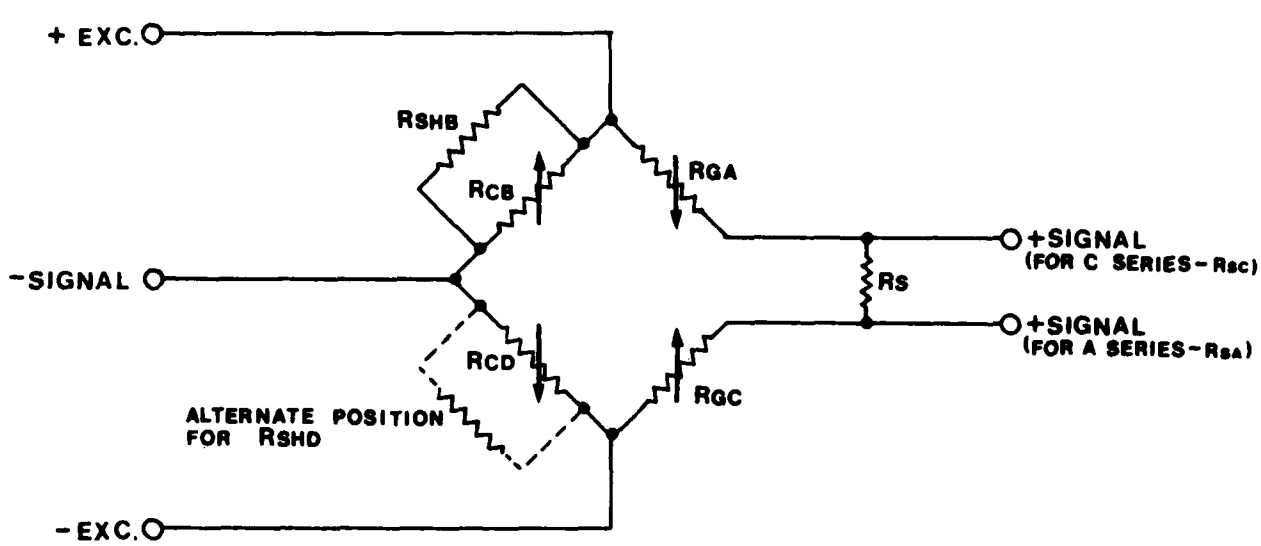

FIGURE 5 6 WIRE ZERO BALANCE AND ZERO COMPENSATION SCHEME FOR ONE HALF ACTIVE BRIDGE

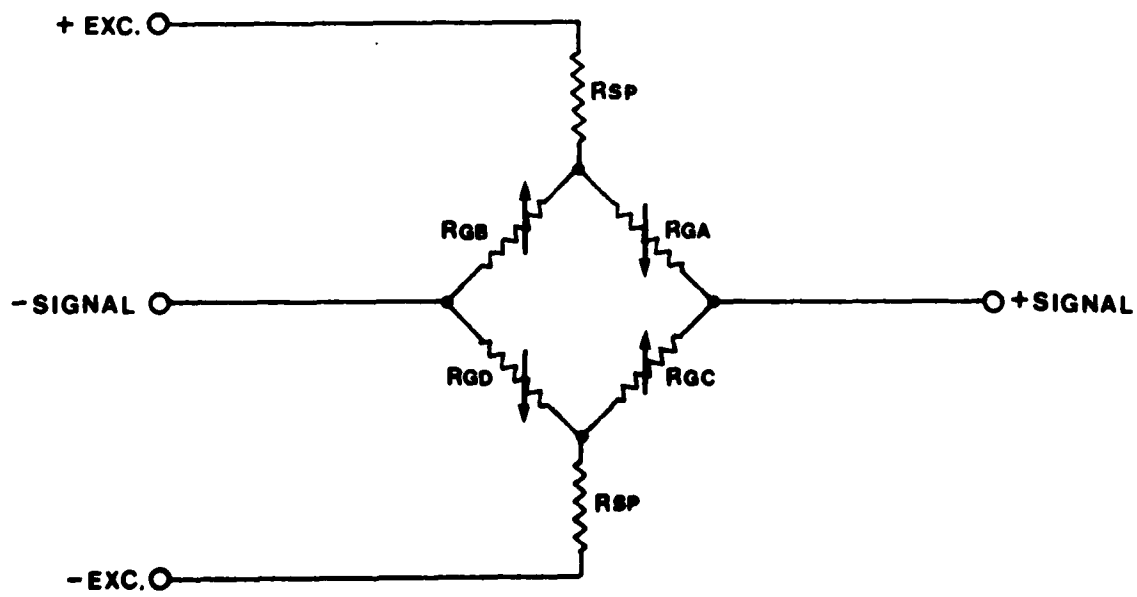

FIGURE 6 PASSIVE TCS COMPENSATION SCHEME

bridge of only two active gages, and two passive completion resistors is accomplished somewhat more simply than the compensation of a fully active bridge. The half active bridge of fig 5 is tested for convenience with two equal completion resistors R_{cb} and R_{cd}. As before, the offset V_o and the average gage resistance R_g is measured at two temperatures. R_g can be conveniently measured indirectly by measuring the bridge input resistance R_b and using the relationship,

$$R_b = \frac{2 R_g R_c}{R_g + R_c} \tag{5}$$

A series resistor R_s is used to adjust the TCR of the gage having the higher TCR. As in equation (1), V_o' is given by,

$$V_o' = V_o - S \frac{V_e R_s}{4 R_g} \tag{6}$$

$$\Delta V_o' = \Delta V_o + S \frac{V_e R_s \Delta R_g}{4 R_g (R_g + \Delta R_g)} \tag{7}$$

Solving equation (7) for R_s with $\Delta V_o' = 0$,

$$R_s = - \frac{4 S R_g \Delta V_o' (1+\alpha \Delta t)}{V_e \alpha \Delta t} \tag{8}$$

Using relation (5), the gage TCR (α) can be replaced by the effective bridge input TCR (α_b), as follows,

$$\alpha_b = \frac{\Delta R_b}{R_b} = \frac{R_c \, \alpha \, \Delta t}{R_c + R_b \, (1+\alpha_b) \, \Delta t} \tag{9}$$

Equation (8), can now be expressed as,

$$R_s = \frac{2 \, S \, R_b \, \Delta V_o \, (1+\alpha \, \Delta t)}{V_e \, \alpha \, \Delta t} \tag{10}$$

Once R_s is selected to compensated ΔV_o, the original offset V_o changes to a new value V_o' but remains essentially independent of temperature. An appropriate completion resistor R_{cb} or R_{cd} can be shunted to adjust V_o' to zero without disturbing the null shift compensation. Null compensation of a half bridge is accomplished by this circuit by choosing two elements R_s and R_{sh} simultaneously without the inconvenient interaction between V_o and TCV_o found in the five wire circuit.

Both of the above techniques are generally implemented by the use of a computer algorithm. In general, transducers are tested for relevant temperature parameters and the compensation resistors are chosen and hard wired into the circuit. Most families of integrated sensors are sufficiently repeatable in their uncompensated temperature parameters that room temperature data only need be taken with known values used

for TCR and TCV_o. The algorithm is sufficiently accurate that compensation is normally achieved on the first try as verified by a subsequent acceptance testing.

COMPENSATION OF *TCS*

The temperature coefficient of sensitivity *TCS* of integrated sensors is intrinsically temperature sensitive and typically linear in temperature with a negative coefficient *TCS* of the order of -4.5%/100 °F. Consequently, such transducers will exhibit a full scale output voltage at full scale applied pressure which decreases with increasing temperature for fixed excitation voltage V_e. The full scale bridge output V_{fso} can be expressed as,

$$V_{fso(t)} = V_{b(t)}\ V_s\ V_{fso}\ (1+B\Delta T) \qquad (11)$$

where,

V_b is the bridge voltage

B is the fractional change in V_s per °F

ΔT is the change in temperature $(t - t_o)$ relative to the reference temperature t_o

TCS compensation is a simple circuit technique in which a span resistor R_{sp} is placed in series with the bridge input and a constant voltage source V_e . Since bridge resistance R_b typically increases with temperature, the voltage divider effect generates a temperature varying bridge voltage V_b which matches the rate of decrease of V_{fso}. From the circuit of fig 6, V_b is seen to be,

$$V_b = V_e \frac{R_{b(t)}}{R_{b(t)} + R_s} \tag{12}$$

where R_b is a linear function of temperature given by,

$$R_{b(+)} = R_{bo} (1+\alpha_b \Delta T) \tag{13}$$

The variation of output voltage with temperature is obtained by combining equations (10 thru 13) and is given by,

$$\Delta V_{fso} = \frac{\left[(1-Z) \alpha_b - B \right] \Delta T - \alpha_b B \Delta T^2}{1 + Z \alpha_b \Delta T} \tag{14}$$

where,

$$V_{fso} = V_e Z V_s \quad @ \quad t = t_o \tag{15}$$

$$Z = \frac{R_{bo}}{R_{sp}\, R_{bo}} \tag{16}$$

Now, $\Delta V_{fso} = 0$ @ $t = t_o$ and, if Z is chosen such that ΔV_o is zero at some higher temperature t_c, then Z is given by,

$$Z = \frac{B\ (1+\alpha_b\ \Delta T_c)}{\alpha_b} \tag{17}$$

$$R_{sp} = \frac{R_{bo}\ B\ \ (1+\alpha_b\ \Delta T_c)}{\alpha_b - B\ (1+\alpha_b\ \Delta T_c)} \tag{18}$$

Inserting this value of R_{sp} into equations (14) and (15), we have,

$$\frac{\Delta V_{fso}}{V_{fso}} = \frac{\alpha_b\ B\ (t - t_o)\ (t_c - t)}{1 + \left[\alpha_b - B\ \ (1+\alpha_b\ \Delta T_c)\right]\Delta T} \tag{19}$$

$$V_{fso} = V_e\ V_s \left[1 - \frac{B\ \ (1+\alpha_b\ \Delta T_c)}{\alpha_b\ \Delta T_c}\right] \tag{20}$$

@ $t = t_o$ or $t = t_c$

Equation (20) represents the residual span shift with temperature after compensation as shown in fig 7. It is appoximately quadratic in temperature being zerc at the temperature t_o and t_c, and passing through a positive maximum at the mid

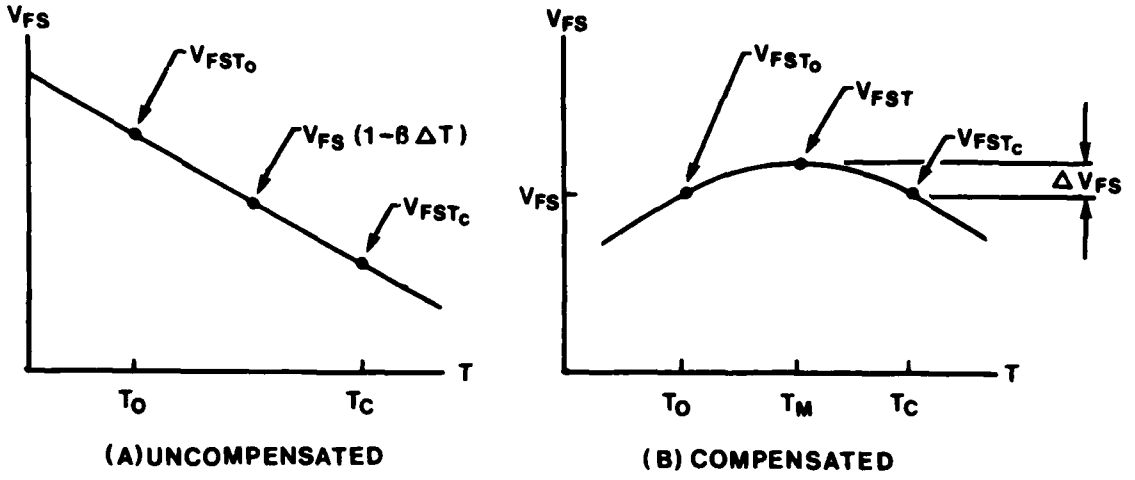

FIGURE 7 COMPENSATED AND UNCOMPENSATED TCS FOR INTEGRATED SENSOR

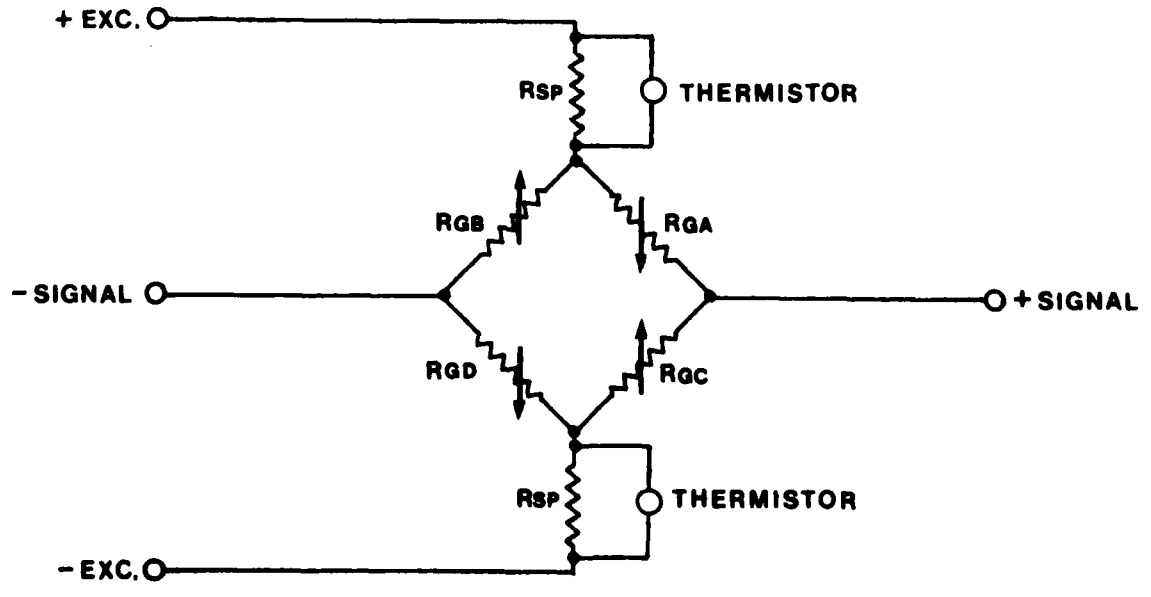

FIGURE 8 ACTIVE TCS COMPENSATION SCHEME

temperature $T_m = 1/2\ (t_o + t_c)$ at which point,

$$\Delta V_{fso} = \frac{V_o \alpha_b B\ (t_c - t_o)^2}{4} \qquad (21)$$

Now the parameter Z must be less than unity for a bridge to be span compensated with a temperature insensitive resistor R_{sp} and the constant voltage excitation. From equation (18) it is clear that the bridge TCR (α_b) must be greater than the transducer TCS. Inspection of fig 2 will show the impurity concentrations for which this is achievable. The closer α_b and B approach each other, the larger R_{sp} must be employed for compensation and the lower the compensated output V_{fso}, for a given excitation V_e. As R_{sp} is increased, the condition of constant current excitation is approached.

The quantities α_b and B are derivable from measured data or, more usually, from previously known standard values for a given design of a given impurity concentration.

As a numerical example let,

$V_e = 10$ volts

$t_o = 75\ ^oF$

$t_c = 175\ ^oF$

$\Delta T = 100\ ^oF$

V_{fso} = 240 mv @ 75 °F

R_{bo} = 500 Ω @ 75 °F

V_{fso} = 228 mv @ 175 °F

R_{bc} = 550 Ω @ 175 °F

Then, by using the above equations, we can calculate,

R_s = 611 Ω From Equation (18)

Z = .450 From Equation (19)

V_{fso} = 108 mv

ΔV_{fs} = .135 From Equation (21)

Thus, the original room temperature output V_{fso} of 240 mv and the -5%/100 °F TCS will be reduced to 108 mv at 75 °F and 175 °F. Using equation (21), we can construct a table of residual shifts after compensation with R_{sp} = 611 Ω.

TABLE I - COMPENSATED OUTPUT vs. TEMPERATURE

TEMPERATURE	UNCOMPENSATED	COMPENSATED
25 °F	246.00 mv	107.59 mv
75 °F	240.00 mv	108.00 mv
125 °F	234.00 mv	108.13 mv
175 °F	228.00 mv	108.00 mv
225 °F	222.00 mv	107.59 mv

It is noted that the above compensation of *TCS* is fairly linear. This analysis assumes a linear *TCR* and TCV_o. For the relatively degenerate doping levels employed at Kulite, this is a good assumption. For wider temperature ranges of certain special cases, the nonlinearity of these parameters must be considered. This linearity can be improved especially over an extended temperature range -65°F to 325 °F by use of additional temperature active components such as thermistors, linear negative resistors or positive temperature coefficient resistors. Since such components are used only to trim the nonlinearity of compensated *TCS*, their effects are small and thermal gradient errors can be neglected.

If such active components, however, are used to achieve most of the compensation for *TCS*, thermal gradient errors can be an important factor.

Referring to fig 2, it is seen that maximum sensitivity at realistic values of surface concentration is achieved only with $B < \alpha$. For such a situation, the active compensation circuit of fig 8 is commonly employed. Such a circuit performs quite well over a limited temperature range but is quite nonlinear over an extended temperature range, particularly, at very low temperatures (-65 °F). Moreover, since the thermistors must be at the same temperature as the diaphragm, it is very sensitive to thermal gradient errors. Assume the thermistors are placed in the body of the transducer and a 50 °F gradient exists between the diaphragm and the compensation components due to transient heating, for instance, as the air in a wind tunnel warms up. Assuming an uncompensated TCS of -10%/100 °F, the error in the measured dynamic pressure would be 5%. If the temperature sensor is placed at the diaphragm, this error can be greatly reduced.

ON-CHIP COMPENSATION

It can be seen from fig 3 that the uncompensated value of TCV_o for an integrated sensor transducer is quite low. The zero compensation scheme presented in this paper is in effect a method of adjusting the offset without adversely affecting TCV_o by the addition of external near zero balance resistors. The device shown in fig 9 contains on-chip

balancing resistors which are arranged in a binary ladder configuration. These resistors may be selected by a proprietary technique to effect a bridge balance. Such a technique allows the bridge zero offset to be reduced to near zero without affecting TCV_o because the balance network is fabricated simultaneously with the piezoresistors and has a near identical *TCR*. This technique has proven to be quite effective and is in current high volume production for medical, consumer, and military applications. If constant current excitation is employed and the impurity concentration is appropriately chosen, then a completely compensated device meeting the performance specifications listed below can be manufactured without the use of compensation resistors. Such a device is typically supplied, mounted in a TO-5 can for high volume, low-cost applications.

Pressure Range	5-1000 psi
I_e	1.5 ma
V_{fso}	200 mv
V_o	3% V_{fso}
TCV_o	1%/100 °F
TCS	1%/100 °F
Temperature Range	0 °F to 200 °F

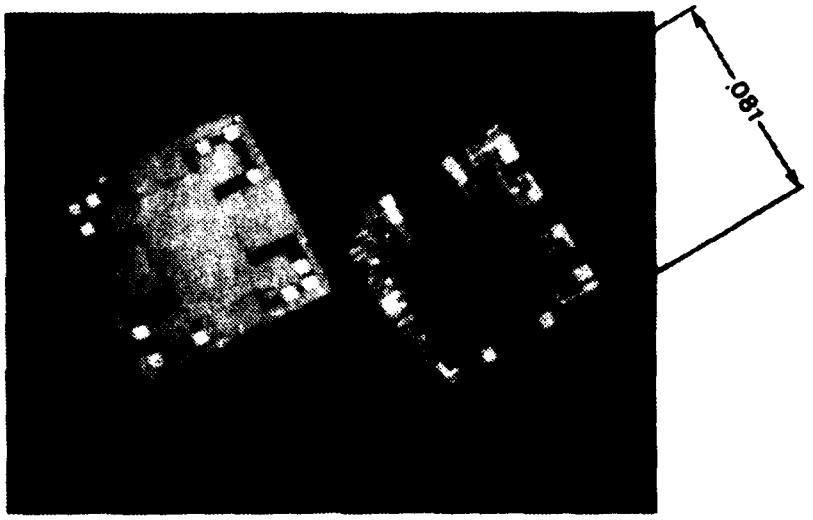

FIGURE 9 MICROPHOTOGRAPH OF INTEGRATED SENSOR WITH ON-CHIP COMPENSATION AND NORMALIZATION

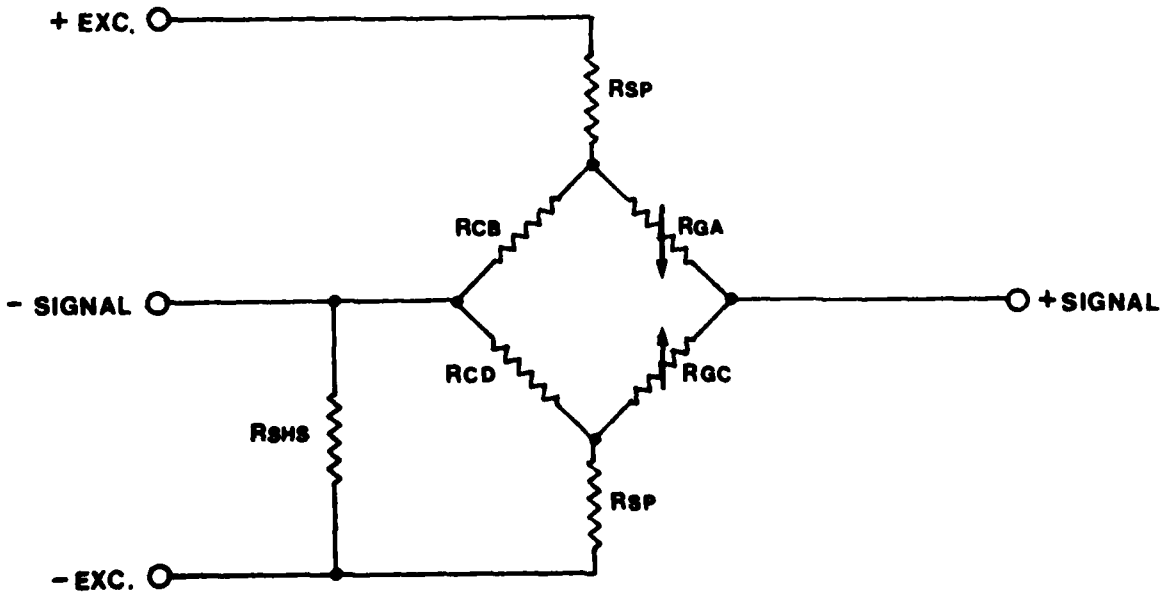

FIGURE 10 SHUNT CALIBRATION CIRCUIT FOR ONE HALF ACTIVE BRIDGE

This technique which is described in ref 16, represents a significant advance in the state of the art. Temperature compensation using this technique will be employed in a broad line of product as the technology evolves.

SHUNT CALIBRATION

Shunt calibration is the addition of a resistor across a single bridge arm to produce an output V_{sso} usually 80% of full scale for the calibration of signal conditioning circuits or amplifiers.

It is generally understood that semiconductor transducers are not suitable for shunt calibration. This is because of the substantial bridge TCR associated with these devices. If a resistor is chosen such as to produce an appropriate shunt calibration output V_{sso} at room temperature, then this resistor will produce an output V_{sso} in substantial error at other temperatures due to the change of bridge resistance with temperature. However, for a transducer employing a one half active bridge this is not true. If the shunt calibration resistor R_{shs} is placed across the inactive completion side of the bridge, then it is found that the temperature error vanishes. A suitable circuit is shown in fig 10.

For a fully active bridge circuit which includes span compensation resistors R_{sp} a shunt R_{shs} placed from the positive excitation terminal to the positive signal terminal produces an output voltage V_{sso}.

$$V_{sso} = \frac{V_e R_g}{2 (R_g + R_{shs}) + R_{sp}} \tag{22}$$

If a specific voltage V_{sso} is required, usually some percentage of full scale output, then R_{shs} is calculated as,

$$R_{shs} = \frac{R_g}{2} \left[\frac{V_e - 1}{2 V_{fss}} \right] - \frac{R_{sp}}{2} \tag{23}$$

As an example let,

$R_g = 500\ \Omega$

$R_{sp} = 1000\ \Omega$

$V_e = 10$ volts

$V_{fso} = 100$ mv

$V_{sso} = 80$ mv = .088 v

The value of R_{shs} required to produce a voltage V_{sso} of 80% of full scale output (V_{sso} = 80 mv) is given by,

$R_{shs} = 13.56\ K\Omega$

Such a resistor, however, will not produce an output that is independent of temperature due to the bridge TCR of typically 10%/100 °F. According to equation (22), the output voltage V_{sso} will increase at about the same rate.

In the case of a half bridge, however, the shunt can be connected across a completion resistor R_{cd} as in fig 10, equation (22) then becomes,

$$V_{sso} = \frac{V_e R_{gc}}{2 (R_c + R_{shs}) + 4 R_{sp}} \qquad (24)$$

and the calibration is temperature independent.

This has been verified, and experimental results show that a given shunt calibration resistor produces an output V_{sso} essentially independent of temperature.

In general, all transducers manufactured by Kulite can be supplied with this type of shunt calibration circuit, and with specified values of R_{shc} for plus or minus 80% of full scale. Transducers which are normally supplied in a full bridge configuration may require a reduction of up to half the full scale sensitivity.

CONCLUSION

The technique presented in this paper represents the most common of the various methods of temperature compensation developed at Kulite over the last twenty-five years. Of course, the broad range of products available often require a variety of special compensation techniques including active compensation, compensation with electronic circuits, cryogenic and high temperature compensation, special techniques for controlling common mode voltage, input and output impedance, and microprocessor based compensation. Passive circuit techniques also exist for controlling pressure nonlinearity (ref 17).

The techniques discussed here, however, account for 70 to 90% of transducers produced at the authors' institution. It is hoped that the detailed discussion of these circuits are of interest and of value to the community of transducer users.

REFERENCES

1) The term Integrated Sensor® is a registered trademark of Kulite Semiconductor Products. The term is meant to indicate a structure with an integrated piezoresistive element and a force collector manufactured by integrated circuit techniques.

2) Venture Development Corp., "The Pressure Transducer and Transmitter Industry: A Strategic Analysis, Second Edition", Sept. 1982.

3) Mallon, J.R., Kurtz, A.D., Bernstein H., "A Solid State Bonding and Packaging Technique for Integrated Sensor Transducers", Presented at the ISA Aerospace Instrumentation Symposium, May 1973, Las Vegas, Nevada.

4) Kurtz, A.D., "Adjusting Crystal Characteristics in Semiconductor and Conventional Strain Gages", Academic Press, New York, New York pgs. 259-272, 1961.

5) Kurtz, A.D. and Gravel, C.L., "Semiconductor Transducers Using Transverse and Shear Piezoresistance". Presented at the 22nd ISA Conference and Exhibit, Sept. 1967, Chicago, Illinois.

6) Mallon, J.R., Kurtz, A.D., "Static Performance of Integrated Sensor Transducers", Presented at the Twenty-Fifth International Aerospace Instrumentation Symposium, May 1979.

7) Mallon, J.R., Germanton, D.C., "Advances in High Temperature Ultra-Miniature Solid State Pressure Transducers", Presented at ISA Silver Jubilee Conference, Oct. 1970. Philadelphia, Pennsylvania.

8) Kurtz, A.D., Kicks, J.C., "Development and Application of Ultra-Miniature Pressure Transducers for Use in Wind Tunnel Measurements, Part I and II", Presented at the Aerospace Instrumentation Symposium, May 5-7, 1969, Las Vegas, Nevada.

9) Kurtz, A.D., "The Design and Fabrication of Transducers for the Measurement of Fluctuating Pressures from DC to over 100 kHz in Jet Engine Testing", Presented at the ISA Aerospace Instrumentation Symposium, May 1971, Las Vegas, Nevada.

10) Gravel, C.L., Mallon, J.R., "Sensing with Semiconductors", Industrial Research, March 1971.

11) Mallon, J.R., Nunn, T.A., Kurtz, A.D., "Piezoresistive Shear Gage", Presented at the First Symposium on Gages and Piezoresistive Materials", Sept. 1981, Arcachon, France.

12) Mallon, J.R., Kurtz, A.D., Nunn, T., "Microfabricated Structures for Silicon Piezoresistive Transducers", Presented at The Second International Conference on Solid State Transducers". June 1983, Delft, The Netherlands

13) Petersen, J. "Silicon as a Mechanical Material". Proceedings of the IEEE, 70, 5, May 1982.

14) Staff, R.T.I., "Integrated Silicon Device Technology Volume V - Physical/Electrical Properties of Silicon", July 1964. Dept. of Commerce AD-605 558.

15) Brosh, A., "Miniature Pressure Transducers for Use in Wind Tunnel Models", Presented at the 17th International ISA Aerospace Instrumentation Symposium, Las Vegas, Nevada, May 1971.

16) Mallon, J.R., Kurtz, A.D., "Binary Balancing Appartus for Semiconductor transducer Structures", U.S. Patent 4,333,349, filed Oct. 1980.

17) Kurtz, A.D., "Compensated Pressure Transducer Employing Digital Processing Techniques", U.S. Patent 4,192,005, filed Nov. 1980.

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APPLICATION OF THE SMALL BODY PRESSURE TRANSDUCER

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APPENDIX A

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ABSTRACT

The small body pressure transducers were used in both fixed-wing and rotary-wing scale models to measure dynamic and static pressures. These models were then tested under controlled wind tunnel conditions and the transducer signals recorded for either on- or off-line analyses.

One experiment using the small body pressure transducers was conducted in the American Aeromechanics Wind Tunnel (7 × 10 #2, NASA Ames, Moffett Field) in order to compare different geometrically shaped rotary-wing airfoil sections under dynamic stall conditions. An additional application for the small body pressure transducer was a series of tests conducted in both the French Tunnel, Saclay, France, (~~CEPRA 19~~) and the Dutch-German Amsterdam, The Netherlands (DNW) wind tunnel. During the foreign tests, data were obtained on helicopter rotor noise generated by blade pressure disturbances due to helicopter blade-vortex interaction. Both the acoustic signature and the blade pressure transducer outputs were recorded simultaneously. In all of these experiments, special purpose electronic and mechanical hardware for the small body pressure transducers was developed.

INTRODUCTION

The need for determining the pressure distribution on aerodynamic shapes both in wind tunnel and in full-scale flight tests has brought about a steady evolution in both the mechanical design and the electrical properties of the pressure transducer. Twenty-five to thirty years ago, the majority of wind tunnel pressure surveys were for static measurement only. These measurements were taken with liquid manometers that, for the most part, were either read manually or photographed for later analysis. In the early 1950s, a project was undertaken at the NACA Ames Aeronautical Laboratory and other centers around the country to develop and apply a technique whereby dynamic pressures could be measured. Previously, these unsteady pressures could not be recorded on liquid manometers. The resulting efforts at Ames developed a series of pressure transducers starting with a single active leg, going to a half bridge, and then to a full bridge in the form of a "bud" rosette gauge. The full-bridge transducers were powered by the CEC 20KC carrier equipment, and the output was recorded on Consolidated Electrodynamics Corporation (CEC) oscillographs. These pressure transducers were 1/4 in. diameter by 1/8 in.

deep with the strain gauge bonded to the interface of a stainless steel diaphragm. This diaphragm was then spot-welded to the case body. In the case of either the single leg or the one-half bridge transducer, the bridge completion resistors were mounted near the transducer on a steel block; if precision resistors were used, they were located on the inner surface of the model. The desire was to keep temperature effects to a minimum.

In the 1950s, a big step forward in transducer development came with the advent of the piezoresistive-semiconductor gauges that opened a whole new field for development. Such representative entrepreneurs as Micro-Systems and Kulite-Bytrex and then Schaevitz-Bytrex and Kulite in the 1960s led the way in the development of this new technology. They were able to supply the testing market with a valuable new tool which had great potential. The current transducer state of the art offers many advantages including small size, high output, and both static and dynamic response. The major objective of this paper is to report two recent small body pressure transducer applications and some of the hardware developed for improved calibration and monitoring techniques.

EXPERIMENTAL RESULTS

A. Oscillating Airfoil Studies

An oscillating airfoil test using the small body pressure transducer was conducted in the 7- by 10-foot wind tunnel at NASA Ames Research Center (ARC). This test used the Kulite model YQCH-250-1 and YQCH-093-15D pressure transducers (Fig. 1). The purpose of the test was to determine the dynamic stall characteristics of the advanced rotary-wing airfoil sections.[1] Twenty-six Kulite transducers were distributed over the upper and lower surfaces of eight different geometrically shaped airfoil sections (Figs. 2 and 3). These transducers were differential in type and referenced to tunnel total pressure. Each transducer was powered by 5 VDC and the output balanced for zero voltage whenever the differential pressure was known to be zero. The signal was then filtered and gained for recording on an Ampex 32 channel analog magnetic recorder (Fig. 4).

Transducer calibrations were performed at 8- to 10-hr intervals. A set of starting zeroes was taken after tunnel warmup and again after each run (20 min). This procedure was to maintain a good DC zero reference level for measuring both steady and unsteady loads on the airfoil sections. Specifically, the calibration process made use of the pressure stepping ability of a Scanivalve (model SGM), a commutator, and a step-drive system (Fig. 5, Appendix A). The adaption of the Scanivalve allowed the rapid stepping of a multilevel pressure source without disconnecting any tubing, and then returned the transducers back to an operating reference pressure (P_T). Replacing the normal transducer in the Scanivalve with a dummy plug allowed six preset pressures to be ported out to a manifold which connected the reference side of all the

small body transducers. The pressure regulators were used to establish a nominal pressure value for each step. The absolute value of each step pressure was measured by means of the Parascientific Model 600 pressure computer, and with a quartz reference transducer connected in the pressure line between the Scanivalve and the model reference manifold. Of particular note was the outstanding durability of the small body transducers used in this test. The duration of tunnel occupancy for the model and the transducers was slightly over 1 yr. Following an initial shakedown run, during which several units were replaced, there were no further transducer failures during this period. (These initial failures during the shakedown were due to broken wires and occurred at the time of installation.)

An outstanding piece of electronics hardware that was developed for the oscillating airfoil program is the on-line pressure profile monitor (Fig. 6, Appendix A). It was designed and built by Don Humphry of the Electronic Development Branch, ARC. This instrument allows the operator to visually monitor any 10 pressure transducers at one time, for either the upper or lower surface of the model (Fig. 2). The resulting data are presented on a CRT of any standard laboratory oscilloscope. The display is calibrated for psi along the y-axis and for x/c transducer location along the x-axis. Ten pressure transducers could be selected and displayed as a continuous line representing the pressure profile at a predetermined angle of attack of the model in the air system. The airfoil motions are generated by means of a mechanical device (Fig. 7) and are controlled in both amplitude and rate of oscillation.

Helicopter Blade-Vortex Interaction Study

Two sequential wind tunnel tests were conducted using the small body pressure transducers, model XCQ-63-093-25A and the model XCQ-65-096-10D (Fig. 8). The purpose of these tests was to study the scaling of helicopter blade-vortex interaction. The first test was conducted in CEPRA 19 anechoic wind tunnel configured with a 3-m open test section.[2] (CEPRA 19 is located south of Paris, near Saclay, France.) The second wind tunnel test was conducted in the new DNW wind tunnel, an aerodynamic and aeroacoustic low speed facility.[3] (The DNW is a German-Dutch cooperative project, located northeast of Amsterdam, The Netherlands.)

The rotor stand (Fig. 9), which was used to mount and run the rotor blades, was designed and built for the U.S. Army Aeromechanics Laboratory, ARC.[4] Also, two instrumented pressure blades for these tests (Figs. 10 and 11) were fabricated and instrumented with small body transducers at ARC.

A method was devised to select and to precalibrate all of the pressure transducers that were installed into the two rotor blades. This preinstallation calibration determined the transducer response to pressure in units of volts per psi, and the sensitivity to both temperature and time (see Appendix B for typical calibration format). With few exceptions it was found that the transducers were well matched and the

assignment of position of transducers on the rotor blade presented no problem. After the transducers were installed on the rotor blade and the blade then mounted on the rotor stand, an end-to-end calibration technique was devised whereby all absolute transducers could be calibrated at one time. This procedure allowed setting excitation voltages to produce a common-slope calibration for all transducers, both absolute and differential, thereby giving on-line quantitative monitoring of blade pressure responses. This end-to-end calibration device consisted of a clear plastic cylinder which could be sealed at both ends. The cylinder is shown enclosing the blade instrumented with absolute pressure transducers in Fig. 12. This cuffing technique for calibration had been tried in the past but with little success. Appropriate attention to blade construction, transducer installation, and calibrator design resulted in leak-free pressure calibrations, making it simple to simultaneously and accurately calibrate many transducers.

The sealed calibration cylinder was pneumatically connected to a volumetric pressure piston and monitored by a Parascientific Model 600 pressure computer, using a 15 psid quartz transducer as a reference (Fig. 13). A series of 0.5 psi reducing pressure steps was generated and the transducer outputs were recorded on a 32-channel Ampex tape recorder. The transducer signals were gained to match the recorder level of 1 V rms for the largest Δp step of approximately 4 psid. The recordings were made at 30 ips and FM wide Band 1, which allowed a playback band pass of 20K Hz.

The end-to-end calibration for the second blade, which was instrumented with differential pressure transducers, presented a more complex problem as the sealed volume calibrator technique inherently would not work. The problem for the differential transducers occurred because there was no practical way to seal one side of the transducer. Many techniques and materials including various types of tape were attempted but always induced zero shifts that could not be calibrated. All tapes that were tested resulted in deformable cavities under pressure at the orifice opening and the transducer diaphragm never returned to original zero condition. Therefore, a transducer-by-transducer calibration was performed instead. A corollary technique for simultaneous calibration of blade-installed differential (both sides open) small body transducers is still needed.

The transfer of data from the rotating blade system was made possible by means of a 156-channel, high speed, Poly-Scientific slip-ring. An important requirement in the use of this slip-ring was to maintain a very clean brush-to-ring environment. Both the CEPRA 19 and the DNW wind tunnel tests were conducted using the same slip-ring assembly and without any channel failures. The slip ring used during these tests proved to be a well-manufactured unit and was maintained by flushing the slip-ring brush areas on a regular basis. Specifically, after every 20 hr of use, a mixture of one part synthetic oil (Exxon 2380) and nine parts freon was forced into the contact area and allowed to drain.

CONCLUSION

The small body pressure transducer has proven to be a very useful tool in the acquiring of both static and dynamic data. With the advent of the piezoresistive-semiconductor gauge, the state of the art in pressure measurements has increased in such areas as pressure range, sensitivity, and in the reduction of physical size of transducers. These improved properties have allowed the test engineer to more reliably measure and monitor the physical changes taking place in the test environment. In addition, the interfacing instrumentation has also kept pace with this change and has enabled the engineer to monitor, to record and to accurately calibrate, the transducer prior to and during its application in a test situation.

REFERENCES

[1]McCroskey, W. J., McAlister, K. W., Carr, L. W., Pucci, L., Lambert, O., and Indergand, R. F., "Dynamic Stall on Advanced Airfoil Sections," Paper presented at the 36th Annual Forum of the American Helicopter Society, Washington, D.C., Vol. 26, No. B, July 1981, pp. 40-50.

[2]Schmitz, F. H., Boxwell, D. A., Lewy, S., and Dahan, C., "A Note on the General Scaling of Helicopter Blade-Vortex Interaction Noise," Paper presented at the 38th Annual Forum of the American Helicopter Society, Anaheim, California, May 1982.

[3]Seidel, M. and Maarsingh, R. A., "Test Capabilities of the German-Dutch Wind Tunnel DNW for Rotor, Helicopter and V/STOL Aircraft," Paper presented at the 5th European Rotorcraft and Powered Lift Aircraft Forum, Paper No. 17, Sept. 1979, Amsterdam, The Netherlands.

[4]Laub, G. H., "A Unique Drive System for Testing Model Scale Rotors," Article in VERTIFLITE, Vol. 29, No. 2, Jan./Feb. 1983, pp. 50-51.

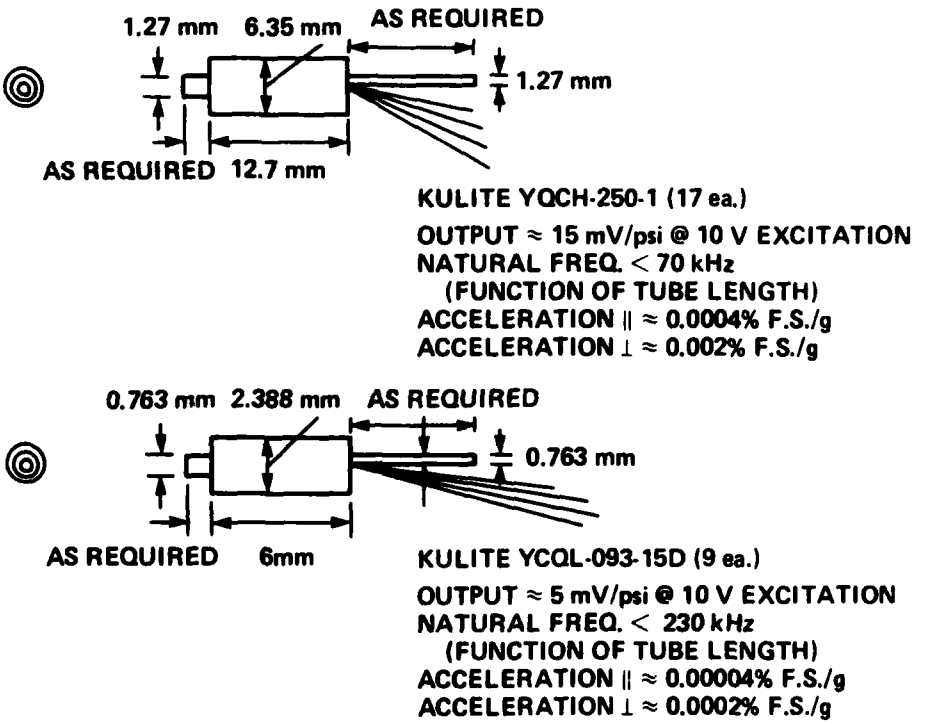
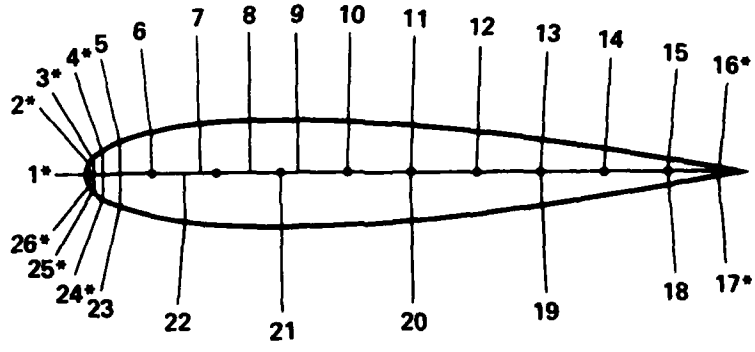


Figure 1 Pressure transducers for oscillating air foil



=	X/C	=	X/C	=	X/C	=	X/C
1	0.000	8	0.250	15	0.900	21	0.300
2	0.005	9	0.325	16	0.980	22	0.150
3	0.010	10	0.400	17	0.980	23	0.050
4	0.025	11	0.500	18	0.900	24	0.025
5	0.050	12	0.600	19	0.700	25	0.010
6	0.100	13	0.700	20	0.500	26	0.005
7	0.175	14	0.800				

TRANSDUCERS USED YQCH-250-1
AND YCQL-093-15D*

Figure 2 Upper and lower surface pressure transducer locations for all eight stall models

Figure 3 Installing transducers in the oscillating airfoil

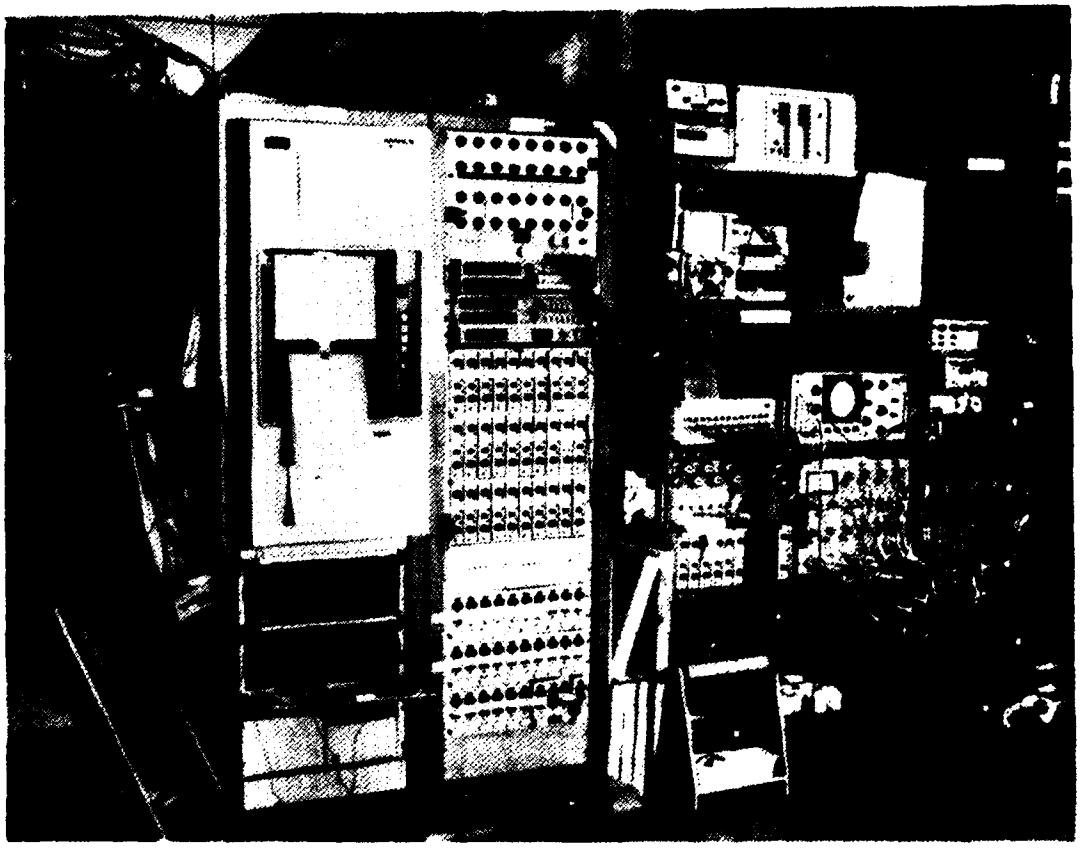


Figure 4 Electronics involved in monitoring and recording data signals

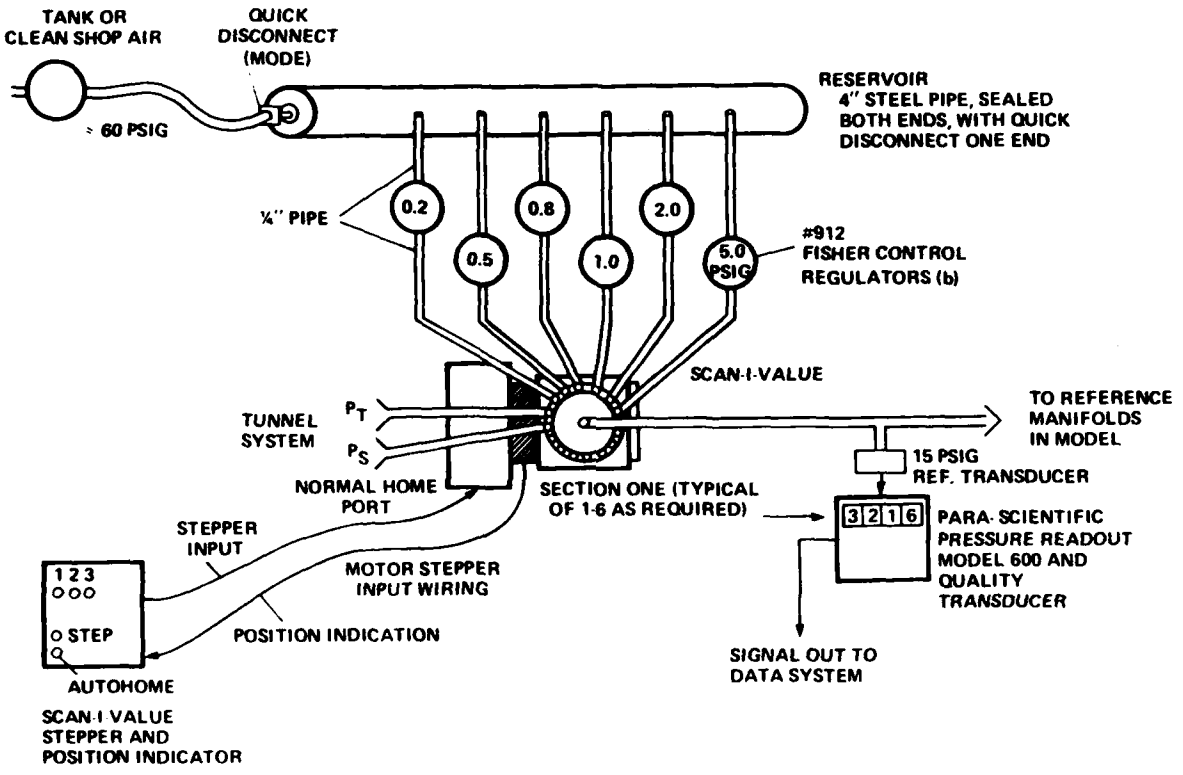


Figure 5 Pressure calibration stepping device

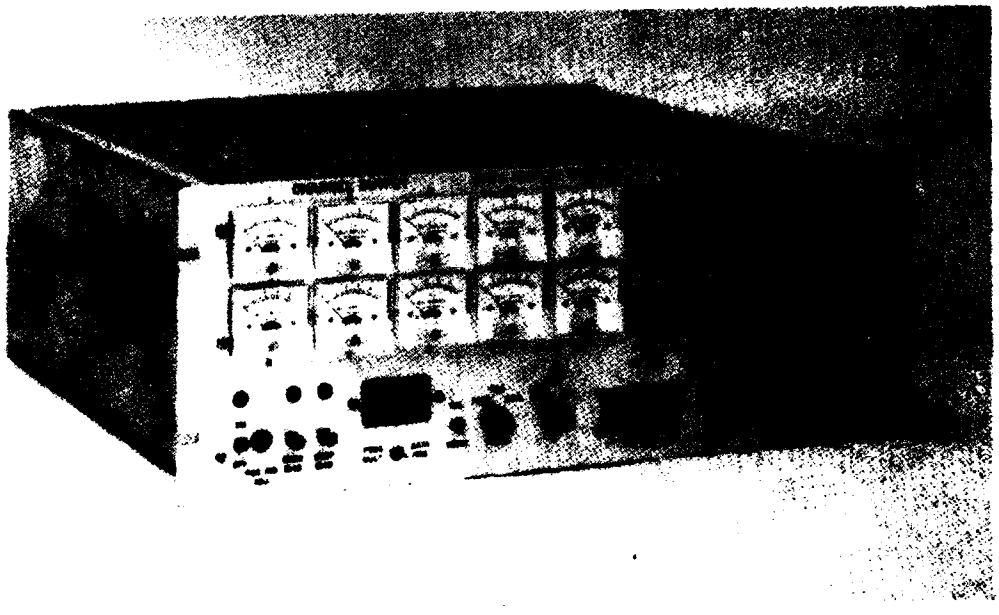


Figure 6 On-line pressure profile monitor

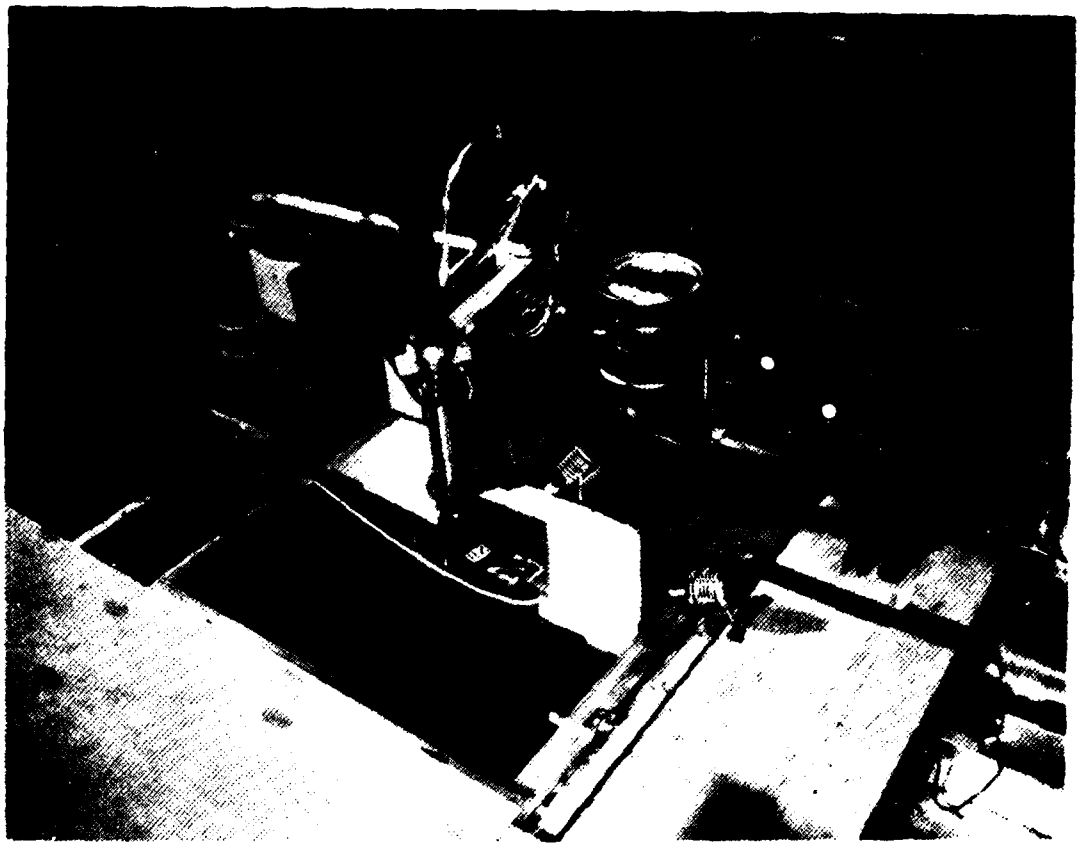
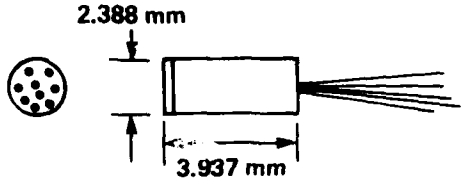


Figure 7 View of mechanical device to drive oscillating airfoil

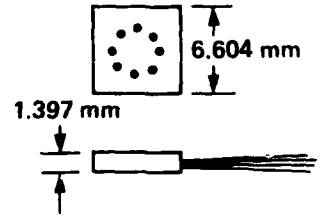
• ABSOLUTE PRESSURE TRANSDUCERS (BLADE #1)



KULITE XCQ-63-093-25A MOD. 2
USED WITH "M" SCREEN (29 ea.)

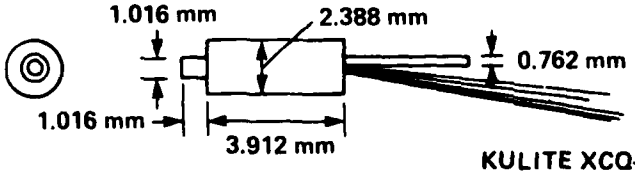
OUTPUT ≈ 1.5 mV/psi @ 10 V EXCITATION
NATURAL FREQ. ≈ 230 kHz
ACCELERATION ∥ ≈ 0.00004% F.S./g
ACCELERATION ⊥ ≈ 0.0002% F.S./g

KULITE FLAT PACK
LQS-34-125-15A (3 ea.)



OUTPUT ≈ 5 mV/psi @ 10 V EXCITATION
NATURAL FREQ. ≈ 230 kHz
ACCELERATION ∥ ≈ 0.00004% F.S./g
ACCELERATION ⊥ ≈ 0.0002% F.S./g

• DIFFERENTIAL PRESSURE TRANSDUCER (BLADE #2)



KULITE XCQ-65-093-10D (18 ea.)

OUTPUT ≈ 5 mV/psi @ 10 V EXCITATION
NATURAL FREQ. < 230 kHz
ACCELERATION ∥ ≈ 0.00004% F.S./g
ACCELERATION ⊥ ≈ 0.0002% F.S./g

Figure 8 Pressure transducers for small body model rotor blades

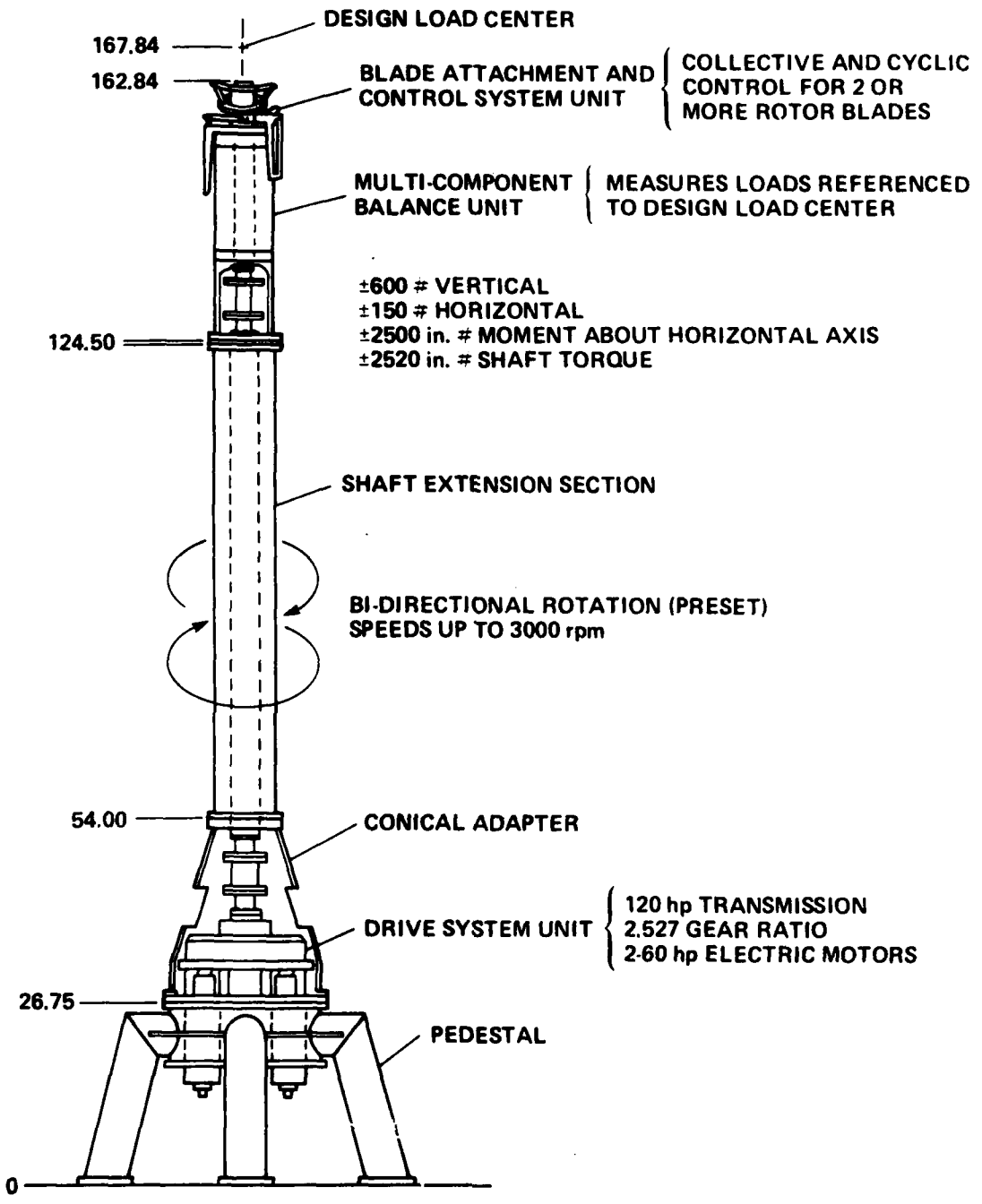


Figure 9 Operational characteristics rotary wing test stand

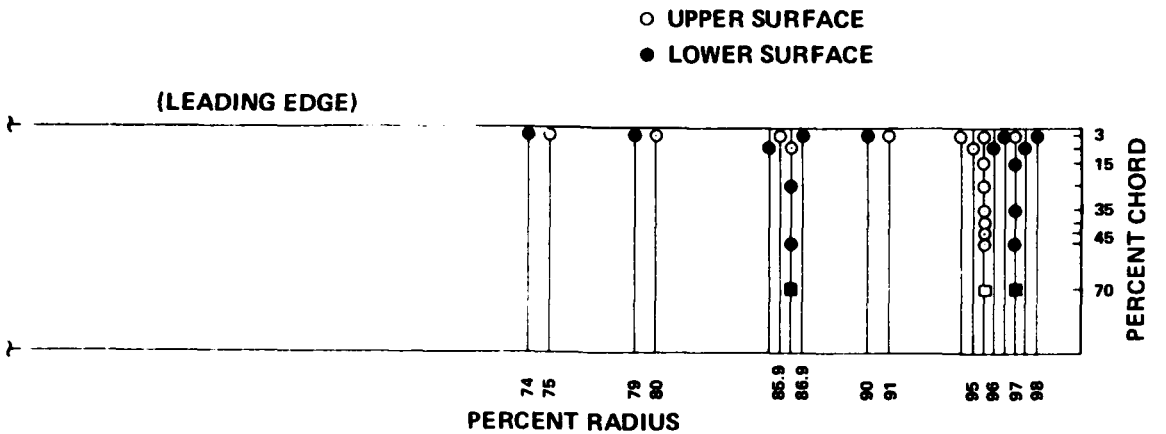


Figure 10 Scale model AH-1/OLS rotor blade absolute pressure transducer locations

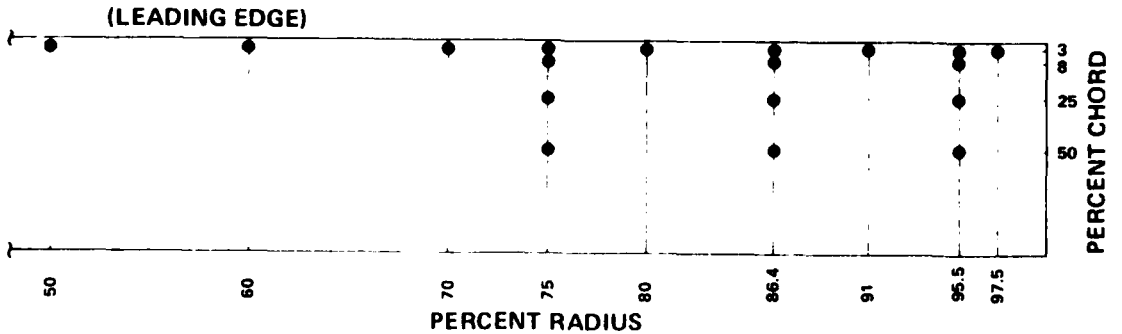
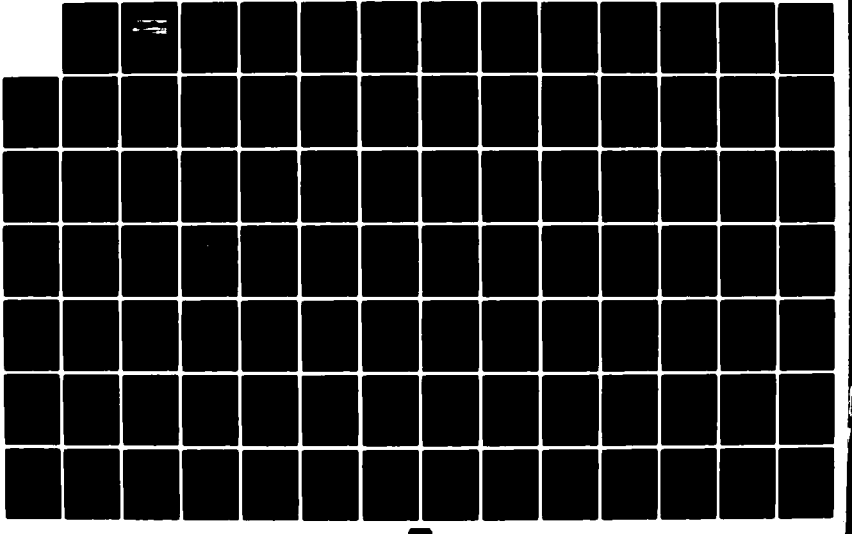
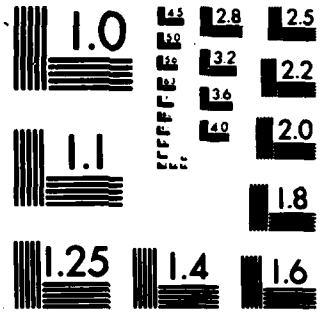


Figure 11 Scale model AH-1/OLS rotor blade differential pressure transducer locations

AD-A137 304 TRANSDUCER WORKSHOP (12TH) HELD AT MELBOURNE FLORIDA ON 7-9 JUNE 1983(U) RANGE COMMANDERS COUNCIL WHITE SANDS MISSILE RANGE NM TELEMETRY GROUP L BATES ET AL. JUN 83 1/7

UNCLASSIFIED F/G 9/1 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

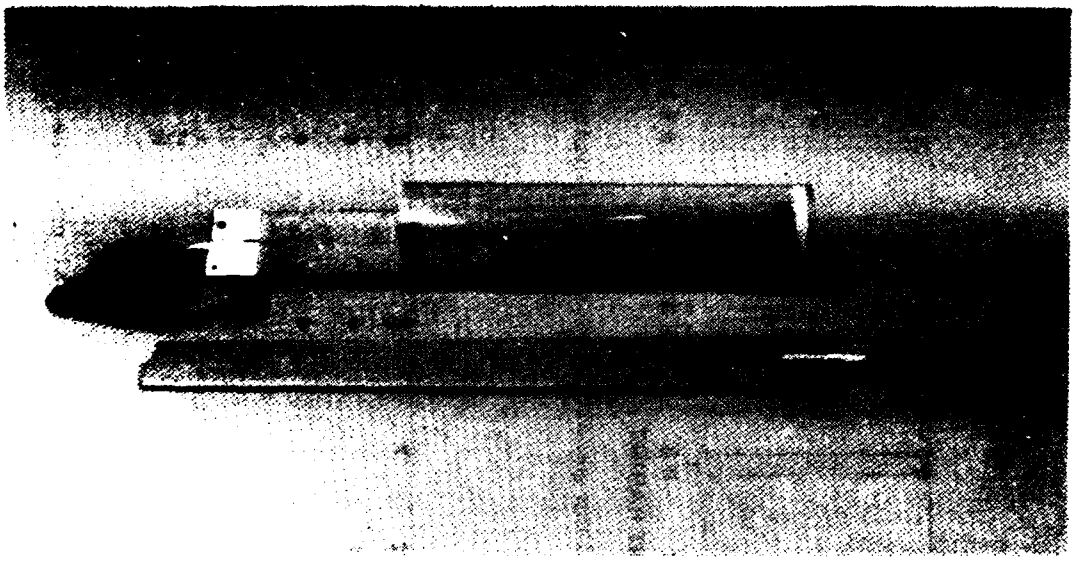


Figure 12 Pressure transducer calibration sleeve and the rotor blades

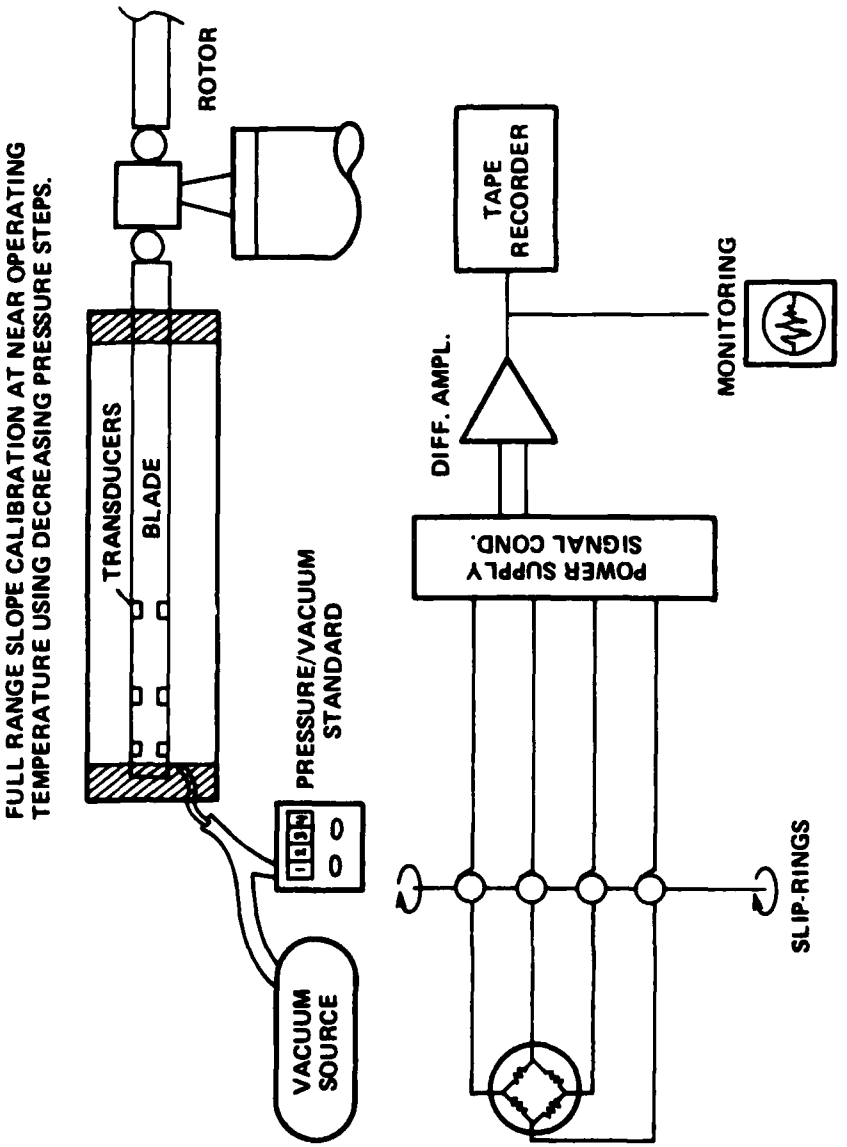


Figure 13 Post installation transducer calibration and recording

APPENDIX A

DATA DISPLAY SYSTEM

Donald E. Humphry

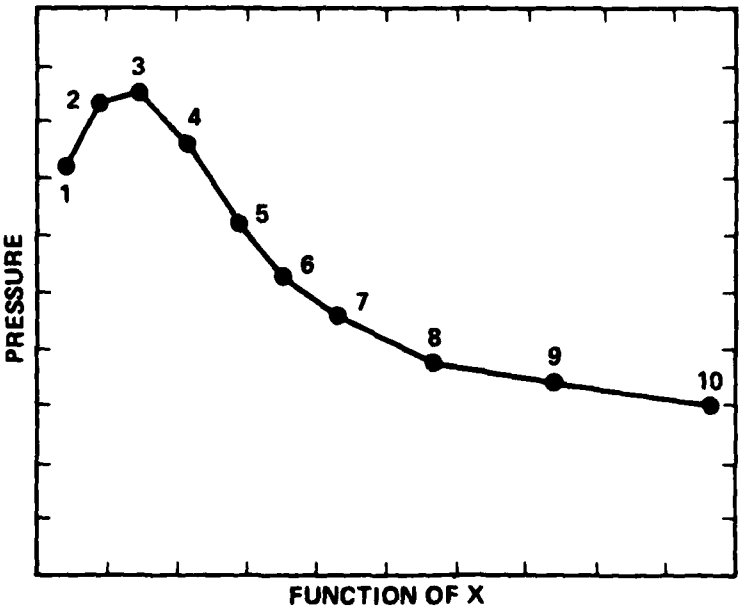
A 10-channel data-display system has been developed to illustrate a pressure profile of a moving airfoil during wind tunnel testing. The inputs to the system are the 10 analog signals from the pressure transducers and a synchronizing pulse that corresponds to the zero rotational angular position of the airfoil. This pressure profile is presented on an oscilloscope. A typical display is shown in Fig. 1. Each brightened point or dot on the trace indicates the pressure reading at that particular location with the vertical distance being the pressure, and the horizontal distance between dots being proportional to the horizontal spacing of the pressure transducers on the airfoil. This pressure profile is also for a selected rotational angle of the rotating or oscillating airfoil. The 10 simultaneous pressure readings are taken at the selected rotational angle. Thus the display system acts like a strobe, with the pressure profile being taken at any selected angular position of the airfoil.

Also displayed on the oscilloscope is a second trace, which shows the selected rotational angle of the airfoil at which the pressure readings are occurring as shown on the pressure profile. This is indicated by the position of a brightened point or dot on this trace, which corresponds to the selected rotational angle.

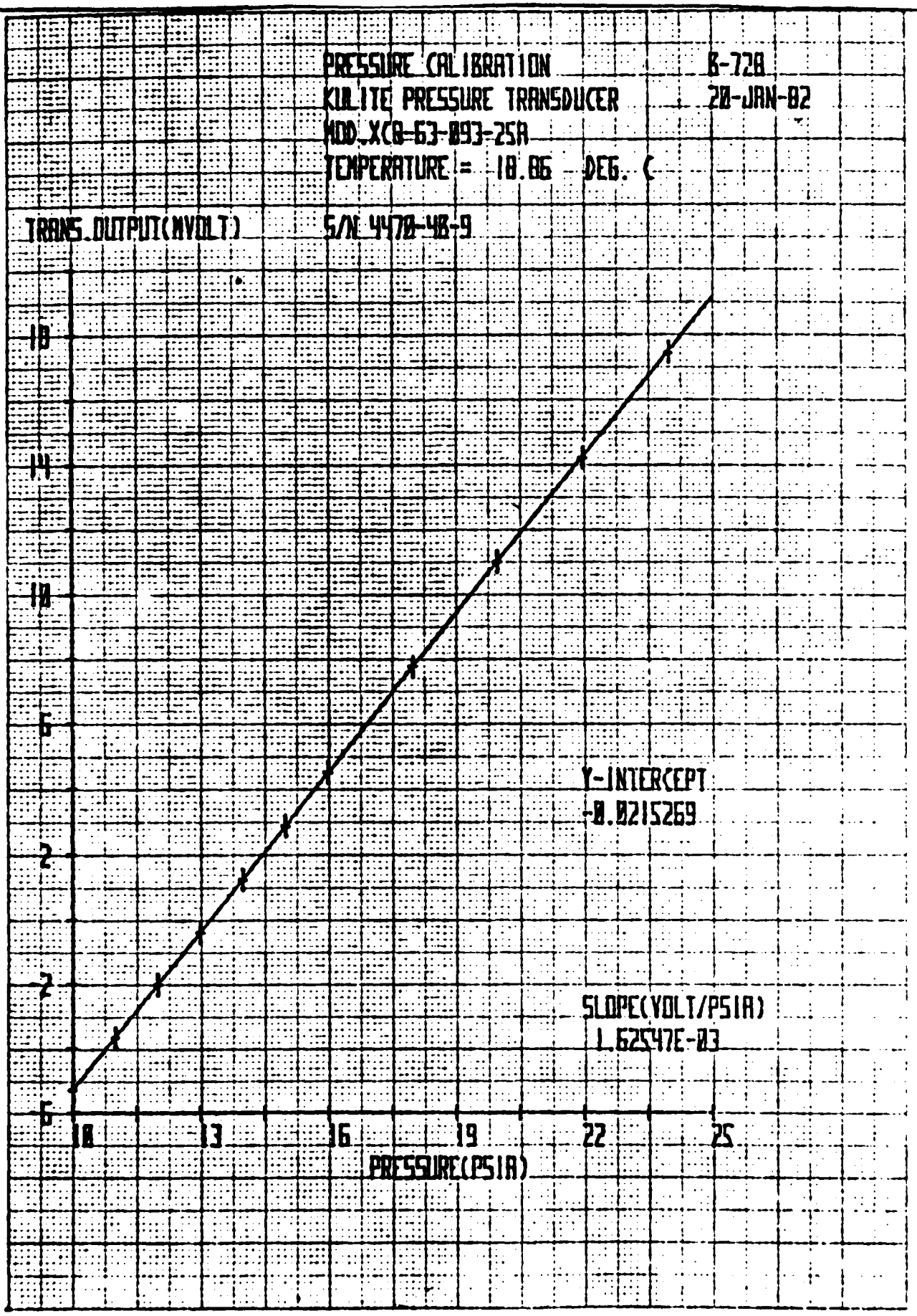
The horizontal position of each of the 10 channels on the pressure profile trace is adjustable, so that they correspond to the actual physical location of each of the pressure transducers on the airfoil.

The rotational angle of the airfoil at which the pressure reading is recorded is adjustable from 0 to 360°. For instance, to take a pressure reading at a rotational angle of 45°, select a 45° by means of a front panel switch and then each time the airfoil passed through 45°, a pressure reading would be taken at all 10 channels and displayed on the scope as a pressure profile. The system can also be programmed to scan through different angular readings at varying rates, which can be set by means of some front panel switches.

This system has also proven useful in the calibration of the pressure transducers since all 10 pressures can be observed simultaneously and any variations between them are easily observed.



Appendix A - Figure 1. Typical display off the on-line pressure profile monitor


PRESSURE CALIBRATION
B-728
KULITE PRESSURE TRANSDUCER
20-JAN-82
MOD.XCB-63-093-25A
TEMPERATURE = 18.86 DEG. C
TRANS.OUTPUT(MVOLT)
S/N 4478-48-9
18
14
10
6
2
-2
-6
Y-INTERCEPT
-0.0215269
SLOPE(VOLT/PSIA)
1.62547E-03
10
13
16
19
22
25
PRESSURE(PSIA)

APPENDIX B

PRESSURE CALIBRATION
KULITE PRESSURE TRANSDUCER B-728
MOD.XCQ-63-093-25A 20-JAN-82
S/N 4470-4B-9
CALIB. RANGE : 10 TO 24.0 PSIA
EXCITATION= 10.00 VDC
TEMPERATURE = 18.857 DEG. C

.#	PRESS(PSIA).	OUTPUT VOLT.	CALC.PRESS	DEV.(PSIA)
1	10.002	-0.005293	9.9872	0.0148
2	11.000	-0.003652	10.9966	0.0036
3	12.000	-0.002018	12.0022	-0.0018
4	13.000	-0.000389	13.0044	-0.0043
5	14.001	0.001238	14.0053	-0.0048
6	15.000	0.002868	15.0077	-0.0074
7	16.001	0.004499	16.0112	-0.0100
8	18.000	0.007752	18.0123	-0.0124
9	20.001	0.010995	20.0074	-0.0064
10	22.001	0.014220	21.9915	0.0091
11	24.001	0.017450	23.9789	0.0218
12	22.001	0.014220	21.9915	0.0092
13	20.001	0.010993	20.0067	-0.0060
14	18.001	0.007750	18.0110	-0.0102
15	16.000	0.004496	16.0093	-0.0089
16	15.001	0.002865	15.0062	-0.0053
17	14.001	0.001236	14.0040	-0.0030
	13.001	-0.000392	13.0023	-0.0016
..	12.001	-0.002021	12.0003	0.0003
20	11.001	-0.003655	10.9948	0.0060
21	10.001	-0.005299	9.9833	0.0174

INTERCEPT	SLOPE(VOLT/PSIA)	R↑2	STD.DEV.(PSIA)
.152690E-02	1.625470E-03	0.999994	0.009661

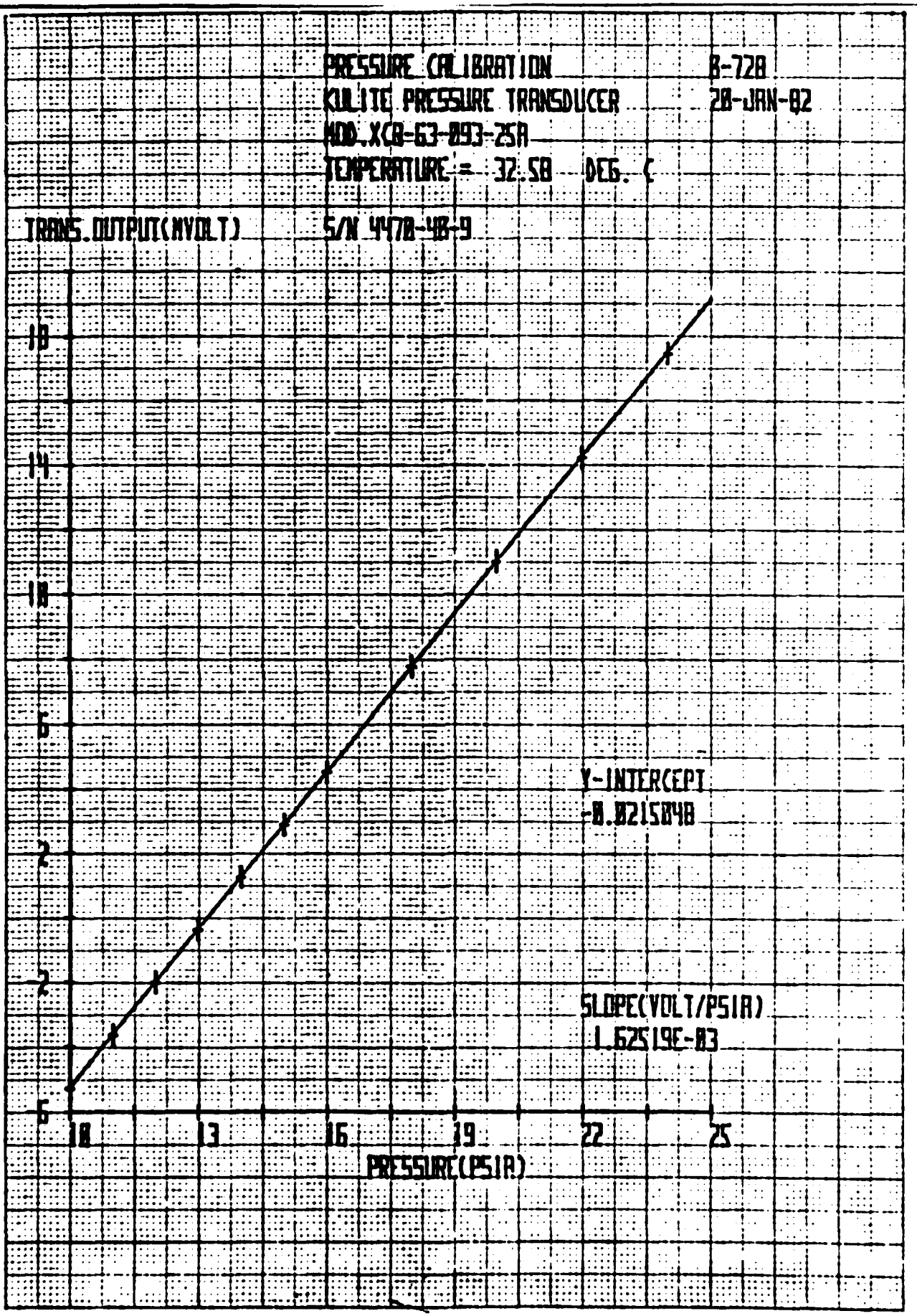
NOTE : CALC. PRESS = (OUTPUT VOLTAGE--0.0215269)/ 1.625470E-03

PRESSURE CALIBRATION
KULITE PRESSURE TRANSDUCER 6-728
MOD.XCQ-63-093-25A 20-JAN-83
S/N 4470-4B-9
CALIB. RANGE : 10 TO 24.0 PSIA
EXCITATION= 10.00 VDC
TEMPERATURE = 32.577 DEG. C

.#	PRESS(PSIA)	OUTPUT VOLT.	CALC.PRESS	DEV.(PSIA)
1	10.001	-0.005276	9.9855	0.0154
2	11.000	-0.003634	10.9959	0.0044
3	12.001	-0.002001	12.0009	-0.0004
4	13.001	-0.000371	13.0039	-0.0031
5	14.001	0.001256	14.0052	-0.0047
6	15.001	0.002885	15.0070	-0.0064
7	16.001	0.004513	16.0093	-0.0087
8	18.001	0.007767	18.0113	-0.0105
9	20.000	0.011010	20.0065	-0.0061
10	22.001	0.014235	21.9911	0.0097
11	24.001	0.017467	23.9795	0.0212
12	22.001	0.014236	21.9918	0.0089
13	20.001	0.011011	20.0073	-0.0068
14	18.001	0.007768	18.0120	-0.0114
15	16.000	0.004514	16.0099	-0.0096
16	15.001	0.002885	15.0072	-0.0066
17	14.000	0.001256	14.0049	-0.0047
18	13.001	-0.000371	13.0040	-0.0034
	12.001	-0.002001	12.0010	-0.0004
20	11.000	-0.003637	10.9946	0.0058
21	10.000	-0.005279	9.9841	0.0163

INTERCEPT	SLOPE(VOLT/PSIA)	R↑2	STD.DEV.(PSIA)
.150480E-02	1.625190E-03	0.999994	0.009531

NOTE : CALC. PRESS = (OUTPUT VOLTAGE--0.0215048)/ 1.6251 90E-03


PRESSURE CALIBRATION
KULITE PRESSURE TRANSDUCER
MDL.XCR-63-093-25A
TEMPERATURE = 32.58 DEG. C
S/N 4478-48-9
B-728
28-JAN-82
TRANS.OUTPUT(MVOLT)
18
14
10
6
2
-2
-6
Y-INTERCEPT
-0.0215848
SLOPE(VOLT/PSIA)
1.625195E-03
10
13
16
19
22
25
PRESSURE(PSIA)

VOLTAGE DRIFT TEST
KULITE PRESSURE TRANSDUCER
MOD.XCQ-63-093-25A
S/N 4470-4B-9
MEAN PRESSURE - 14.518 PSIA
EXCITATION= 10.00 VDC

A-728
20-JAN-82

DINT #	TRANS.OUTPUT	DRIFT	TEMP. C	TIME(MIN)
1	0.002092	0.000000	32.033	0.000
2	0.002092	0.000001	32.003	0.750
3	0.002090	-0.000001	31.902	1.500
4	0.002090	-0.000002	31.923	2.167
5	0.002091	-0.000001	31.843	3.000
6	0.002090	-0.000002	31.785	3.750
7	0.002091	-0.000001	31.639	4.500
8	0.002090	-0.000002	31.634	5.250
9	0.002090	-0.000002	31.536	6.000
10	0.002088	-0.000004	31.971	6.750
11	0.002088	-0.000004	31.461	7.500
12	0.002088	-0.000004	31.505	8.167
13	0.002086	-0.000006	31.470	9.000
14	0.002086	-0.000006	31.462	9.750
15	0.002085	-0.000006	31.518	10.500
16	0.002085	-0.000007	31.502	11.250
17	0.002086	-0.000006	31.537	12.000
18	0.002086	-0.000006	31.507	12.750
19	0.002087	-0.000005	31.517	13.500
20	0.002088	-0.000004	31.512	14.250
1	0.002087	-0.000004	31.597	15.000
22	0.002088	-0.000004	31.524	15.750
23	0.002087	-0.000005	31.553	16.500
24	0.002087	-0.000004	31.574	17.250
25	0.002087	-0.000005	31.575	18.000
26	0.002087	-0.000005	31.584	18.750
27	0.002087	-0.000005	31.535	19.500
28	0.002087	-0.000005	31.580	20.167
29	0.002087	-0.000005	31.576	21.000
30	0.002087	-0.000005	31.526	21.750
31	0.002087	-0.000005	31.468	22.500
32	0.002087	-0.000005	31.503	23.167
33	0.002086	-0.000005	31.483	24.000
34	0.002087	-0.000005	31.475	24.750
35	0.002087	-0.000005	31.544	25.500
36	0.002087	-0.000005	31.529	26.250
37	0.002087	-0.000004	31.591	27.000
38	0.002087	-0.000005	31.628	27.667
39	0.002087	-0.000005	31.536	28.500
40	0.002088	-0.000004	31.504	29.250

TEMPERATURE DRIFT TEST
KULITE PRESSURE TRANSDUCER
MOD.XCQ-63-093-25A
S/N 4470-48-9
MEAN PRESSURE - 14.523 PSIA
EXCITATION= 10.00 VDC

A-728
20-JAN-72

POINT #	TRANS.OUTPUT	DRIFT	TEMP. C	TIME(MIN)
1	0.002089	0.000000	31.503	0.000
2	0.002089	0.000000	31.073	1.000
3	0.002089	0.000000	27.724	2.000
4	0.002089	0.000000	25.361	3.000
5	0.002088	-0.000001	22.958	4.000
6	0.002086	-0.000002	22.192	5.000
7	0.002083	-0.000005	21.693	6.000
8	0.002080	-0.000009	21.407	7.000
9	0.002078	-0.000011	21.277	8.000
10	0.002075	-0.000014	20.889	9.000
11	0.002072	-0.000016	20.945	10.000
12	0.002069	-0.000019	20.795	11.000
13	0.002066	-0.000022	20.811	12.000
14	0.002067	-0.000022	20.733	13.000
15	0.002066	-0.000023	20.684	14.000
16	0.002064	-0.000024	20.261	15.000
17	0.002063	-0.000026	19.981	16.000
18	0.002061	-0.000028	19.839	17.000
19	0.002058	-0.000030	19.773	18.000
20	0.002058	-0.000031	19.739	19.000

ADP002688

EFFECT OF MEASUREMENT SYSTEM PHASE RESPONSE ON SHOCK SPECTRUM COMPUTATION

BY

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Albuquerque, NM 87185

PRESENTED AT

53D SHOCK AND VIBRATION SYMPOSIUM
Danvers, MA
October 26-28, 1982

Effect of Measurement System Phase Response on Shock Spectrum Computation

Introduction

One of the standard methods for characterizing mechanical shock is by means of the shock spectrum. The principal application of the shock spectrum in aerospace technology is to permit component shock test specifications to be generated, independent of specific time histories. Inattention to the dynamics of the instrumentation system used to measure mechanical shock can result in distorted test data. Erroneous component test specifications will originate from shock spectra calculations based on these distorted data.

A shock spectrum is the envelope of peak responses of an infinite number of single-degree-of-freedom linear oscillators to an input transient at their foundation. The shock spectrum can be specified for a variety of input-response relationships. For each particular input-response relationship, there are at least nine different ways of specifying shock spectra; the major divisions are primary (during pulse application), residual (after the pulse), and maximax (all time), with subdivisions of positive, negative, and maximum. The shock spectrum provides a technique to assess the results of different shock stimuli by comparing the similarities in peak responses they elicit from the assemblage of oscillators. In this article, the oscillators are treated as undamped.

The shock spectrum concept originated at the Department of Aeronautics, California Institute of Technology. First reported in 1933[1], a theory was presented which provided a method of evaluating the action of random impulses on vibrating systems.

Computation of a shock spectrum first depends on a successful measurement of the transient acceleration-time history which a component experiences in application. As a minimum, an acceleration measurement system is comprised of an accelerometer, signal conditioning amplifier, and FM tape recorder. If data are required in digital form, the FM tape recorder is replaced by an anti-aliasing filter, analog to digital converter, and a digital tape machine or a computer. If the system cannot be continuously connected by cables, it may contain an intermediate radio frequency link for space transmission.

These measurement systems can all be described as low-pass filters; i.e., systems which pass frequencies from at or near 0 Hz to a specified upper frequency limit. This upper frequency limit, typically characterized by 3 dB attenuation, is due to constraints in the bandwidth of the analog signal conditioning amplifiers, filtering due to distributed cable capacitance, anti-aliasing filters designed into digital systems, or analog filters associated with FM demodulators. All transient acceleration data pass through some combination of these filters.

The frequency response function of any linear measurement system* can be represented as:

$$H(j\omega) = A(\omega)e^{-j\phi(\omega)} \qquad (1)$$

where $A(\omega)$ describes the system amplitude response and $\phi(\omega)$ its phase response with frequency (ω). If $A(\omega)$ is not a constant, the amplitude of the spectral content of a transient acceleration signal recorded by the system will be modified causing signal distortion with resultant error in the computed shock spectrum. Figure 1a illustrates a transient acceleration signal and Figure 1b its spectral content. In this example, a filter with constant amplitude response to 300 Hz will not introduce distortion due to signal attenuation; however, the influence of filter phase response is not so apparent.

Figure 2 presents the amplitude-frequency and phase-frequency responses of two typical filters. The six-pole Chebyshev is the best approximation to an ideal "boxcar" filter in the amplitude domain (see Figure 2a), but its phase response is more nonlinear than that of the six-pole Bessel as shown in Figure 2b.

The remaining portion of this article investigates the effect of nonlinear phase response in systems which measure transient signals and the influence of this response on computed shock spectra. The general problem of acquiring valid structural dynamics measurements has been described elsewhere.[3]

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*Reference 2 discusses the problem of nonlinear measurement systems.

Nonlinear Phase Effects on Signals

The effects of nonlinear phase response on the input signals to measurement systems are qualitatively depicted in Figures 3 and 4. Figure 3a illustrates a pulse train with a period of one second. Over any period, the time function f(t) can be represented as:

$$f(t) = 1, \quad .3 \le t \le .7 \tag{3}$$

$$f(t) = 0 \text{ elsewhere in } 0 \le t \le 1.$$

The Fourier series representation of this periodic function is:

$$f(t) = 0.4 + (2/\pi) \sum_{n=1}^{\infty} [(-1)^n/n]\sin(0.4\pi n)\cos(2\pi nt+\phi_n) \tag{4}$$

where ϕ_n is initially equated to zero. This function will be approximated by summing its first 25 harmonics. This is equivalent to passing the function through the ideal "boxcar" filter described in Figure 3b with no accompanying phase shift. The resultant filtered signal can then have the various linear and nonlinear phase responses of Figure 3c associated with it. These are respectively:

$$\phi_n = \sqrt{2\pi\omega_n}, \tag{5.1}$$

$$\phi_n = .2\omega_n, \tag{5.2}$$

$$\phi_n = \omega_n^2/(250\pi), \text{ and} \tag{5.3}$$

$$\phi_n = \omega_n^3/(12{,}500\pi^2) \tag{5.4}$$

where $\omega_n = 2\pi n$. These phase responses are normalized to produce

a phase shift of 10π radians at 25 Hz, the highest harmonic in the filtered signal.

Figure 4a shows the result over one period of the time function when it is passed through the filter in Figure 3b. The ripple on top of the pulse is due to truncation of the higher frequencies and is called Gibbs phenomenon.[4] Figure 4b shows the effect of shifting the phase of the signal in Figure 4a in the linear fashion described by Eq. (5.2) and illustrated in Figure 3c. As predicted by theory[5], only a constant time delay occurs and signal distortion is avoided.

Figure 4c superposes results of shifting the phase of the signal in Figure 4a in a nonlinear fashion according to Eqs. (5.1), (5.3), and (5.4) also illustrated in Figure 3c. (In Figure 4c α denotes proportional.) The distorted waveforms, erroneous signal amplitudes, and modified pulse durations are solely attributable to the various nonlinear filter phase responses.

Application to Shock Spectra

In practice, an infinite variety of acceleration transients exist in nature and can be input to measurement systems. Each measurement system will add varying amonts of linear or non-linear phase shift to the spectral content of these input transients.

The initial and terminal peak sawtooth pulses of Figure 5 will be used to illustrate the influence of measurement system phase

response on shock spectrum computation. The terminal peak sawtooth pulse is widely used in component shock testing due to unique properties of its shock spectrum.[6]

Figure 6a plots the magnitudes of the Fourier transform of both the initial and terminal peak sawtooth pulses. Note that these magnitudes are identical! Figure 6b and 6c show the pulse phase relations, however, to be quite different. Both pulses then contain identical frequency content but differ in its time of occurrence. An initial peak sawtooth can be turned into a terminal peak sawtooth by modifying its phase relationship and vice-versa.

Figure 7 shows that the maximax undamped acceleration shock spectra of these two pulses are grossly different. Since both pulses contain identical frequency content, dissimilarities are due solely to the difference in phase relations. While measurement systems are often designed only around amplitude response considerations, this example demonstrates the important role of measurement system phase response in subsequent shock spectrum computations. Nonlinear phase response can result in severe distortion of recorded acceleration transients and the resultant computed shock spectra.

Measurement System Design Guidelines

The majority of the phase shift associated with the systems being considered is introduced by analog filters. Since the introduction

of the modular transistorized operational amplifier in the 1950's, active filters have become almost universally applied in structural measurements. As noted earlier, these filters are used to preclude aliasing in digital systems and as part of FM signal demodulation.

Modern filter theory involves the approximation of the filter specifications by a frequency response function and the design of a network which realizes this frequency response function. The rate of attenuation of a filter is specified in decibels/octave. Each filter pole provides 6 dB/octave ultimate attenuation. The more common filters in current use are the Butterworth, Bessel, and Chebyshev.

Frequently, filters are selected solely due to their amplitude response characteristics with phase considerations ignored. The following table, based on calculations made by the author, provides improved selection guidelines for the three previously described filter types with two, four, six, and eight poles of attenuation. Numeric values presented are the ratio of the upper frequency limit at which the filter should be used to that of its -3 dB frequency. This upper frequency limit is based on the lesser of the two values at which the filter deviates either five percent from a flat amplitude response or five degrees from phase linearity based on its initial phase slope. These criteria should assure waveform reproduction without distortion.

	Filter Type		
	Butterworth	Bessel	0.1 dB Chebyshev
2 poles	.573	.399	.522*
4 poles	.575*	.399	.489*
6 poles	.541*	.392	.418*
8 poles	.506*	.389	.372*

*upper limit due to phase nonlinearity

An example will show how to use this table. A six-pole Butterworth and a six-pole 0.1 dB Chebyshev filter with a 1,000 Hz -3 dB frequency would be limited in application to 541 and 418 Hz respectively because of phase nonlinearities. A six-pole Bessel would become limited at 392 Hz due to its deviation from a flat amplitude response.

This document's premise is ~~Conclusion~~ that Measurement system design is frequently based upon amplitude response considerations with phase response ignored. In structural testing, nonlinear phase response in measurement systems results in distorted transient data being recorded for analysis with resultant error in the computed shock spectra. Design guidelines are provided in this work to preclude these errors from occurring.

References

1. Biot, M., "Theory of Elastic Systems Vibrating Under Transient Impulse with an Application to Earthquake-Proof Buildings", Proceedings National Academy of Sciences, 19, 262-268 (1933).
2. Stein, P. K., "Measurement on and with Non-linear Systems: Problems and Approaches", International Measurement Confederation, IMEKO IX, Berlin, West Germany (May 1982).
3. Walter, P. L., Nelson, H. D., "Limitations and Corrections in Measuring Structural Dynamics", Experimental Mechanics, 19(9), 309-316 (Sept. 1979).
4. Chirlian, P. M., Signals, Sytems, and the Computer, Intext Educational Publishers, NY, Ch. 2, 47-50 (1973).
5. Harris, C. M., Crede, C. E., Shock and Vibration Handbook, McGraw Hill Book Co., NY, Ch. 12, 12-15 (1976).
6. Lowe, R., Cavanaugh, R. D., "Correlation of Shock Spectra and Pulse Shape with Shock Environment", Environmental Engineering, 24-29 (Feb. 1959).

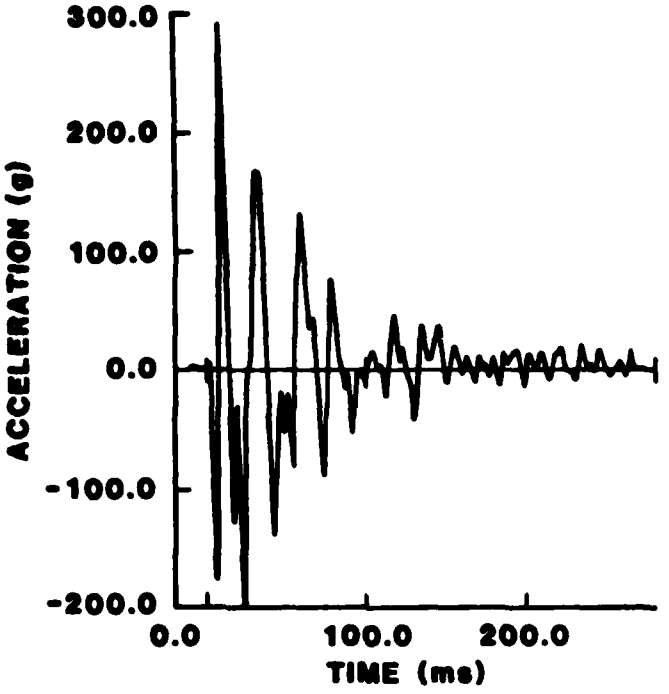

Fig. 1a: Acceleration Time Record

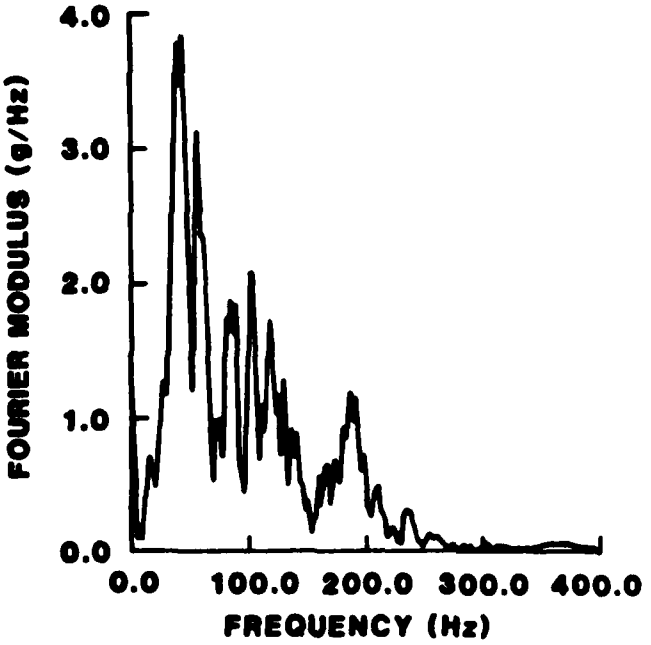

Fig. 1b: Magnitude of Fourier Transform of Acceleration-Time Record

Fig. 1: Acceleration Measurand Which Might Be a Stimulus to a Measurement System

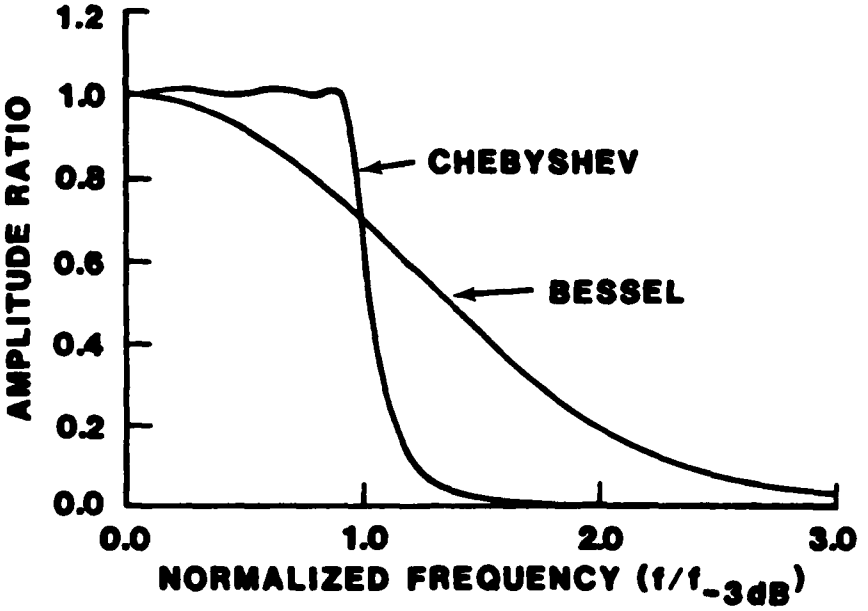

Fig. 2a: Amplitude Frequency Response

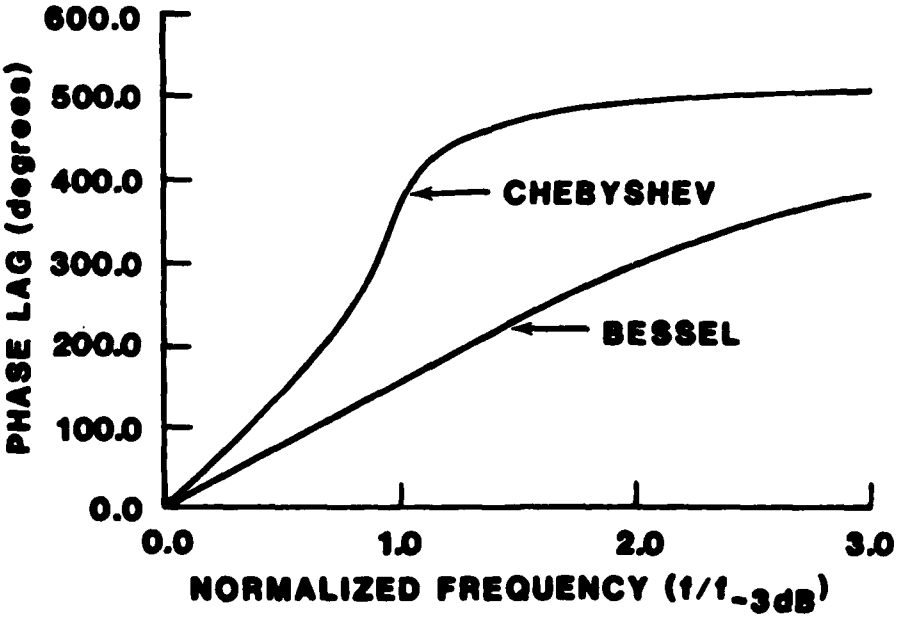

Fig. 2b: Phase Frequency Response

Fig. 2: Amplitude Frequency and Phase Frequency Plots For 6-Pole Chebyshev and Bessel Filters

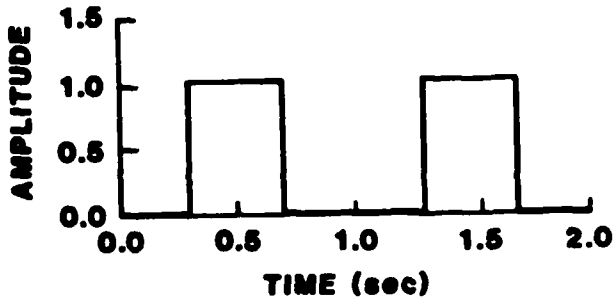

Fig. 3a: Periodic Time Function

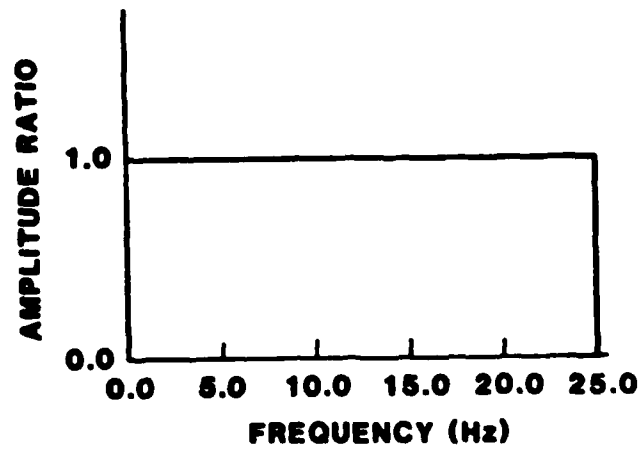

Fig. 3b: Amplitude Frequency Response

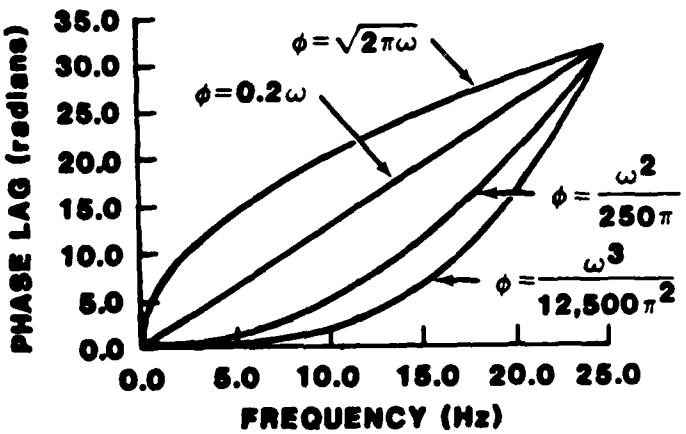

Fig. 3c: Phase Frequency Responses

Fig. 3: Periodic Time Function And Idealized Filter Response Plots

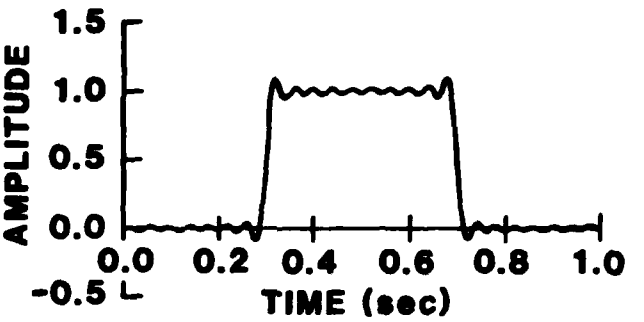

Fig. 4a: Amplitude Distortion Only

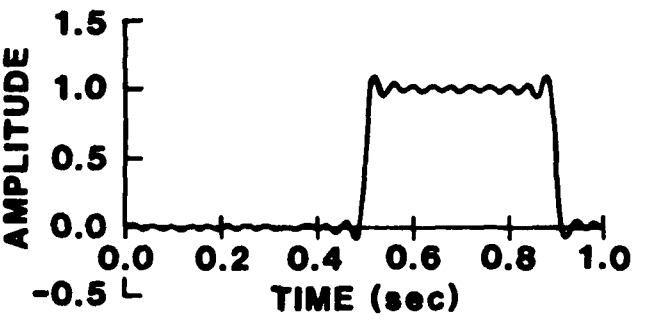

Fig. 4b: Linear Phase Shift

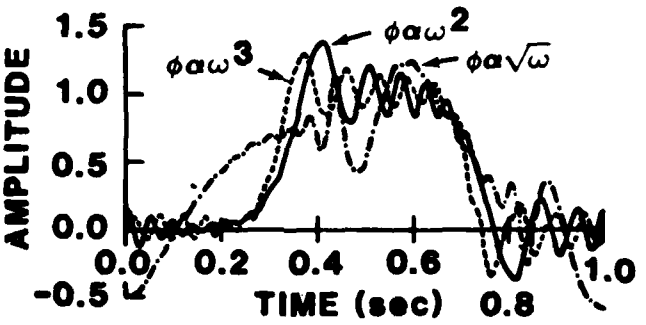

Fig. 4c: Nonlinear Phase Shifts

Fig. 4: One Cycle Of Periodic Time Function Passed Through Idealized Filter Of Figure 3

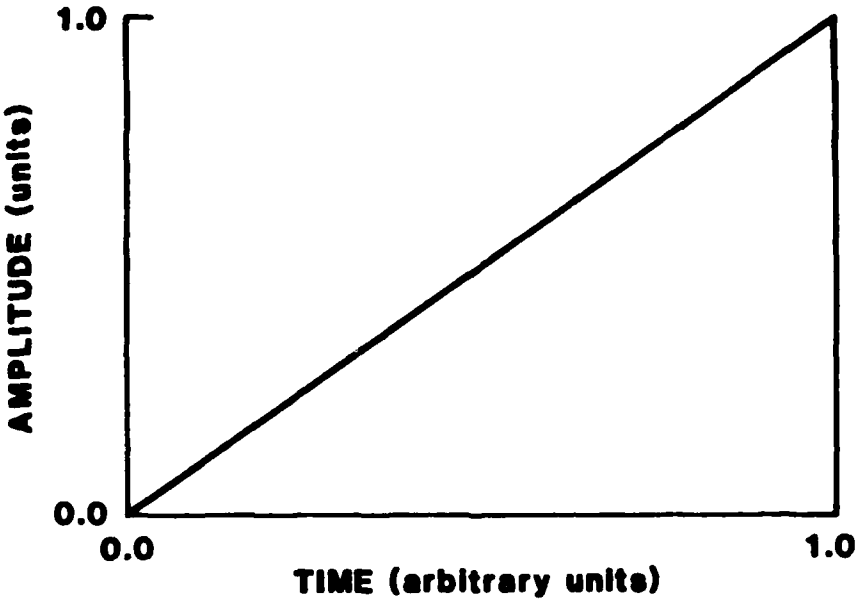

Fig. 5a: Terminal Peak Sawtooth Pulse

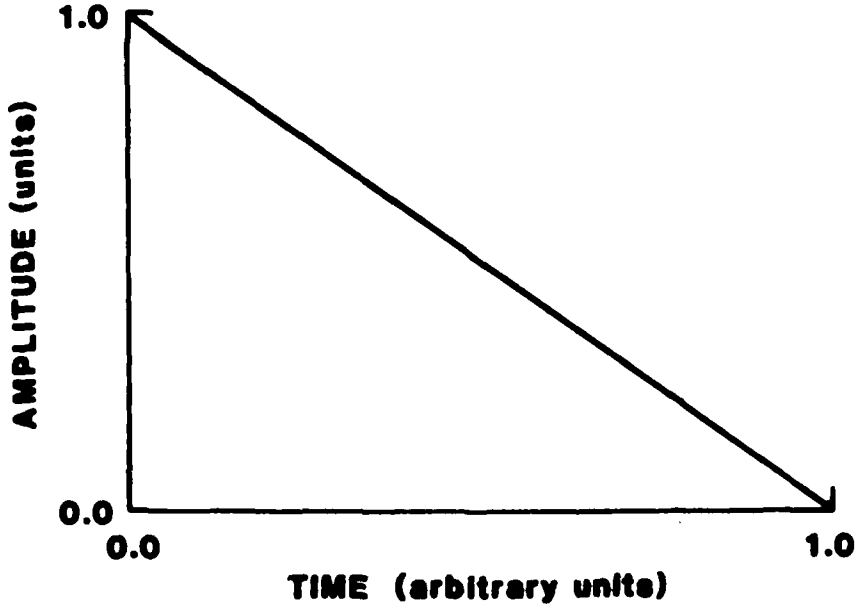

Fig. 5b: Initial Peak Sawtooth Pulse

Fig. 5: Sawtooth Pulses

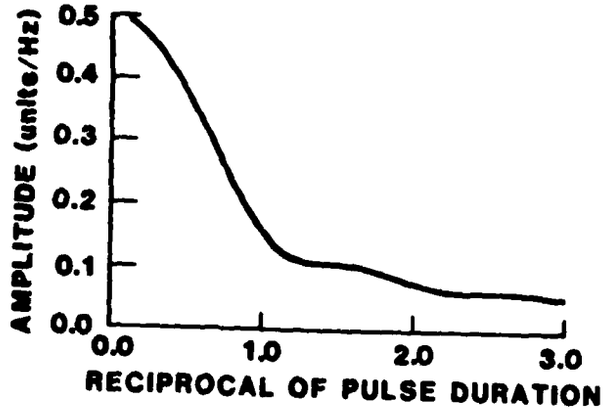

Fig. 6a: Magnitude of Fourier Transform of Both Terminal and Initial Peak Sawtooth Pulses

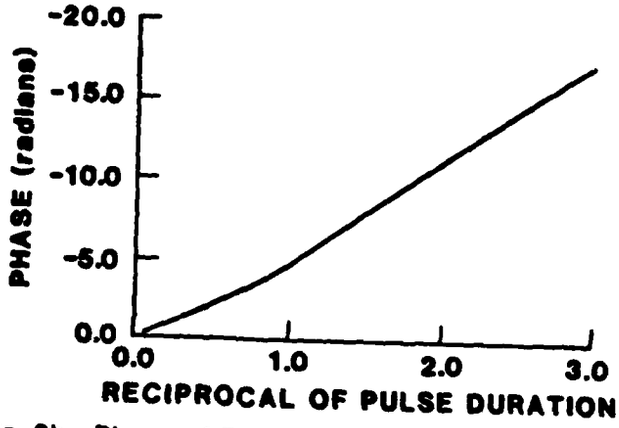

Fig. 6b: Phase of Fourier Transform of Terminal Peak Sawtooth Pulse

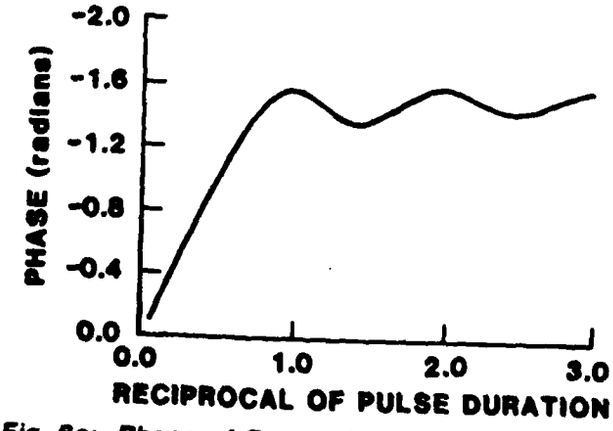

Fig. 6c: Phase of Fourier Transform of Initial Peak Sawtooth Pulse

Fig. 6: Fourier Spectra of Sawtooth Pulses of Figure 5

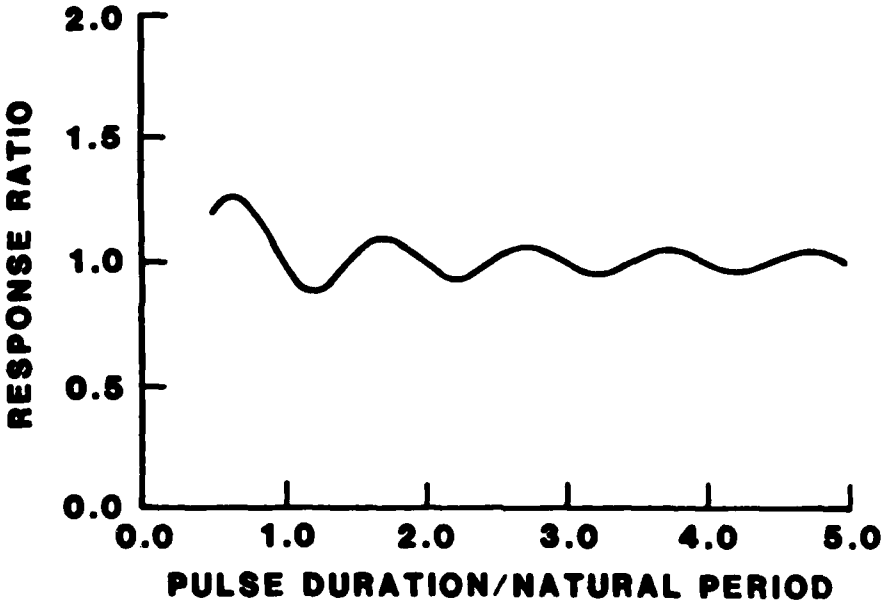

Fig. 7a: Shock Spectrum of Terminal Peak Sawtooth Pulse

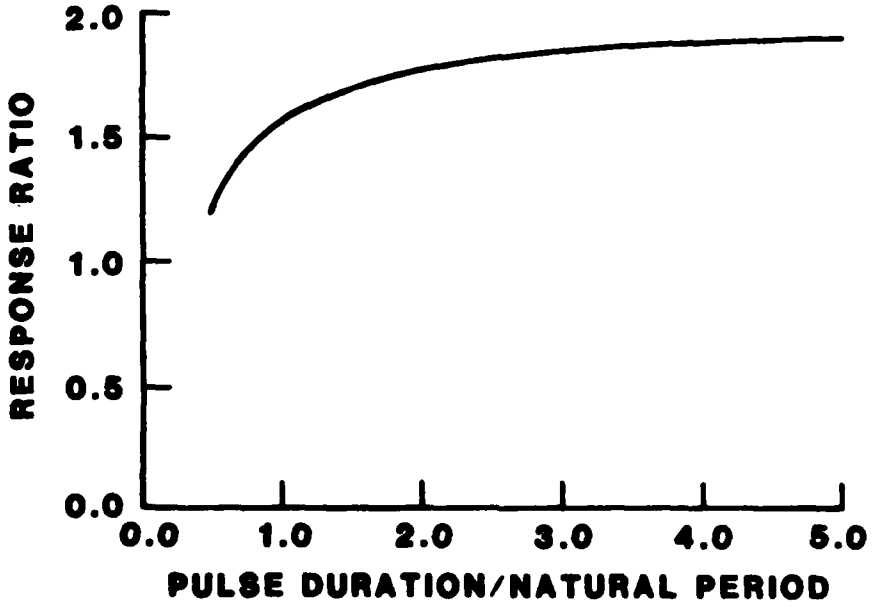

Fig. 7b: Shock Spectrum of Initial Peak Sawtooth Pulse

Fig. 7: Maximax Undamped Acceleration Shock Spectra of Terminal and Initial Peak Sawtooth Pulses

ADP002689

PIEZOMETER PROBE TECHNOLOGY FOR GEOTECHNICAL INVESTIGATIONS IN COASTAL AND DEEP-OCEAN ENVIRONMENTS

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ABSTRACT

Three multisensor piezometer probes were developed and field tested for use in coastal (shallow water) fine-grained marine soils. Offshore sites were investigated in the Mississippi Delta. Pore water pressure measurements were determined at several depths below the sea floor using both absolute and differential pressure sensors placed in a four inch diameter probe.

Pressure sensors were hard-wired to nearby platforms where signals were conditioned and analog recording devices monitored pore water pressure changes in the marine soils. Pore water pressures were monitored for several months.

Two single sensor piezometer probes, eight millimeters in diameter, were developed for deep-ocean investigations. These probes use differential pressure sensors and were tested in a hyperbaric chamber pressurized to 55 MPa (8000 psi). Testing was performed for a period of five weeks under high hydrostatic pressure with the probes inserted in reconstituted illitic marine soil. Small differential pore water pressures responded to both mechanically and thermally generated forcing functions.

During shallow water investigations and deep-ocean simulated pressure tests, the sensors exhibited excellent sensitivity and stability. These developments in piezometer probe technology provide a means of assessing important geotechnical parameters of fine-grained seabed deposits.

INTRODUCTION

Increasing seafloor utilization for commercial, military, and governmental activities has stimulated both engineering and scientific investigations of submarine deposits, particularly during the past 15 years. Although descriptive geological and geophysical studies have provided an important understanding of the seafloor features and geological materials, geotechnical investigations add additional critical quantitative dimension to the evaluation of seafloor deposits. In situ measurements of soil properties provide "ground truth" and quantitative geotechnical data that are critical in providing confidence in seafloor engineering analyses for a wide range of applications.

Shallow-water and deep-ocean piezometer probes have been developed to provide in situ data on soil pore water pressures and related geotechnical properties (Bennett and Faris, 1979; Bennett et al., 1981, 1982). The importance of pore pressure, specifically excess pressure, has been recognized for decades by engineers as a critical property affecting the consolidation state and stability of soil deposits (Bennett et al., 1982). In shallow coastal waters, the effect of surface wave activity during storm periods is considered a major factor in triggering slope failure and submarine sediment mass movement (Bea and Arnold, 1973; Bea et al, 1975; Wright, 1976; Henkel, 1970). In order to gain further insight into the role of pore pressure in submarine sediments and its importance in seafloor engineering applications, multisensor shallow water piezometer probes were developed and field tested in offshore areas of the Mississippi Delta (Bennett et al., 1976).

The purpose of the shallow water piezometer investigations was (1) to determine the feasibility of making long-term measurements of pore pressure in the ocean environment using prototype and improved design concept systems; (2) to assess ambient and dynamic pore pressures in selected submarine sediments; (3) to determine insertion pore pressures and their decay characteristics; and (4) to assess the effective stress (state of stress) at the probe sites. Details of these tests can be found in Bennett et al., 1982.

A deep-ocean piezometer probe was developed for making in situ soil pore water pressure measurements at nominal ocean depths of 6000 m and at seafloor subbottom depths of 1.0 m. The piezometer measurements are an integral part of the In Situ Heat Transfer Experiment (ISHTE).

The in situ heat transfer experiment is being developed in support of the U.S. Subseabed Disposal Program (SDP). The SDP is examining the feasibility of emplacing high level nuclear waste in fine-grained clay formations located in deep, tectonically stable regions of the world ocean basins (Hollister, et al., 1981). As presently envisioned, the in situ heat transfer experiment (ISHTE) will be fielded for a 1-year period in the Central North Pacific Ocean. The experiment will be conducted on the seafloor using a recoverable platform (Fig. 1) and a 400 W isotopic heat source. The heat source will be implanted to approximately 1 m depth in the illitic sediments. The response of the sediment to the thermal field produced by this heater will be evaluated using various in situ measurement devices including piezometer probes, thermal sensors, a vane shear device and a porewater sampler. A comparison of such in situ measured responses with the predictions of numerical models for thermal, mechanical, and chemical behavior of the sediment will be used to evaluate the applicability of the modeling tools, being developed, to evaluate the feasibility of subseabed disposal (Percival, et al., 1980).

A major step in developing the technology needed to field ISHTE was the completion of a scaled laboratory experiment designed to simulate environmental conditions that are expected for the field experiment (Percival, 1982). This laboratory experiment was done using a cylindrical container of approximately 1 m^3 of remolded, reconsolidated illite sediment and a large pressure vessel capable of maintaining 55 MPa pressure at $4^{o}C$ for approximately a one month long duration experiment. The simulation experiment was used to test essentially all of the components that will be part of ISHTE.

The purpose of this report is to review the instrumentation and engineering aspects of the shallow-water and deep-ocean piezometer probes. Of particular interest in this report is the evaluation of prototype

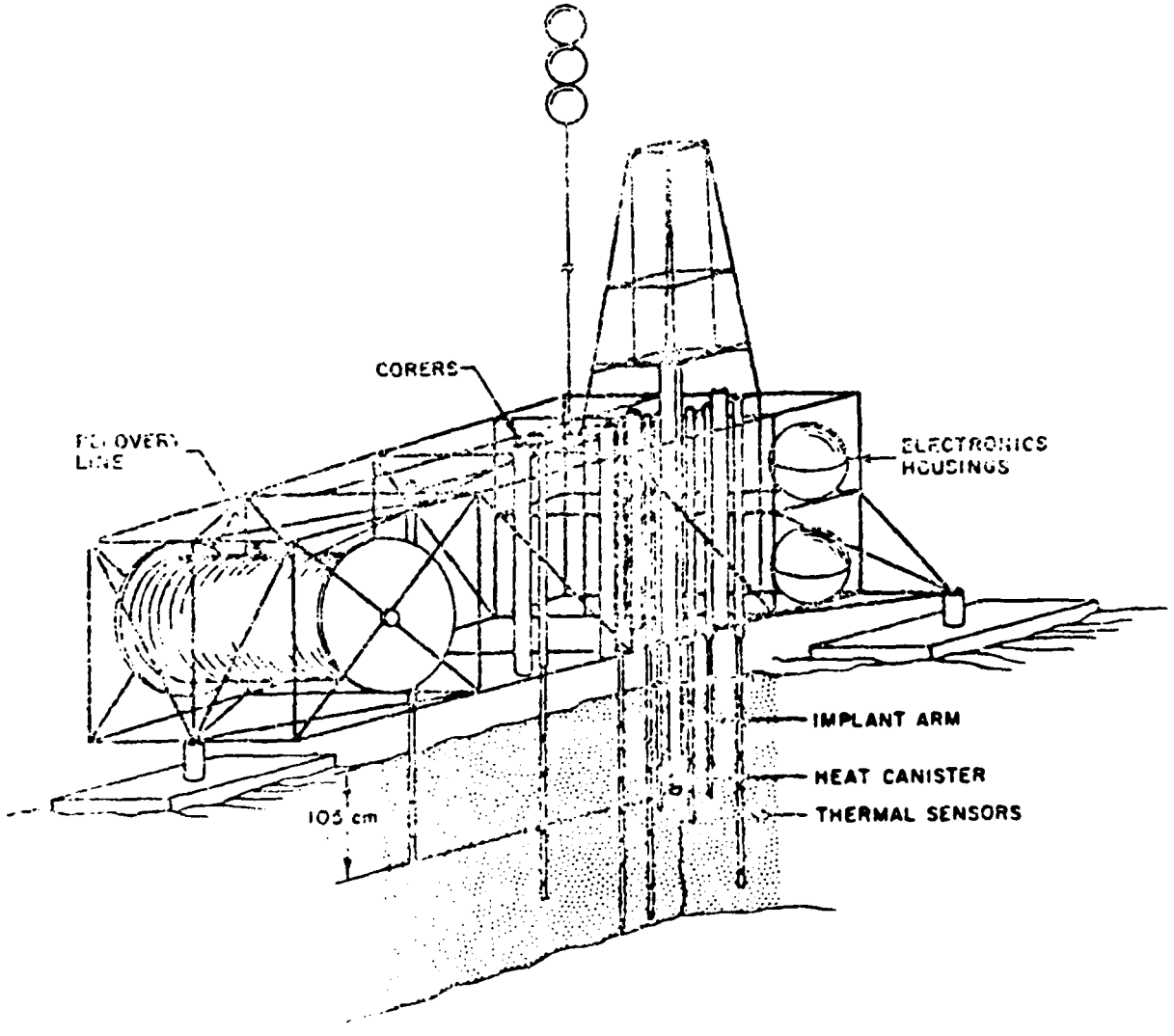


Fig. 1 ISHTE platform on sea floor. (Olson, L.O. and J.G. Harrison, 1979)

deep-ocean piezometer probes that were tested in the simulation experiment. Selected, limited data will be presented in order to demonstrate the type of information obtained and the significance of the pore water pressures observed in the soils under various environmental conditions.

SHALLOW WATER PIEZOMETER PROBE: INSTRUMENTATION

The piezometer system was designed specifically for the study of shallow-water submarine sediments on continental shelves. An essential requirement of the system was to continuously record at high data rates for long periods of time (days and months) while leaving the system unattended. Synchronous measurements of all pressure sensors were desired in order to evaluate wave effects on pore pressures.

The major components of the piezometer system include several subsystems. These are a probe with pressure sensing transducers; an underwater junction box for cables; signal-conditioning electronics; data recorder(s); and a power package (Fig. 2). The probe shell enclosing the pressure transducers is a 0.10 m diameter seamless steel pipe composed of several 3.05 m length segments with "O" ring sealed couplings (Figs. 3, 4). This design allows selection of the sensor and porous filter positions along the probe length.

Pressure sensors are of the variable-reluctance type transducers. Two absolute pressure transducers are used to measure the "hydrostatic" or free water column pressure inside the probe at selected depths. Absolute pressure sensors also are used to measure pore pressure at selected intervals and excess pore pressure is measured directly with differential pressure sensors placed at selected intervals along the probe length. Excess pore pressure can be obtained from the absolute difference between the pore water measurements and the free water column measurements. Transducers are enclosed and sealed in oil-filled capsules (Figs. 5, 6), and they are connected to porous filters on the exterior of the pipe. Filters are coarse corundum and high-air-entry stones having approximate porosity (n) and permeability (k) values of n = 45-50%, k = 0.1-0.3 mm/s

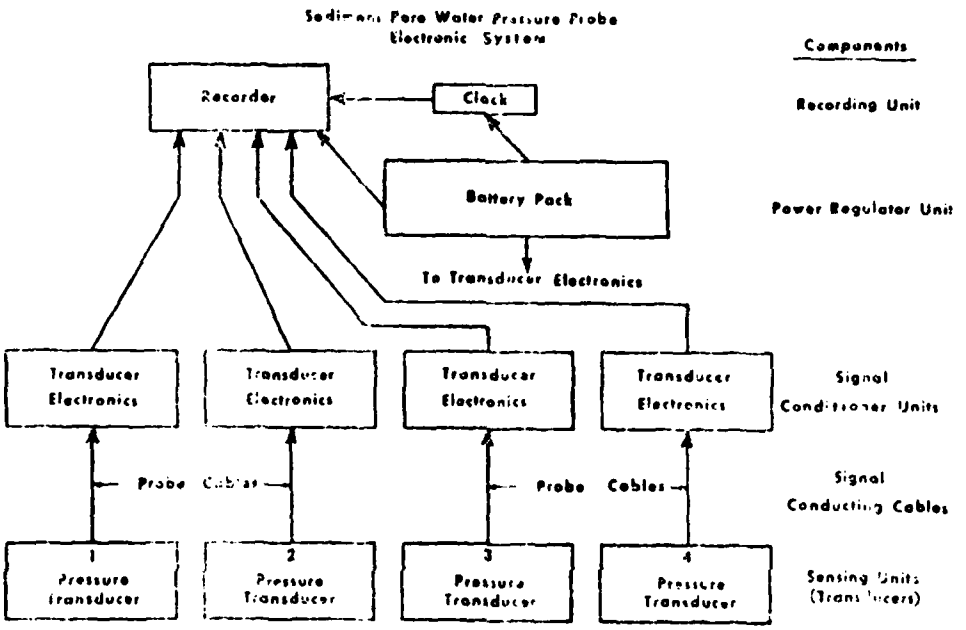


Fig. 2 Block diagram of major components of a prototype shallow-water piezometer system. Later improved design concepts employed a larger number of sensors in the system.

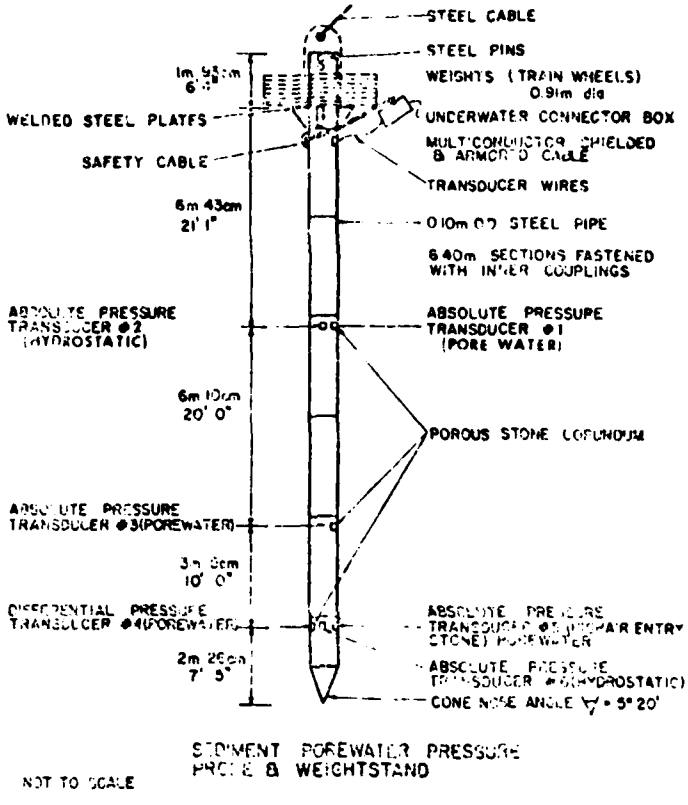


Fig. 3 Shallow-water piezometer with location of pressure sensors and filters. (Bennett, R. H. and J. R. Faris, 1979)

SEDIMENT POREWATER PRESSURE PROBE
(Piezometer)

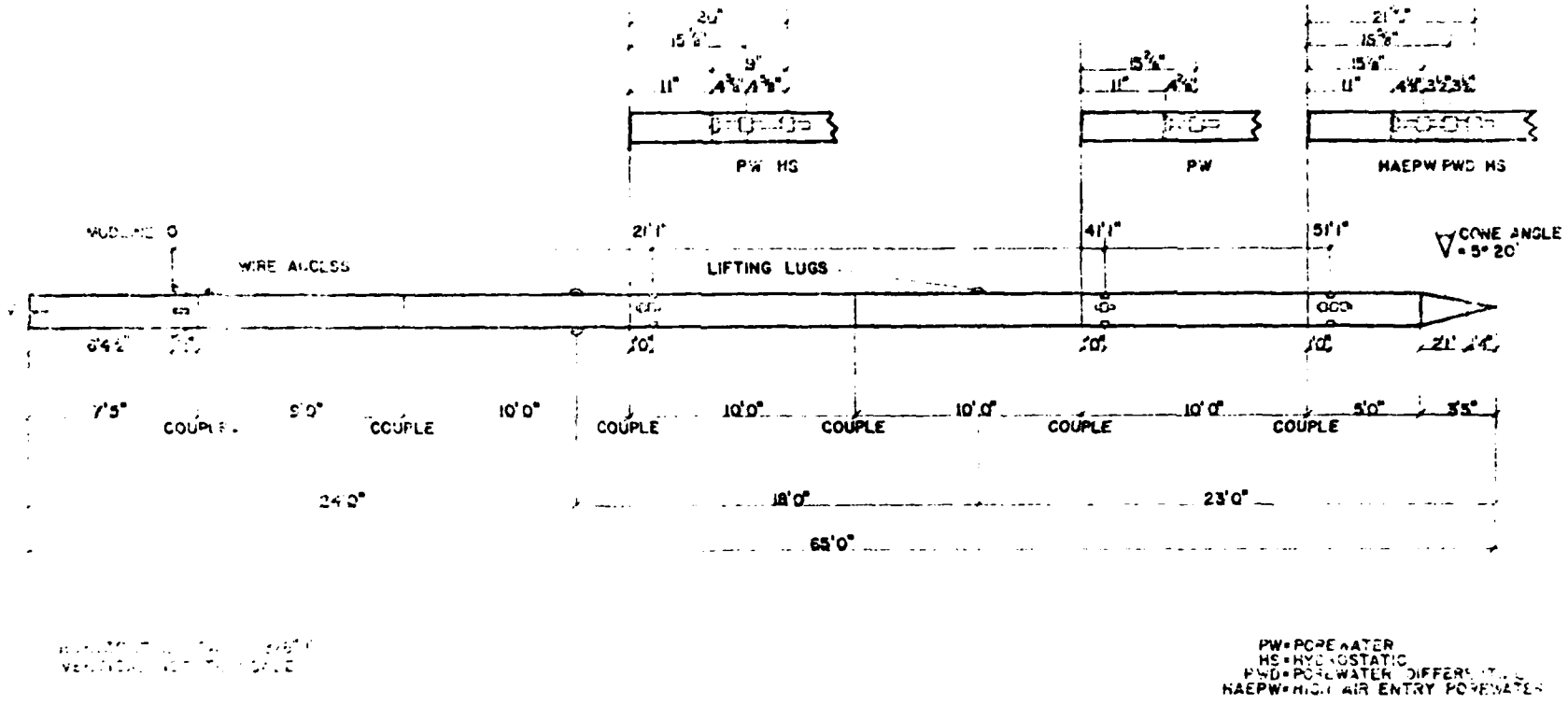


Fig. 4 Piezometer probe with locations of pressure sensors, pipe section lengths, and specifications of probe tip.

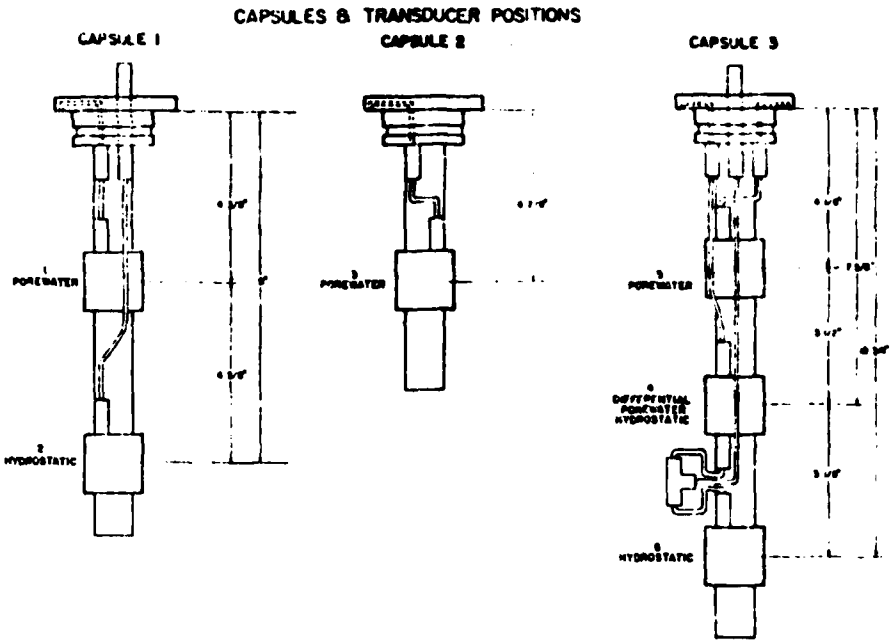


Fig. 5 Pressure sensor locations inside transducer capsules.

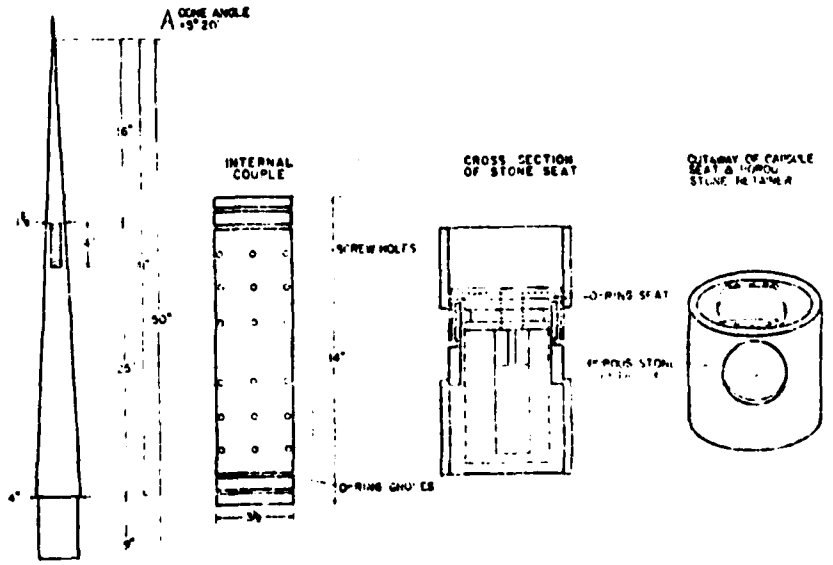


Fig. 6 Detailed probe tip design specifications, internal couple, filter seats, and capsule placement in pipe.

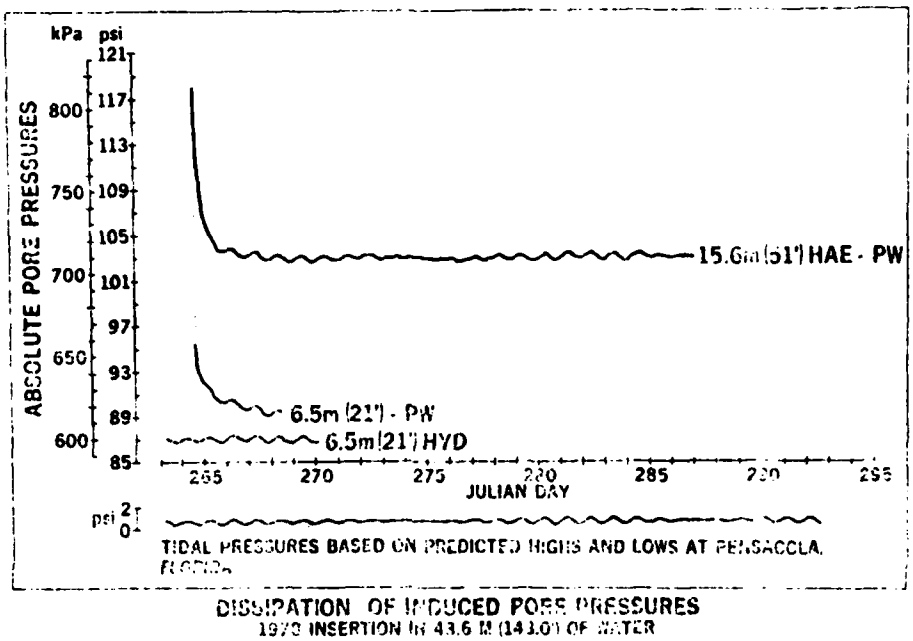
and n = 35-38%, k = 1-3mm/s, respectively. The rationale for the use of different types of filters has been discussed by Bennett and Faris (1979).

The piezometer uses three two-channel analog pen recorders as a back-up to a 14-channel analog magnetic tape recorder. The probe tip (approximately 5^{0} cone angle) was designed to control sediment disturbance and to produce simulated plane-strain soil deformation during probe insertion (Fig. 6). Using this design for the tip, the induced pore pressures during probe insertion can be related directly to the undrained shear strength of the sediment (Esrig et al., 1977; Bennett and Faris, 1979).

PIEZOMETER INSERTION DATA: MISSISSIPPI DELTA

Selected examples of the piezometer insertion data and long term pore pressure response in fine-grained soil is depicted in Figures 7A and B. Absolute pressure was measured at depths of 15.6 and 6.5 m below the mudline in 43.6 m of water off Main Pass, Mississippi Delta. Differential pore pressures were determined at depths of 15.6 and 12.6 m below the mudline. Significant induced pore pressures were generated due to probe insertion (Figs. 7A, 7B). The time required for the insertion pressures to dissipate to ambient pressure is, to a first approximation, a function of the probe pipe radius and the soil coeficient of consolidation which is dependent upon the permeability of the material. Using the log-fitting technique from consolidation theory, (Lambe and Whitman, 1969), t_{100} values (the time for induced pressures to dissipate) ranged from 19 hours to 140 hours (Bennett et al., 1982). These differences were a function of the different soil types penetrated at depths below the mudline.

Following dissipation of the induced pressures, measurements recorded over periods of days revealed pore pressure response to tidal pressures (Fig. 7A). Tidal variation was on the order of only 0.5 m (range of high to low tide). Similar correlations were observed at earlier test sites (Bennett and Faris, 1979). Limited dynamic surface wave activity due to tides and short period waves were observed to have an effect on the pore pressures at significant depths below the mudline. Details of these



DISSIPATION OF INDUCED PORE PRESSURES
1978 INSERTION IN 43.6 M (143.0') OF WATER

Fig. 7A Dissipation of pressures induced by probe insertion and ambient pore pressure as measured by absolute sensors. Note correlation of absolute pressures (pore water and "hydrostatic") with tidal pressures. Block 73, Main Pass area. (Bennett, R.H., et al., 1982)

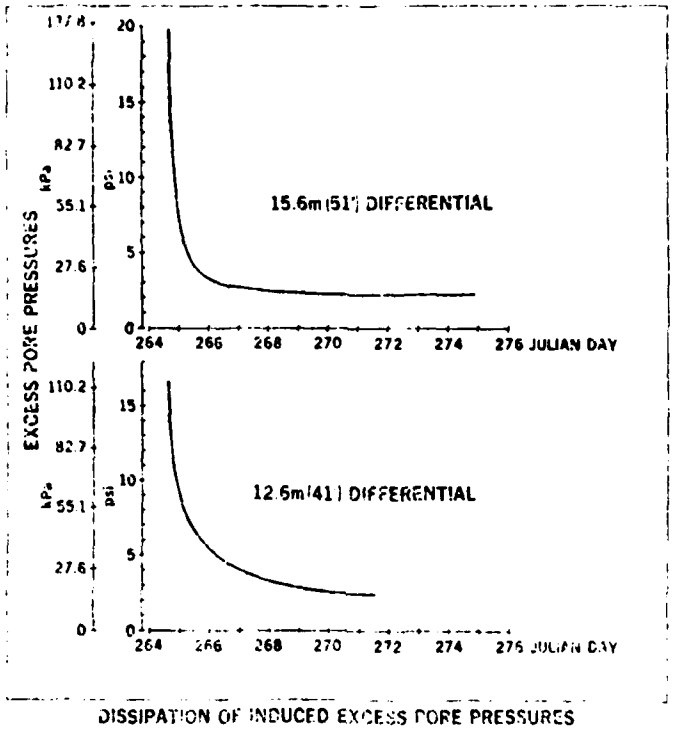


Fig. 7B Dissipation of excess pore pressures due to probe insertion. Block 73 (1978), Main Pass area. (Bennett, R. H., et al., 1982)

investigations can be found in the references cited above. These field investigations demonstrated the feasibility of making pore pressure measurements with multisensor probes in coastal invironments.

DEEP-OCEAN PIEZOMETER PROBE: INSTRUMENTATION

The piezometer probe design specifications and the types of materials required were established on the basis of ISHTE experimental objectives and environmental conditions. Limitations were placed on the probe size (that portion of the probe inserted into the sediment) in order to minimize perturbations in the thermal field induced by the heat source. Materials and electronic components were selected on the basis of their ability to withstand rather severe environmental conditions such as: high ambient hydrostatic pressure (68.9 MPa), high temperature differentials along the length of the probe (approximately 296^{o} and range of $4^{o}C$ to $300^{o}C$), strong electrolite in contact with materials (approximately 35 $^{o}/oo$ seawater salinity), potential for thermogalvanic corrosion, and the predicted small changes in sediment pore water pressures, spacially and temporally. These factors were considered the most important in the design of the probe, however other environmental factors were studied such as: soil strength, biofouling, oxidation/reduction potential and probe proximity to other experimental instruments.

The piezometer probe consists of an 8mm diameter titanium tube that attaches to a tip having a cone angle of approximately 5.3^{o} (Bennett and Faris, 1979). A porous stone, which allows pore water pressure to be transmitted to the pressure sensor, is fastened between the titanium tube and the probe tip (Figure 8, Table 1). Pore pressure is transmitted through the porous stone to an internal tube fastened to the pressure sensor. The differential pressure sensor is pressure balanced by a similar internal tube that runs from the pressure sensor to the top of the porous stone retainer. The pressure sensor is enclosed in a stainless steel housing which is pressure compensated to in situ hydrostatic pressure (Figure 8). The stainless steel pressure sensor housing is physically separated from the titanium by high dielectric polycarbonate material. The total lengths of the piezometer probes can be changed

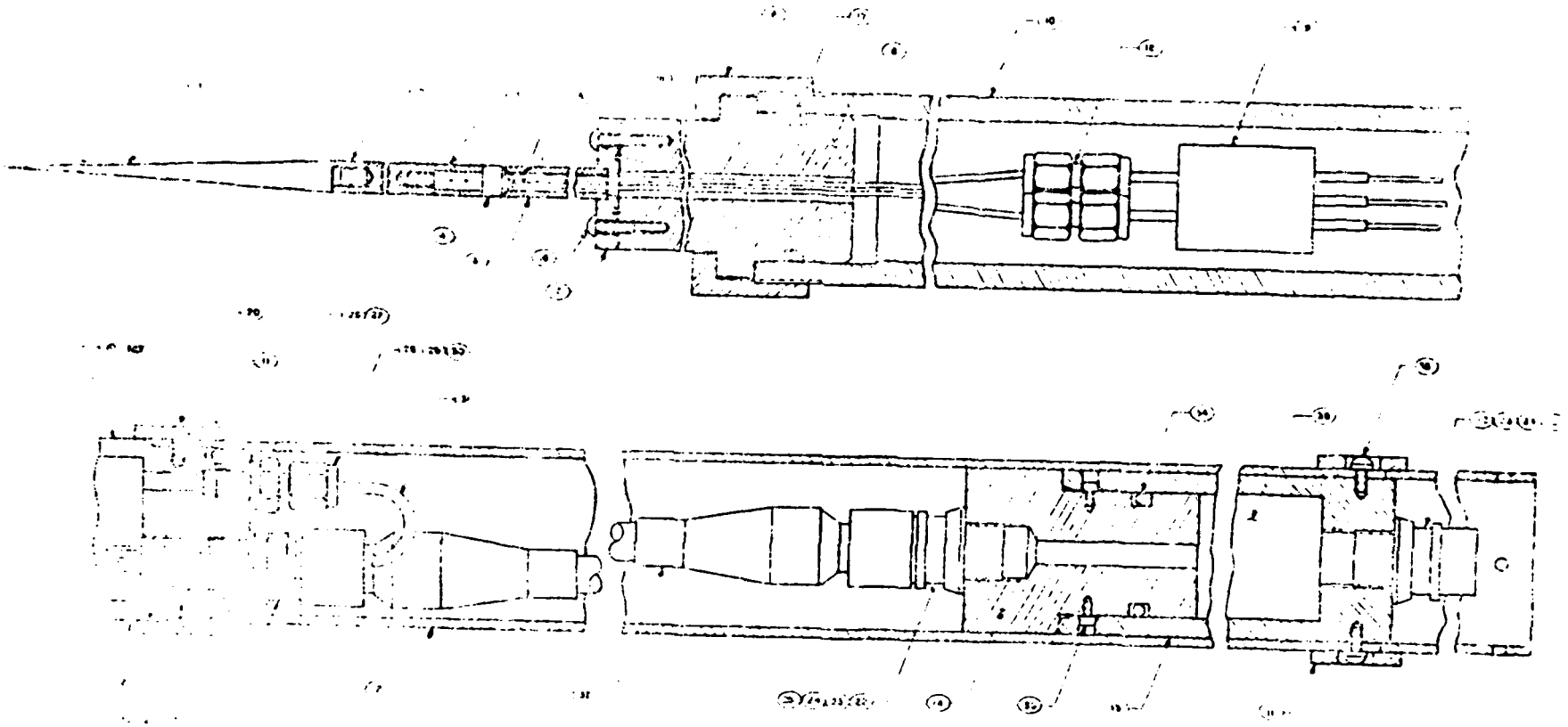


Fig. 8 ISHTE deep-ocean piezometer probe.

TABLE 1
PARTS LIST
ISHTE DEEP OCEAN PIEZOMETER

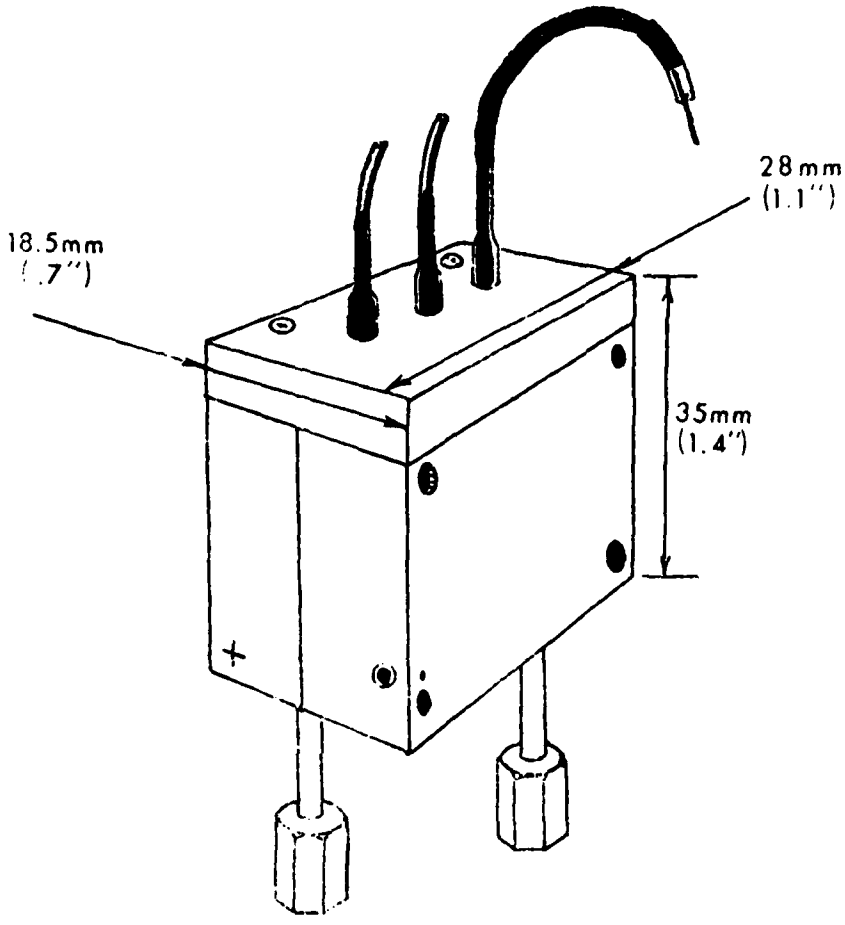
PART NO.	PART DESCRIPTION
1	PROBE TIP
2	PROBE TIP EXTENSION
3	STONE
4	STONE HOLDER
5	PROBE BARREL
6	TRANSDUCER TUBING
7	THRUST PLATE
8	COUPLING
9	NUT
10	TRANSDUCER HOUSING
11	GUIDE BEARING
12	SLEEVE
13	ELECTRONICS HOUSING
14	ELECTRONICS END CAP
15	"O" RING - PARKER
16	SCREW, TITANIUM 6-32 x 12.7 mm, UNITED TITANIUM
17	"T" SEAL - PARKER
18	UNION - SWAGELOK
19	TRANSDUCER - VALIDYNE
20	SCREW, 8-32 x 7.938 TYPE 316 SST, FILLISTER HEAD
21	"T" SEAL - PARKER
22	BULK HEAD CONNECTOR - BRANTNER
23	"O" RING - PARKER
24	"O" RING - PARKER
25	"O" RING - PARKER
26	O-SEAL - SWAGELOK
27	"O" RING - PARKER
28	NUT - SWAGELOK
29	FRONT FERRULE - SWAGELOK
30	BACK FERRULE - SWAGELOK
31	TUBING, .125 TYPE 316 SST
32	CABLE ASSY. 10.5" L - BRANTNER
33	SCREW, ALLEN HEAD, 6-32 x 7.938 mm TYPE 316 SST
34	"T" SEAL - PARKER
35	SCREW, 8-32 x 6.35 TYPE 316 SST, FILLISTER HEAD
36	ELECTRONICS ASSY. - VALIDYNE

depending upon the experimental design objectives for ISHTE. Only one pore pressure measurement at a preselected depth below the sediment-water interface (mudline) is possible with each piezometer probe. This limitation is imposed on the probe design because of the requirement to limit the maximum size of the probe diameter to 8 mm.

Solid state signal conditioning electronics are enclosed (at atmospheric pressure) in a stainless steel capsule and located directly above the pressure sensor capsule (Figure 8). A variable reluctance differential pressure transducer (Fig. 9) measures excess pore water pressure directly (differential above hydrostatic). A 5 kHz sine wave is supplied to the differential transducer by a carrier oscillator in the signal conditioner unit, producing an AC output from the Wien bridge-type transducer circuitry which is amplitude proportional to transducer unbalance. The AC signal is amplified, demodulated, and filtered by the signal conditioning unit producing a $\pm$ 5 VDC output level corresponding to the plus or minus full scale range of the transducer ($\pm$ 69.8 kPa [$\pm$ 10 psid]). The experimental design required that pressure sensors have a precision of 0.34 to 0.69 kPa. Test results indicate better than expected performance of the system. Data were recorded for the duration of the experiment with both analog strip charts and a data acquisition system with a hard copy printer.

TESTING AND CALIBRATION OF PRESSURE TRANSDUCERS

Pressure transducers were laboratory tested at high hydrostatic pressure (68.9 MPa) over a period of 750 hours to determine sensor characteristics and long term stability (Bennett et al 1981). The pressure sensors exhibit a zero shift during pressurization but display excellent long term stability under high pressure. The two piezometer probes were calibrated at atmospheric temperature and pressure prior to their installation on the APL support structures. Immediately following the simulation experiment, the pressure sensors were checked and calibrated (Figs. 10, 11). The transducer calibrations exhibit excellent linearity over the full pressure range, however a zero shift is observed in both sensors following depressurization (Figs. 10, 11). Correlation



VARIABLE RELUCTANCE
PRESSURE TRANSDUCER

Fig. 9 Drawing of differential pressure transducer depicting approximate dimensions.

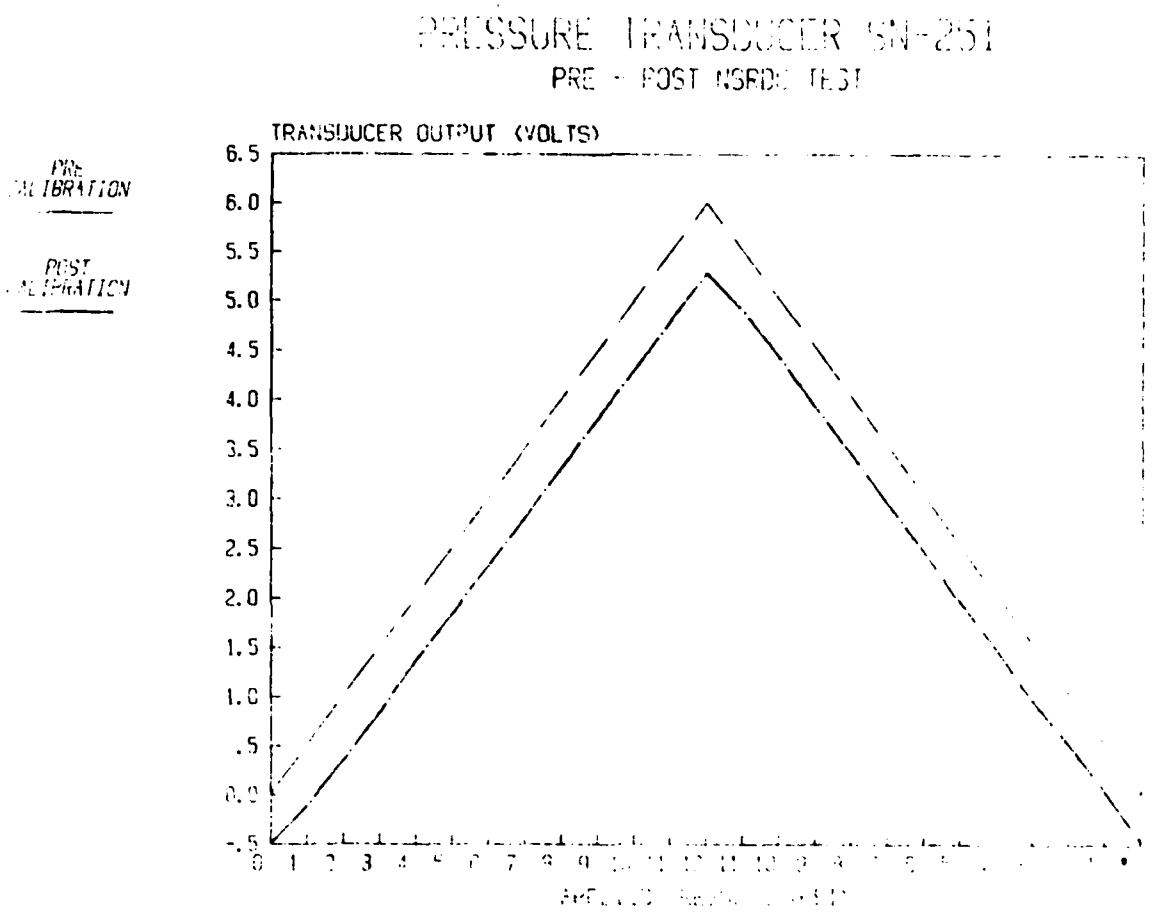


Fig. 10 Pre and post-simulation calibration of near field pressure sensor.

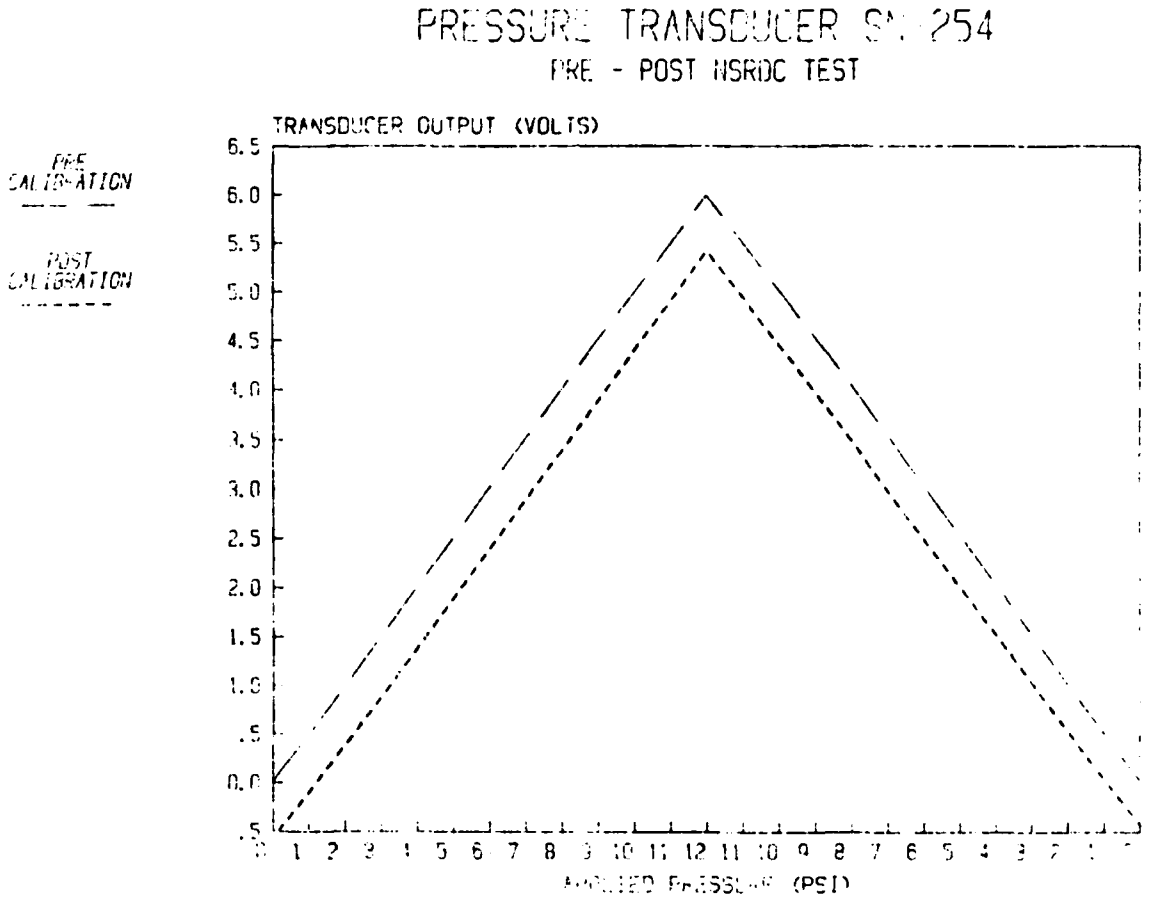


Fig. 11 Pre and post-simulation calibration of far field pressure sensor.

coefficients were determined for transducer output (volts) versus applied pressure for both differential pressure transducers using least squares linear regression analysis. The near field piezometer (No. 1) transducer (SN-251) showed a correlation coefficient of 0.999. The far field piezometer (No. 2) transducer (SN-254) showed a correlation coefficient of 1.000. Both pressure sensors displayed excellent linearity of voltage (output) versus applied pressure during calibrations at standard atmospheric temperature and pressure, (Figs. 10, 11).

Equations expressing the relationships of transducer output in volts (V) to applied pressure (P) are:

(pre-test) piezometer No. 1: $V = P\ (0.499) + 0.014$ (Equation 1)
(post-test) piezometer No. 1: $V = P\ (0.488) - 0.590$ (Equation 2)

(pre-test) piezometer No. 2: $V = P\ (0.500) + 0.006$ (Equation 3)
(post-test) piezometer No. 2: $V = P\ (0.469) - 0.818$ (Equation 4)

Although aesthetically undesirable, the zero shift is not detrimental to the measurement of sediment pore water pressure since an initial zero base line can be established following pressurization. Work is currently underway to calibrate the transducers at pressures comparable to the pressures used during the simulation test (approximately 55 MPa). A block diagram of the electronic system is depicted in Fig. 12.

PIEZOMETER INSERTION DATA: SIMULATION TEST

Pore water pressures were monitored with two piezometer probes placed at different positions from the heater. One near field piezometer (designated as probe number 1) monitored pore pressures 1.5cm from the heater (skin-to-skin) and 16.9cm below the mudline which placed the center of the porous stone 10.1cm above the center of the heater. Far field piezometer (designated as probe number 2) measurements were monitored 26.4cm below the mudline and 34.2cm from the heater (skin-to-skin) as depicted in Figure 13. Each probe was inserted independently.

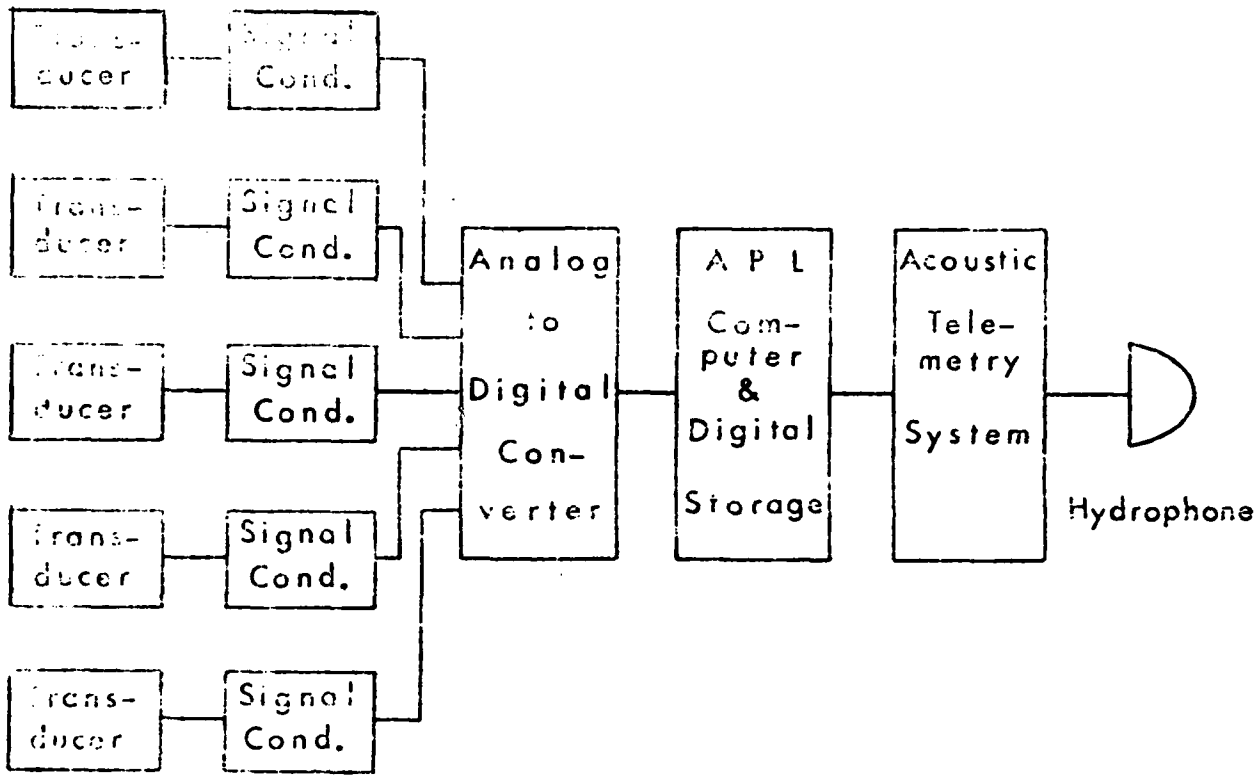


Fig. 12 Block diagram of major components of Deep-Ocean Piezometer System and interface with the APL Data Acquisition Systems.

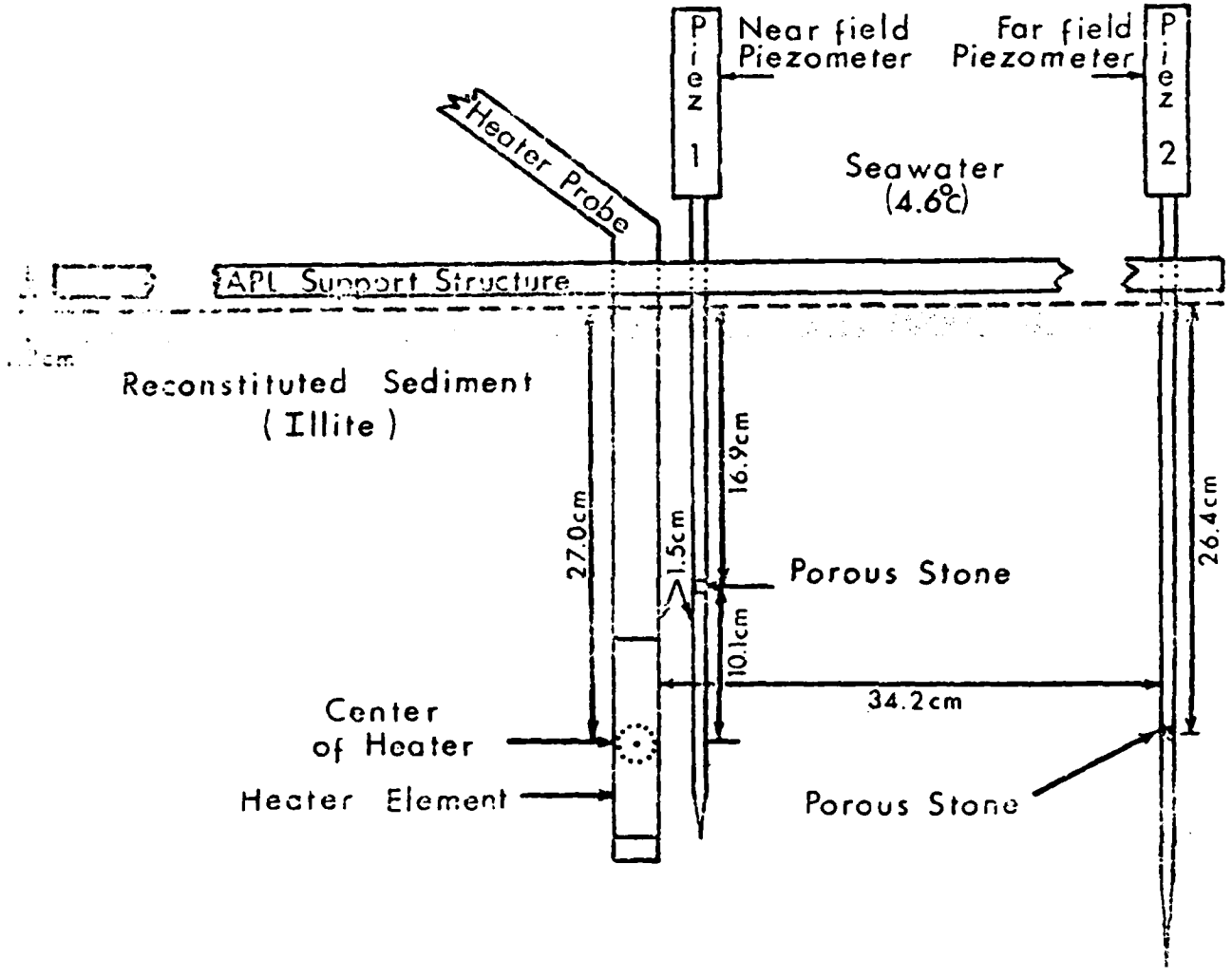


Fig. 13 Diagram depicting location of piezometers in reference to the heater.

During probe insertion, soil deformation occurs and excess pore water pressures (U_e) are generated and reach a maximum pressure along the probe-soil interface. Both near and far field insertion pressures were determined prior to pressurization of the soil in the hyperbaric chamber, thus the pre-test calibrations are considered reliable for the pore pressure tests and analysis at atmospheric temperature and pressure.

During probe insertion, induced pore pressures were determined and pore pressure decay was monitored (Figure 14). Normalizing the induced excess pore pressures (U_e) with respect to percent dissipation and plotting the data as a function of the log of time reveals significant differences in the decay curves (Figure 15). Applying the log-fitting method from consolidation theory (Lambe and Whitman, 1969), t_{100} is approximately 20.3 minutes for the near field piezometer and 61.5 minutes for the far field probe. In addition, induced pore pressure of probe number 2 displays a time delay of approximately 0.6 minutes, whereas probe number 1 (near field) displays nearly instantaneous decay of pressure following probe insertion. In concert with the major differences observed in the induced pore pressure characteristics between probes 1 and 2, the maximum induced pore pressures generated by probes 1 and 2 are 0.96 psi (6.6 kPa) and 1.87 psi (12.9 kPa) determined by applying equations 1 and 3 respectively.

The differences observed in the induced pore pressures and their respective decay characteristics suggest significant differences in the geotechnical properties of the soil in proximity to the two probes. The significantly lower induced pore pressure of probe 1 and its rapid pore pressure decay compared with observations from probe 2, indicates: 1) a reduction of soil strength (approximately 51% less at the near field probe compared with the far field data), and 2) a significantly shorter drainage path (at the near field probe) for the induced pore pressures to dissipate compared with the far field. The time delay of induced pressure prior to dissipation at the far field probe also supports these conclusions. Severe cracking of the soil observed during heater insertion is probably a major factor responsible for the observed differences in the induced pore pressure characteristics.

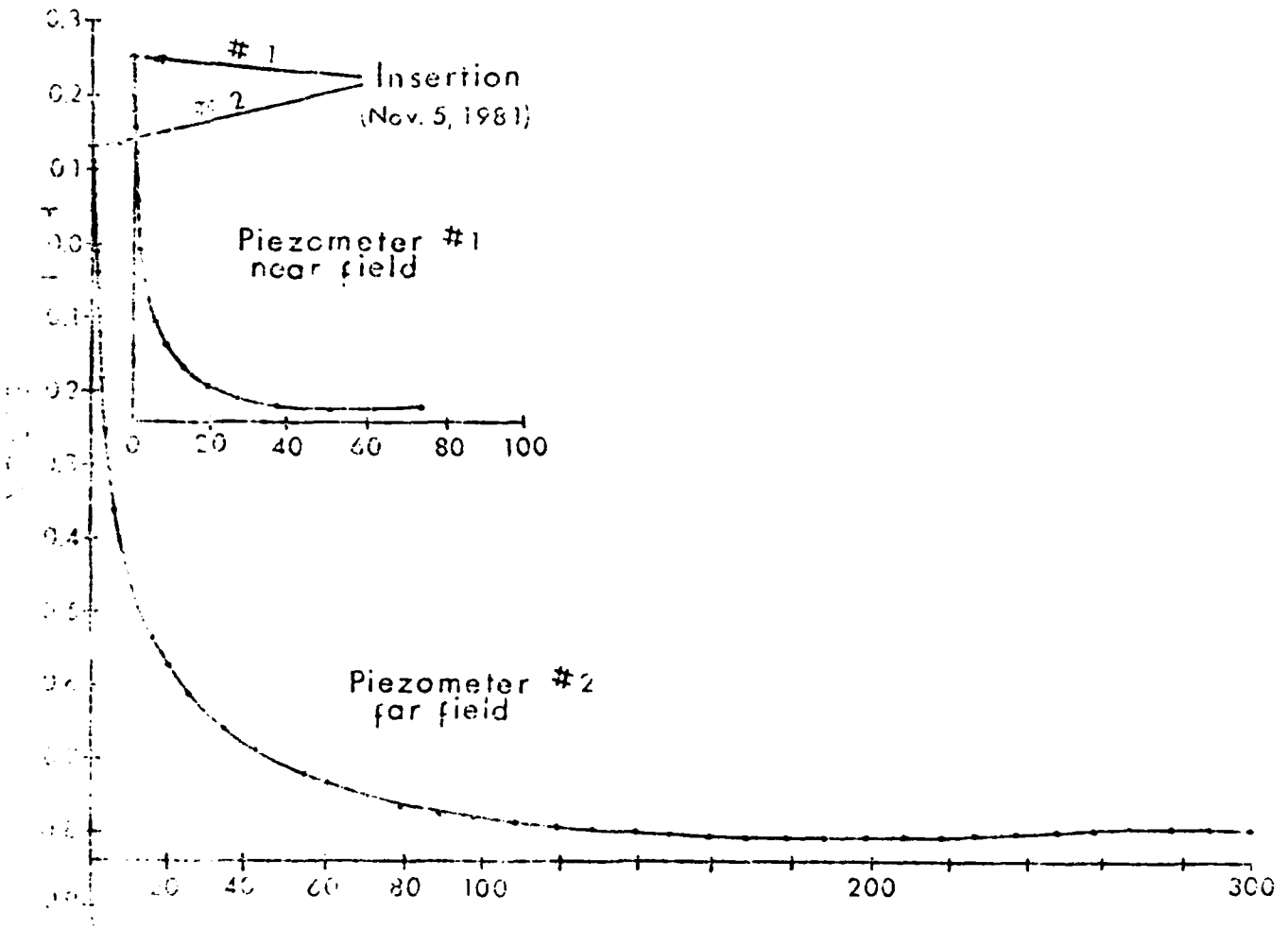


Fig. 14 Dissipation of induced pore pressures due to probe insertion (volts vs time).

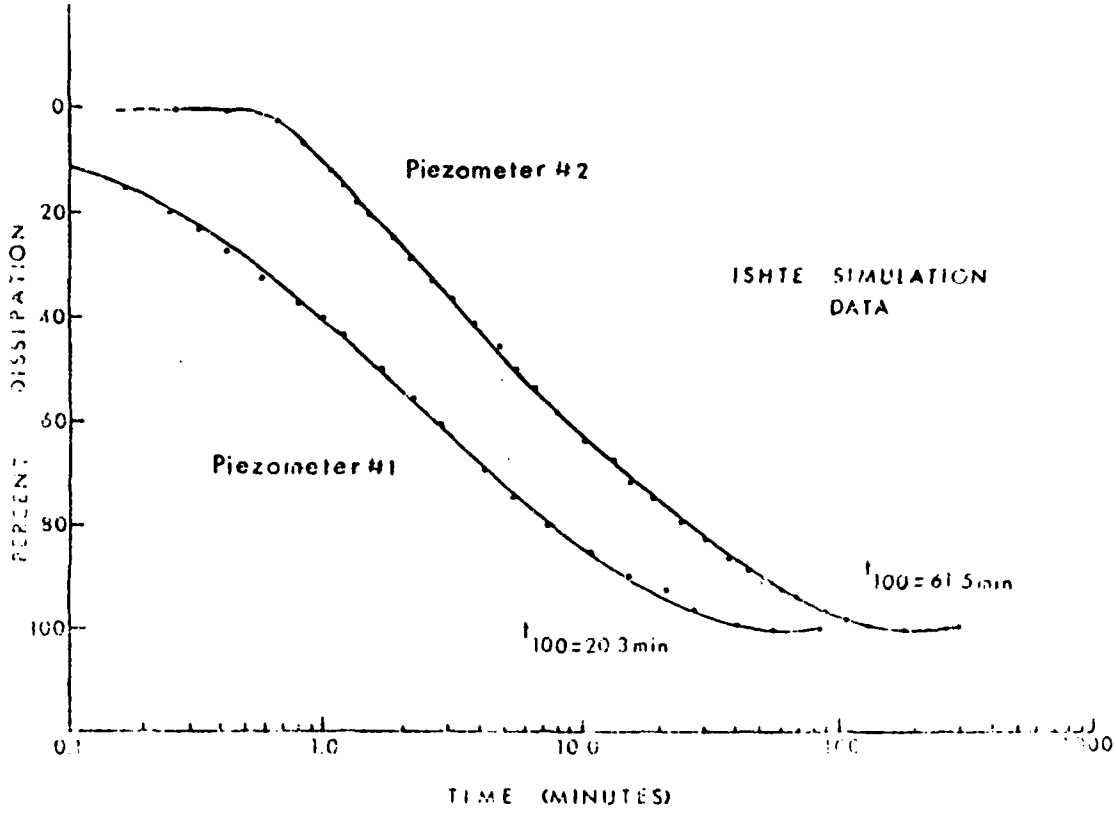


Fig. 15 Induced pore pressures normalized with respect to percent dissipation versus the logarithm of time. Note difference in decay times for the near field and far field piezometers.

During the simulation test, pore pressures responded (excess pore pressures were developed) to thermal gradients induced in the soil due to temperature increases generated by the heater. Discussion of these data, however, is beyond the scope of this report.

SUMMARY

Multisensor piezometer probes tested in fine-grained marine soils in shallow water coastal environments have demonstrated the feasibility of making pore pressure measurements offshore over extended periods of time. These investigations and high pressure simulation tests with small diameter probes have shown the criticality of pore pressures to seafloor engineering applications and other geotechnical site evaluations. Determination of the in situ pore pressure provides a quantitative means of assessing the consolidation state of soil deposits and the time dependent changes in the vertical effective stress in response to environmental forcing functions.

ACKNOWLEDGEMENTS

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REFERENCES

Bea, R.G., Bernard, H.A., Arnold, P., and Doyle, E.H., 1975. Soil Movements and Forces Developed by Wave-Induced Slides in the Mississippi Delta. Journal of Petroleum Technology, 1975, p. 500-514.

Bea, R.G., Arnold, P., 1973. Movements and Forces Developed by Wave-Induced Slides in Soft Clays. Fifth Annual Offshore Technology Conference, 1973, p. 731-742.

Bennett, R.H., Bryant, W.A., and Keller, G.H., 1976. Initial Results and Progress of the Mississippi Delta Sediment Pore Water Pressure Experiment. Marine Geotechnology, Vol. 1, No. 4, p. 327-335.

Bennett, R.H., Faris, R.J., 1979. Ambient and Dynamic Pore Pressures in Fine-Grained Submarine Sediments: Mississippi Delta. Applied Ocean Research, 1979, Vol. 1, No. 3, p. 115-123.

Bennett, R.H., Burns, J.T., Lambert, D.N., 1980. Design and Development of Deep-Water Piezometer for the Sandia Subseabed Disposal Program (SDP). Status Report, 1980.

Bennett, R.H., Burns, J.T., Clarke, T.L., Faris, R.J., Forde, E.B., Richards, A.F., 1982. Piezometer Probes for Assessing Effective Stress and Stability in Submarine Sediments. Marine Slides and Other Mass Movements, p. 129-161.

Bennett, R.H., Burns, J.T., Lambert, D.N., 1982. Development of Deep-Ocean Piezometer System for the Subseabed Disposal Program. Status Report for FY82.

Bennett, R.H., Burns, J.T., and Lambert, D.N., 1982. Fabrication and Testing of Deep-Ocean Piezometer System and Components for the Sandia Subseabed Disposal Program (SDP). Status Report, Jan-Sept, 1981, p. 643-646. Sandia Report: Subseabed Disposal Program Annual Report, Jan-Sept, 1981, Vol. II, Part 1, p. 1068.

Esrig, M.I., Kirby, R.C., and Bea, R.G., 1977. Initial Development of a General Effective Stress Method for the Prediction of Axial Capacity for Driven Piles in Clay. Proc. 9th Annual Offshore Technology Conference, 1977, p. 495-501.

Henkel, D.J., 1970. The Roll of Waves in Causing Submarine Landslides. Geotechnique, Vol. 20, p. 75-80.

Hollister, C.D., Anderson, D.R., Heath, G.R., 1981. Subseabed Disposal of Nuclear Wastes. Science, 213, p. 1321-1326.

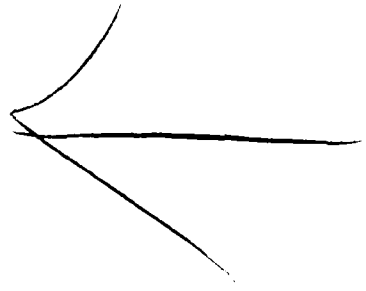
Lambe, T.W., and Whitman, R.V., 1969. Soil Mechanics. John Wiley & Sons, 553 p.

Olson, L.O., and Harrison, J.G., 1979. Sea Floor System for an In Situ Heat Transfer Experiment. Oceans '79, IEEE publication No. 78 CH 14 78-7 OEC, p. 421-423.

Percival, C.M., Mevey, D.F., Olson, L.O., and Silva, A.J., 1980. In Situ Heat Transfer Experiment (ISHTE). Marine Technology 80 - Proceedings: The Decade of the Oceans, 1980, October 1980.

Percival, C.M., 1982. Laboratory Simulation of Deep-Ocean In Situ Heat Transfer Experiment. Marine Technology '82 - Proceedings of the Annual Conference of the Marine Technology Society, Sept. 82.

Wright, S.G., 1976. Analyses for Wave Induced Seafloor Movements. Proceedings of 8th Annual Offshore Technology Conference, Vol. 1, 1976, p. 41-50.



Q: FRED SCHELBY, SANDIA NATIONAL LABS, TO R. BENNETT, NAVAL OCEAN RESEARCH AND DEVELOPMENT ACTIVITY

This differential pressure transducer, Validyne I guess, how do you get the beat of the Delta P? Both of those ports are so close together. Do you close one port off?

A: DR. BENNETT

It was kind of hard to show in that diagram, but the reference side is actually isolated from the port pressure side. We have the two titanium tubes that come down from the transducer. One is ported directly to the port stone, the other is isolated from that port stone at the bottom. It sees only hydrostatic pressure.

Q: FRED SCHELBY

It's out of the mud or something, or it's far enough away that it looks like you're measuring the same thing with both ports unless the second port is closed off?

A: DR. BENNETT

No, the reference side of the transducer only sees hydrostatic pressure. The other port only sees port through the port stone. I have a diagram that will show this a little clearer than the slide.

Q: FRED SCHELBY

If you're going to do this at 10,000 psi have you measured the effective common load pressure on the pressure transducer? Sometimes you expect the sensitivity of the transducer to shift it at these pressures.

A: DR. BENNETT

Right, we haven't gotten to this stage. I thought we would have it calibrated and checked out at high pressure, but we've had a few problems with our pressure calibrator and had to redesign it. There may be somebody here that can calibrate these babies at high pressure. If so, I would sure like to know about it. But we haven't been able to find anybody that can check them out at high pressure.

Q: DONALD GERIGK

Could you make some comment on the selection of any aliasing filters and cut off frequencies in relation to the phase problem you illustrated?

A: PAT WALTER

Just to talk qualitatively. I think in general the literature relative to anti-aliasing filters has tended to be motivated by the requirement for a steep filter skirt. If you look at anti-aliasing filters as they are used, for example, in modal analysis where you have two channels you really don't care. Because if you have, for example, as it related to modal analysis, if you run both channels of data through the same filter there is a normalizing action that

goes on when you ratio the two channels anyhow and the effects of deviations from amplitude response and phase nonlinearity kinda go out in the wash. I think in general there has been somewhat of a dangerous tendency around the manufacturers of digitizers to put filters in the front end of those digitizers that aren't well thought out. They're motivated by being 40dB down or whatever people require by the niquis frequency and they get so concerned about getting data continuation that, I think in general, or at least quite often in the anti-aliasing filters' phase, just get disregarded.

Q: BOB SILL, ENDEVCO, TO SCOTT WALTON, ABERDEEN PROVING GROUND

You had remarkable accuracy. Did the air bubbles or air gaps have anything to do with your accuracy?

A: SCOTT WALTON

The oil chamber that has the pressure in it is flushed completely with oil. All air bubbles are removed by pumping the oil through. The transducers are packed with heavy silicon grease to make sure that there are no hidden voids in there. As far as position of the diaphragm, they are all positioned about the same, within say 40,000 of an inch of the same position. If there had been air bubbles, we could have had problems not only with the measurements but problems with the machine itself functioning properly. So I'm quite sure that all air gaps had been removed and filled with fluid. As shown in one of the slides, the difference between oil filling the gaps and grease filling the gaps was a small but real difference. Did that answer your question?

Q: PAUL LEDERER, WILCOXON RESEARCH, TO SCOTT WALTON

Do you slow the static pressure calibration set-up? How do you calibrate your piezoelectric gages?

A: SCOTT WALTON

I'm glad you asked that question. I have five viewgraphs to show you. This is a deadweight tester. I'm sure most of you are familiar with it. One of the things that we do for piezoelectric gages is to put a valve number 2 in to isolate the deadweight pressure from the release of pressure which we use for piezoelectric calibration. They are AC coupled and only see a change in pressure. I'll show you a typical output of a deadweight pressure where you can see the pump cycles going up and you see an oval and a dashed circle. The pressure change is where piezoelectric transducers are calibrated, and I'd like to show you those two blown up. Looking first at the oval, there is a good one and a bad one. Here's a poor operator. If you did this you wouldn't be at Aberdeen for very long. But if you see at the very end there, where he closed valve number 2 very rapidly, which causes a small change in volume, he's increased the pressure by roughly half a percent. Because of that uncertainty, some people do not even isolate their piston from the pressure change, and when they release the pressure the whole stack of weights and pistons go slamming down. It's hard on the pistons, but some will take that. Here's a good operator, and you can still see there is a small change of about a tenth of one percent when he closes that valve number 2. So that's an acceptable error to us. The machine I think is spec'd about .1 to .05 percent, something

like that. Here's the circle portion of that original, the return to zero. You can see that there are two different transducers. One's a quartz and one's a tourmaline and in that particular run, with those particular serial numbers, one drifted positive and one drifted negative. And I defy you to pick the proper point better than a tenth of a percent. So, our overall accuracy was maybe .1 to .2 of a percent and by far the least of our problems. If we could ever get that accurate we'd be in good shape.

Q: PAUL LEDERER

The mechanisms, that dynamic calibrator, you said there is an impact on the piston. How do you generate the impact? Do you drop a mass on it, no mass, or what?

A: SCOTT WALTON

That's question 37B. There is the overall mechanism. You can see a large tank that's filled with air pressure to the tune of 10 to 60 psi. Not very much air pressure. It propels a slug about 6" in diameter and 6" long down this tube which impacts the piston. There's a little rubber buffer pad between the piston and the slug.

Q: PAUL LEDERER

So you get very repeatable shots then out of this thing?

A: SCOTT WALTON

No, the shot to shot variation at 50,000 psi was as much as four or five thousand psi. So they are not terribly repeatable. There are things you can do to improve that. But I should point out in the latin square analysis, which is an excellent and very powerful statistical technique, it reduced shot to shot variation, which was to the tune of 5,000 psi, and gage to gage variation, which was to the tune of 500 psi, to show a tiny difference of 68 psi that was real.

Q: PAUL LEDERER TO BOB GEORGE, AEROMECHANICS LAB USARL

In your slide of the calibration set of using a scanivalve, I seem to see a number of pressure labels ranging from about 2 psi to 50 psi. Yet your indicator at the output had arranged a 0 to 15 psi.

A: BOB GEORGE

The slide was supposed to be .2 to 5.

Q: PAUL LEDERER

Is there a significant time lag in this type of system? I think the scanivalve has very small ports. Doesn't it take a while before the pressure builds up in your line when you calibrate it before you can depend on the reading of this pressure gage? About how much time does it take?

A: BOB GEORGE

Absolutely, there is a time lag and if you were measuring backwards, if you want to measure an unknown pressure in the transducer about three a second is about as fast as you want to go with a nominal length of two. But in this case you've got all day if you had to wait, because you're just stepping these manually. Say when you first start out there's no pressure, the backside of all the transducers is a reference to atmospheric pressure. The tunnel is off, the wind is not blowing, so the transducer is reading zero theoretically. You make your first step and wait a few minutes or a minute or two, take your data sample, step the transducer to the next port, pick up the next pressure, wait a minute or two, take your data sample, step again, wait a minute or two, take your data sample. When you've gone through five or six, or as many different valves as you wanted, to have those transducers calibrated to auto-home the device back to your static reference or your total reference whatever is the case. You know the time has no element.

Q: JOE QUINTANA, AIR FORCE WEAPONS LAB, TO SCOTT WALTON

I was just wondering if you've really looked into the acceleration effects of your transducer making your breech pressure measurements? If you have, did you see any effect? The other thing I would like to know is what magnitude of shock acceleration do you feel you're seeing in that application?

A: SCOTT WALTON

The magnitude of the large caliber weapon in recoil is on the order of 250 Gs.

Q: JOE QUINTANA

What I had in mind is on-axis acceleration for the way the transducer is mounted.

A: SCOTT WALTON

That is correct. The transducer is mounted, well can be either way, in the line of recoil, which would be this way in the mushroom of the gun, or perpendicular to the motion of recoil. When we do differential pressure, they're both directions. The magnitude of that is typically 250 Gs. We did do a shock sensitivity check using a shock test machine to 250 Gs. Typical numbers are about .02 - .5 psi per G, in the worst direction. The shock test was considerably worse than the vibration test. But the overall conclusion from all of that, the worst, it was very difficult to do that test and have it make any sense because the hardest problem with the piezoelectric transducers - the cables themselves were much much more sensitive than the gages. So the big problem is the cables.

Q: JOE QUINTANA

Okay, then you probably don't describe some of that error, let's say scatter in your total analysis, to be due to any acceleration effects, right?

A: SCOTT WALTON

I guess I should tell you, I'm not going to describe that. The little paper that is in these proceedings does not address acceleration sensitivity at all.

There is a book this thick which you can get. It's limited to government agencies only, and it's report APG-MT-5649, available through the Defense Documentation Center, but distribution is limited to U.S. Government agencies only. Commercial people with a well-justified need for this information can send a request, in writing, to the Army Materials and Mechanics Research Center, which is the organization that paid for this work.

C: JOE QUINTANA TO DR. BENNETT

You did use a cindered material for your filter and I want to mention a little experience I had. And that is, if you're using a cindered filter or a porous type stone, two things happen. Number one you trap air in the interficial space between the porous articles. Also, air gets trapped under the surface of what it is that your cindered material is. We found that we had much difficulty in calibrating the transducer system to measure pore water pressure after we included the cindered material; in other words, the filter. We even had to get away - we had to leave the approach of using cindered material for the filter because we could not eliminate the air effects. Consequently, what we had to do was go to a slot filter in our head and we also had to redesign our transducer on the surface so we could have the probe totally engulfed in silicon grease. And then we placed the probe down into our media. Then we had to eject the inserta bin hydraulically, remotely, the tip to make sure that all these effects were due to air, because air can give you a real problem.

A: DR. BENNETT

We recognize that is a problem. Saturation is a problem in the shale oil work we've been doing. We have had some anomalies occur. It's conceivable it could have been caused by a saturation problem. We don't believe that is the case. However, we feel that it's not a problem at 10,000 psi because that air is going into solution. I can't conceivably understand how you're going to have a problem with air at 10,000 psi.

Q: DAVE MILLER, SUNDSTRAND, TO SCOTT WALTON

I was wondering in your dynamic calibration if you had an absolute standard or if those were all relative measurements, and also if you have drawn any conclusions as far as using static calibrations for a dynamic test?

A: SCOTT WALTON

To begin with, no, there is no absolute standard for dynamic. Really dynamic calibration is the wrong word. I had dynamic pressure generated. I had no idea what the pressure would be before I shot it and the only way I had of knowing what it was after it had been shot was to compare the four transducer outputs, which brings us to majority rules logic and lots of other things. One of the reasons I'm here is to find out if anybody has anything in the works for dynamic pressure calibration where you know before hand what the pressure will be, and I think we've wanted that for a long time. As far as comparing static

recalibration to dynamic readings, again using majority rules logic because all I have is several different transducers to talk about, most of them worked quite well. The only time I did have a problem was when there was interference with the mount and some of the miniature transducers were put in a large mount so we could swap everything in and out of the same hole. If that mount had a problem interfering with the transducer, that problem acted different statically than dynamically and that's the reason for outliers. That turns out because they responded differently dynamically than statically and the problem was indeed traced and found to be a mount interaction problem.

Q: DAVE MILLER

I also wondered if you've done enough experiements with this that you've noticed any fatigue effects on any particular type of transducer?

A: SCOTT WALTON

No, not fatigue effects. I could show you one particular slide that might be interesting, which is calibration over a number of cycles. That's 10 years of experience for one particular transducer and this fellow never went outside. It was always in the lab and was very good roughly 1/2 percent to 1 percent over a 10-year period, lots of shocks. Other transducers did not work so well, and I don't know whether it was fatigue. And also some of them have been destroyed by the gun, but I guess that's not germaine to this discussion.

Q: CHUCK BELENSKY, GRUMMAN AEROSPACE CORPORATION, TO BOB GEORGE

What type scanivalve did you use or did it make any difference? The model?

A: BOB GEORGE

It was a conventional scanivalve, manufactured in San Diego, the SGM. It really doesn't make a difference. Since I have the floor here let me say in selecting the scanivalve you want to be concerned with how much pressure you are going to put behind it. If you're going to use the technique, you put back-up pressure behind the scanivalve. Remember, the scanivalve is a revolving disk that picks up multiple pressures normally. You don't want to put so much pressure on that that you make the face of the disk part from the inner working face. If you are going to have large pressures, you've got to investigate whether or not that scanivalve can take it or not. The range I'm in, the SRG, anyway that variety is perfectly acceptable for the five pounds through a couple of ports. I think its 2-1/2 pounds psi back up pressure and the port that you're entering is miniscule. It is not adding much load on the disk, on the wafer.

Q: PAUL LEDERER TO SCOTT WALTON

To answer your question, back in 1960 the Bureau of Standards built a quick opening valve pressure dynamic calibrator for Aberdeen Proving Ground. Does it ring any bells?

A: SCOTT WALTON

Yes, and there is yet another one under development by Harwood. It's a positive step, but it is a step, it's not a pulse, which to my way of thinking is a great improvement over a release which is what we currently use with the deadweight tester. However, it is an infinite change. What I want is something that goes up and comes back down and is all done in six milliseconds or anywhere from 1 to 20 milliseconds.

Q: PAUL LEDERER

Okay, I'm not familiar with any such device. All the ones that I have worked with are positive-going, essentially, ramp functions taking different amounts of time. They are basically quick opening valves. You could also use a shock tube, which is again a rapidly rising ramp. What I wanted to ask you about was what about thermal transient effect on the gages? Do you use the degrees as the thermo barrier?

A: SCOTT WALTON

Talk to me later.

Q: HARVEY WEISS, GRUMMAN AEROSPACE CORPORATION, TO PAT WALTER

In the last slide, by the way the paper was quite interesting, specifically there was a factor of something like .5 or in round numbers - I don't have it

memorized - but roughly 50 percent of the 3dB point is the place where you recommended the maximum point of utilization in terms of bandwidth. The two-pole butterworth could be compared, I would imagine, with a simple second-order spring-mass type system. And I don't know if it's dumb luck or what, but this idea of the dependency or the degree of compromise on this dynamic data due to face response, is something that frankly I personally have tended to ignore. But I think dumb luck always worked it out because we've always sort of learned from very very early on experience, maybe the old Stathem instrument notes and stuff like that, to just bring out up to roughly the 5 percent amplitude range of no more than 20 percent of the 90-degree facia point, which might be equivalent to the -3dB point of a two-pole butterworth. Now, if those curves of the second-order system talk about roughly five percent amplitude, at about 20 percent of the natural frequency of the second order system, how did you arrive, without getting too detailed because I'm not smart enough, how did you arrive at the 50 percent of the -3dB point and still maintain some good amplitude characteristics at -5 percent?

A: PAT WALTER

I wish I had that one viewgraph in front of me now so I could pick off the number. But it turns out that if you go to the old second order system that you're talking about with the Stathem curves, if you go in for .707 damping, that is exactly a two-pole butterworth. That's the algorithm for a two-pole butterworth with .7 damping. If you have no damping, then you're flat to within like 5 percent up to about 1/5 of the natural frequency. But if you're damp, you're 5 percent off, and I forget exactly where that point is, but I think it

would be past the 20-percent point significantly. But you are right, normally .7 damping on a second order system, which is your butterworth, that gives you the maximum flight amplitude response and it gives you fairly linear phase. And I think if you would really look at those curves, and if my chart said .5, it just has to come right off those curves.

Q: PETER STEIN

The last slide you showed, showed the shunt calibration possibilities of the four-arm transducer. Are you suggesting that people use an equation to calculate the shunt cal? Or are you suggesting that they should experimentally determine the pressure equivalent of a particular shunt cal? And that's because you have these matched series resistors in series with the bridge.

A: JOE MALLON

No, I would say that it should be done experimentally. Also, there is slight asymmetrically, plus or minus. To get best accuracy you might have a separate plus or minus shunt cal value if you want. We can supply the transducers with either shunt cal resistor or shunt cal value. However, we would pick it experimentally. Of course, it is nice to calculate it in the first instance so you know you are in the ball park.

SESSION IV

MANUFACTURERS' PANEL

Peter K. Stein, Chairman

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MANUFACTURERS' PANEL - 12TH TRANSDUCER WORKSHOP

JUNE 7-9, 1983
MELBOURNE, FLORIDA
(Holiday Inn)

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WEDNESDAY EVENING - INTRODUCTION TO SESSION #4 - MANUFACTURER'S PANEL

Introductions by panel chairman and moderator Pete Stein of Stein Engineering Services, Phoenix, Arizona, follow. Each panelist gave a brief company affiliation and product or services information.

STEPHEN F. KUEHN, SANDIA LABS - organizer of this panel, member of the RCC/TG Vehicular/Transducer Committee.

FRANK HINES - President, RdF Corporation, Hudson, New Hampshire. Specialties: Temperature; line of industrial/commercial probes; airspace-production, aircraft-commercial temperature sensors for windows, radiometers, temperature measurement on re-entry heat shields, heat flow sensors in general; etc. Had over one thousand sensors on first space shuttle flight.

MAX KOPP - President, Validyne Engineering, Northridge, California. Design and Application Engineer - specializing in low range differential pressure transducers (hi-line pressure, wet-wet); also builds signal conditioning carrier demodulator type; data system; transmitter 4 to 20 milliamp and square root outputs for doing flow work, flow measurements, pito type measurements, etc.

BOB LALLY - PCB Piezoelectronics Inc., Depew, New York - slides presented - Expertise and specialties - Piezo type pressure gages, took over production of tourmaline type transducers from Susquehanna Company for shock wave measurements, charge type transducer.

WALT KISTLER - Kistler Morse Corporation, Bellevue, Washington - Voltex Company, Salt Lake City, Utah. Specializes in developing new basic sensors of vibrating quartz elements to measure force, acceleration, pressure and temperature.

JORGEN JENSEN - Bruel & Kjaer Instruments Inc., Marlborough, Maryland. Speciality - vibration and sound equipment instrumentation. Made in Denmark, sales office in Maryland.

LEE MYERS (substitute for John Easton) - SENSOTEC. *Design and Application* Engineer with SENSOTEC Inc., Columbus, Ohio. Specialities - bonded strain gage pressure transducers and load cells and associated electronics; differential wet-wet, wet-dry pressure transducers; integral electronics into transducers; .05 percent accuracy pressure transducers; etc.

PAUL LEDERER - Wilcoxon Research, Rockville, Maryland. Specialities - vibration measurements and vibration generation; piezoelectric accelerometers, both direct charge type and integral electronics; low noise amplifiers; piezoelectric shakers; signal conditioning equipment; hydrophones; etc.

SCOTT WALTON, ABERDEEN PROVING GROUND

We talked a little about dynamic pressure pulse calibrators, and what I would like is a device that goes up 50 to 100,000 psi and back down in anywhere from 1 to 20 milliseconds, known ahead of time to within .25 percent, and is traceable to NBS. I don't know that we need to address that any further. Paul Lederer made one a long time ago that went up but did not come back down. The second question I had was, does anyone have a transducer for measuring side-on pressure shock waves? Shock wave is a directional phenomena, directional blast, and I am interested in measuring the side-on pressure regardless of what direction it comes from. Theoretically it is impossible, but there are various compromises one can make. I wondered if anyone has a magic bullet to measure shock waves anywhere within a hemisphere? You don't know the direction that it comes from other than it is within a hemisphere and I would like you to tell me what the side-on pressure is, not the reflected pressure or the total stagnation pressure, but the side-on pressure of that shock wave. Last question is something that we always make, a tradeoff. Matter of fact I was about to talk about that this morning. Paul Lederer said, 'what about thermal transient response of your transducers?' We used his techniques discussed in his bulletins 905 and 961; several bulletins that he put out in his NBS days on measuring that, which I did by the way. We found ways to protect gages from thermal transients, but we always lose frequency response when we do it. It is a continuing tradeoff and my requirements, should you care to accept this mission, are for 100,000 psi range transducers. We would like frequency response of better than 20 kilohertz and less than ¼ of one percent response to thermal transients on the order of 300 joules per square centimeter. For the shock measurement transducers of the 10 to 20 psi range we would like much higher frequency response, maybe to 500

kilohertz and less than 1 percent response to 10 joules per square centimeter thermal transients.

PETE STEIN, STEIN ENGINEERING SERVICES

Which of the manufacturer's would like to start this one?

BOB LALLY, PCB PIEZOTRONICS, INC.

I can address the questions, I don't think I can provide the answers. Those are what I would call classical problems, in that they have been with us for a long time, and I suspect they will continue to be for a long time to come. What we can generally expect is a kind of evolution or process that will gradually improve existing techniques and existing problems. As far as the blast pressure measurement, there is an intermediate solution to it, very much a compromise solution, using the transducer that is appropriately called the lollipop transducer, and that comes from the shape of it, not from my name. Scott has thought this through himself, where he uses a pancake like transducer, sensitive on both sides, that you can direct towards the source of the blast wave. For the calibration problem he mentioned, again that is a tall order. I suspect that the intermediate solution will be along the lines of this, what I call the free tourmaline transducer, and tourmaline has the unique property that it's volume sensitive, or hydrostatically sensitive. We can suspend a chunk of this tourmaline, as you saw in one slide, and use it as a transfer standard. We can statically calibrate it and then transfer over to one of the hydro-dynamic, or drop calibrators as we call them, and use that as a reference to calibrate the high pressure transducers. Now the present unit is available as a standard to 80,000 psi. I understand that the Bureau of Standards and Sandia both use this

type of transducer. It is further confirmed that we can calibrate a shock wave transducer against a standard in the hydraulic system at one millisecond rise time and go to submicrosecond rise time in a shock tube, come out with calibration sensitivity that agrees with the theoretical calibration of the shock tube within 1 or 2 percent. That work was done by Susquehanna Instruments and originally most of this work was done at Aberdeen. On the gun barrel measurement, to me that is a real-world problem, one that dates back to World War I, and again a lot was initiated at Aberdeen with the original quartz pressure transducer. They had people working on it, we have had people working on it, and Kistler here has worked extensively on it, and still defies the elegant solution that Scott envisions.

PETE STEIN

Any other takers?

PAUL LEDERER, WILCOXON RESEARCH

Scott, I can't give you a solution to your thermal transient problem, but I might suggest an approach. Your approach being that you don't necessarily have to suppress the thermal transient effect, but you delay it beyond the phenomena that you are trying to measure. So possibly some kind of layer sandwich of non-heat conductive material, or heat insulator which is still mechanically very rigid, like a number of ceramic disks on top of each other, might be the way to find a solution to your problem. Where you simply delay the effect, delay the time before thermal transients reach your transducer, without delaying the stress-wear that the pressure generates.

SCOTT WALTON

You mentioned the potential magic bullet. I've heard it twice, and when I hear something mentioned twice, then I pay attention. The word is 'ceramic.' I have heard P.C.B. puts a little ceramic on the end of their transducers. We were thinking about plating or depositing a ceramic on there. You did a study, I think it was in bulletin 961, talked about all kinds of things, tape, RTV, etc.

PAUL LEDERER

We didn't look at anything like ceramics. We were really looking at different kinds of tapes, and I think if life of that project had continued we might have carried this further. I'm just giving you my thinking, the way I would have started to look if my project had continued. I still think it might be a valid approach, but I have no information on it. I haven't tried it.

SCOTT WALTON

Does anybody else have anything to say on ceramic thermal protection?

WALT KISTLER, KISTLER-MORSE CORP

We worked for many years trying to protect gages from the temperature effect, and we designed a diesel engine pressure gage, combustion chamber pressure, with a ceramic end. We found it is more complex, more difficult than we thought it to be. We semi-solved the problem but the reliability still wasn't there. Those

ceramics are sometimes not strong enough, sometimes hard to match with or bond to metallic parts of the sensor. Looking at your problem, measuring pressures in a gun barrel to an accuracy to ¼ of one percent or so, from my experience I would say it is feasible, but it will cost. It's a long drawn out development and normally manufacturers don't have enough money. They design the thing and develop it up to a point and then they have to sell in order to get money in, and that is the way it normally stays. When I worked on this problem several years ago I would have liked to have gone further and developed it further but could not do it. We got to a certain point and then stopped. Now we sell things. Certainly, it is my opinion, it can be done if you have enough money and time.

PETE STEIN

Anyone else on the panel?

BOB LALLY

Quickly, on the ceramic coating on transducers, we do presently on the ballistic transducers use a flame coating ceramic. It adheres very well and substantially does decrease the thermal transients, but again it would need a lot of work to reach the level that Scott envisions.

PETE STEIN

Ron Tussing, how much of this problem would your tourmaline gage solve? Ron makes tourmaline gages for Naval Surface Weapons Center for underwater explosions. Is that an omni-directional animal?

RON TUSSING, NAVAL SURFACE WEAPONS CENTER

Yes, it is bulk sensitive, as Bob mentioned, and of course he mentioned the history of that, it goes all the way back to coal, when the Naval Surface Weapons Center developed the oil booted gage. Now that is bulk sensitive. But I was also going to ask the question, you said something about using it in ballistic or in gun chambers, or something like that, well the question came to mind - what do you do about the pyro-electric effect with tourmaline?

BOB LALLY

Scott Walton or Red Phillips from Yuma could answer that a lot better than I can. They both have used tourmaline extensively in gun barrels, and Scott has a sample there. They have to very extensively thermal insulate it.

SCOTT WALTON

You insulate it for 20 milliseconds time delay which is in effect what Paul was talking about, and after that you don't care.

PETE STEIN

We have at least two other manufacturers of pressure transducers in the audience, Gulton and Kulite. Do you have any quick comments on how you might attack that particular problem? Joe, do you have anything you want to say?

JOE MALLON, KULITE

We have a rather limited experience in ballistics. We do a fair amount of work in blast and we have taken some steps to design our devices so that they have a limited reaction to thermal transients; however, ¼ percent at the energy level he described is very difficult.

PETE STEIN

Endevco has done marvelous things in terms of thermal transients. Who from Endevco would care to say a thing or two on that particular problem that Scott raised?

BOB WHITTIER, ENDEVCO

No I don't really have that much to add, just a little more depth in adding ceramics on a diaphragm type product. You certainly end up lowering the rise time because it adds mass. So that it's a tradeoff, protecting thermally hurts something else.

PETE STEIN

Anyone else on this topic? Mr. Quintana from Air Force Weapons Lab.

JOE QUINTANA, AIR FORCE WEAPONS LAB

For years we have been involved taking air blast load measurements on the surface of a test bed above which we have suspended tons of high explosives. I had to measure that blast pressure there, so naturally the first real problem we had, obviously, was the thermal environment. To this day nobody could really characterize the thermal environment that you have or that you generate when you detonate mega tons of high explosives. So what I did in terms of getting a transducer to work in that environment was to get the best thermal barrier that I could determine at that time in developing the transducer, the blast gage, we were going to use. As it turned out, what I wound up doing was using a thermal barrier system, a GE silicon. I guess in those days it was asbestos re-enforced. I don't know if they let the asbestos out now'a days or not. It was a two part coating and it was low density, had tremendous thermal barrier properties; however, it remains resilient, but because of its low mass, and we put it directly on the surface of the transducer, it wouldn't really affect the frequency characteristics of the gage too much because the gage element itself was extremely stiff. So we found that has been good and put it on a particular mount where the thermal mass, in other words the steel which you have around the transducer itself, is such that it takes a while for the thermal effects to take affect, or to be able to observe the effect from them. So the point is, where you have the thermal mass, to delay the response, also use a material that we had, the name of it is GE TBS 78. That took care of convection conduction. We had a problem for a while making that stay put, due to the turbulence of drag load from the explosives because this was in close proximity to the HE, maybe a foot or so away, so we had to take precautions to also put a device on the

transducer that would retain that material in place so it would not blow away. That was one of the problems we ran into with tapes and things. They leave the face of the transducer at some time. Hopefully, it's after you take your measurement, but usually it is not, it is before. The other thing that happened with us, we had a situation of photon sensitivity. A lot of these crystalline structures, they are really sensitive to the part of the thermal spectrum that you really don't see, and we had to take care of that. The way we did that was with depositing a coating on the surface of the transduction element itself. Now this is a vacuum disposition project. Therefore, the bottom line as far as our transducer is concerned, is that we think we have a very substantial thermal barrier system, that really does delay the thermal effects, and we haven't seen them, we haven't been able to identify them in terms of anomalies to the data. Our data durations have not been longer than 100 milliseconds. But what I am saying is we have seen the whole profile. We don't get any effects that appear to be anomalies from heat response.

PETE STEIN

Thank you Joe. Dr. Reed, have you any comments?

RAY REED, SANDIA NATIONAL LABS

Going back to an earlier comment by Bob Lally, I think, about the fact that tourmaline has a hydrostatic response, as does some other materials that are available now a days: I want to interject a reminder that the question that was asked had to do with the measurement of components' response. He wanted a side-on pressure, not a head-on pressure, not a static pressure. And while it is true

that these materials will respond to hydrostatic pressure, it is unfortunately true that the response, as you know, is non-uniform in direction. Therefore, if they are loaded from an arbitrary direction, the response is ambiguous. You have a mixture of coefficients, and I think people should be aware of that fact. The other thing that occurs to me about the materials is that most of them are extremely sensitive in a pyroelectric sense with a lot of these crystal materials. So the thermal problem is really exaggerated. They are more sensitive to temperature than pressure, and very difficult to isolate.

PETE STEIN

We don't want to stick on this particular topic too long.

RAY REED

All I want to say is we use them underwater and we do not have the problem with the pyroelectric, and years ago we tried them in air blast and they did not work very well. Therefore, we have abandoned them for use in air. Now we only use them underwater where that is not a problem.

PETE STEIN

Scott, how about a water cannon?

BOB LALLY

I have to reply to that. We do not make the underwater version. Also, I did not make myself quite clear on the blast gage. There we should not use tourmaline, we would go to the standard quartz transducers with which we have had a lot of experience and success. We would not use tourmaline in blast transducers.

PAUL LEDERER

Pete, did you want me to summarize briefly some of the transient things we did?

PETE STEIN

Okay, if you can do it quickly.

PAUL LEDERER

We were asked by our sponsors to look at methods for evaluating pressure transducers for thermal transient effects. We realized fairly quickly that it was not really possible to simulate any possible thermal transient. It was John Hilton's idea to take some commercial photo flash lamps, I think they were number 5's and number 22's, and we measured the output with a radiant energy meter. We shot off hundreds of these things, which surprised our purchasing department. Anyway, we found out they were quite uniform

within about 5 to 10 percent of the energy output and we felt they, the photo-flash lamps, were simple, readily obtainable, devices for screening transducers. It doesn't simulate any particular transient, necessarily, but it is a fast acting thing we are talking about, anywhere from 10 to maybe 40 milliseconds duration, and you could compare different transducers if you kept them all at exactly the same distance from the filament. There is an NBS Tech. Manual No. 5 which described the method. In 1961 we looked at the effects of a variety of coatings on pressure transducers by using such things as various RTV rubbers; black tape, white tape, etc. We looked at the thermal transient effect on the transducer as a zero shift when we fire off this flash bulb and also the dynamic response by taking this coated transducer with whatever diaphragm coating we put on and putting in the shock tube and looking at the dynamic response. I don't remember the details, its been awhile, but one of the things that surprised us was that the black tape, which everyone uses, actually made the thermal transient worse.

PETE STEIN

Kenny, you own one of those setups. You built one didn't you?

KENNY COX, NAVAL WEAPONS CENTER

Yes I did, but I would like to change the subject. I received a letter from Harry Norton, JPL. He was sorry he could not be here for this workshop, but he raised the question and it relates to what we did today, the space program, transducers on satellites. There are failures coming up as we all

know from the papers recently. Some things have been happening out there. Harry's questions are: are the manufacturers doing any lifetime testing of any kind, how long do these transducers last? And I have another question later. I guess this question is for the whole panel, maybe I should ask Mr. Hines, he said he had a thousand of these transducers on the first space shuttle.

PETE STEIN

How long do transducers last?

JORGEN JENSEN, BRUEL & KJAER INSTRUMENTS, INC.

Let me give you an answer. First of all I must talk about the material inside the transducer. From my point of view, I will only talk about our gage. The case is made of stainless steel, the insulation materials are normally teflon, or a kind of teflon, and inside there is a piezoelectrical material. All these three can stay forever if you do not go over the maximum limit for stainless steel. The softest point must be the piezoelectric material. So if you can keep the temperature under the critical temperature, you cannot destroy it. I have saved one of our gages for over 18 years. It has never changed over 1 percent; however, I have never gone up to maximum temperature, maximum shock, and everything at the same time.

PETE STEIN

Other comments from the panel?

BOB LALLY

I don't like to use too much time, but there has been extensive experience in detectors in space and that's the pyroelectric devices and the infra-red sensors. Those are essentially crystals used in a different mode to sense heat instead of pressure, or instead of mechanical things, and they also involve an integrated circuit amplifier associated with them. These are used extensively in all of the space satellites. There has been a tremendous amount of information and data collected on piezoelectric or pyroelectric devices in space. They seem to even thrive in a vacuum environment. They work better in cold temperature. A lot of these are cooled down with cryogenic coolers down to near absolute zero where they function even better.

PETE STEIN

Anyone out there waiting with bated breath to get at these guys up here?

KENNY COX

The other question I would like to ask is, this morning I heard a gentleman give a paper and he said something about a $39.00 transducer: I would like to know why, everytime I go to order a precision type transducer, I think he was talking about precision transducers, they start at $700 to $1000? The brochures I get do not say anything about a $39.00 transducer. Now that may be an exaggeration but I wonder why the manufacturers do not let us in on some of these secrets?

PETE STEIN

Joe, you are the one who described that transducer. Can we put you on the spot and ask you to answer?

JOE MALLON, KULITE SEMICONDUCTOR

I don't think I said $39.00, I think it was $39.95. But our technology is actually quite adaptable to low cost transducers. People have not only talked about it, they are doing it, we are doing it. The best we are involved in here is a special business, and because of the high engineering support required and the relatively small volumes, the need to have someone to talk on the telephone and answer the problems, to design a special package for the unit, the price is going to be high; $700 to $1000 is rather high for us. Most of our transducers out of the cataloque sell for about one-half that. We are currently involved in a number of major programs which involve transducers that sell for not $20.00 but $10.00. These are high volume OM applications, quantities are generally 20,000 per year, and the industry is now talking about $2.00 for consumer type applications. In fact, several consumer type applications are currently in production with $2.00 piezo-resistive transducers. Automobiles had $10.00 to $15.00 piezo-resistive transducers with amplifiers, complicated packages with pretty good performance specs over wide temperature range. Therefore, I would say the transducers are here. It is just that this business really does not have the volume requirements to support that price level.

JORGEN JENSEN

I want to give an answer on this. It is correct of course, if you build a cheap transducer you will get an accelerometer, microphone, temperature transducer, and everything at the same time. But if you want to get a microphone that is not sensitive to vibration you cannot get it for $10.00. It is impossible.

PAUL LEDERER

Pete, I want to comment on this too, mostly because of my past exnerience and what I mentioned in my talk on Tuesday. If you want to make a measurement that is worth anything at all you are probably going to take the transducer you get from the manufacturer, even if it is from one of my reputable colleagues, and you are going to calibrate it to make sure nothing happened to it in transit. You probably will use very skilled people and fairly good equipment, so what difference does it make if you spend $200 or $700? In the acceptance testing of the device you are going to spend another $500 to $1000 dollars anyway. End of comment.

JOE MALLON

I just want to make one comment to Mr. Jensen from B&K. I sharply disagree with your comments on the performance. In fact, the performance of these transducers is good. If you go out to your automobile that has a transister ignition system, pull that transducer out of it, do a calibration

on it, you will find that it is surprisingly good. It is normali ed and it operates over a wide temperature range and the performance is there. The fact of the matter is, if you are going to make a product very cheaply you have to make it well, you can't afford to fool around with it. Just has to be good by the nature of its manufacturer.

JORGEN JENSEN

I think I have seen this transducer. Its whole housing is made of apoxy. Is that correct?

PETE STEIN

I understand GM has a plant running on the west coast making hundreds of thousands of those every year. Is that right Joe, specifically for car applications?

JOE MALLON

That is right.

PETE STEIN

So long as they are all identical and automatically made with semi-conductor technology, what you are saying is apparently feasible.

JOHN HAIR, KULITE

I would like to make one comment if I may. I believe you have been addressing your comments to the piezoelectric technology. Having a bit of background in that area I agree, if it is not carefully designed and manufactured then it will measure everything simultaneously. I don't think you can relate that directly to the piezoelectric technology, there is a difference.

PETE STEIN

Ken?

KENNY COX

One more comment on that. I recently received a calculator on a keychain - probably cost $2.00; throw it away when it needs batteries. I can remember when I paid $600 for a calculator, yet transducers keep going up. I don't understand.

PETE STEIN

My wife will probably kill me, but she is wearing a $3.50 wrist watch. Any other comments related to measuring systems, transducers, manufacturers, deliveries, prices or performance?

RAY REED, SANDIA NATIONAL LABS

One of the nice developments that has followed from the solid-state technology is the ability to put the signal conditioning, at lease some of it, within the gage, which means that you have avoided a lot of noise problems, etc. But at the same time, one is exposing the signal conditioning to some environmental influences that were not there before, in particular in accelerometers such as those that PCB makes, and I believe Sensotec, as well as others. There now is the technology of putting amplifiers, impedence matching devices internal to the accelerometer, also filters, in a place where they well deserve to be. I would like to hear some comments from the manufacturers about what they think the susceptability of the signal conditioning might be to those situations, in particular on very high G range accelerometers that are used sometimes on high stress fields. I have seen the experiences of having zero shifts, etc., that have not been well explained. I wonder if the manufacturers would care to comment on that aspect?

BOB LALLY

That question is addressed to me. I can see that it is another one of those fields where there is probably more that we don't know than we do know, except that we have had a great deal of practical experience in that area. Quite often when we get in these extreme environments we get into strange looking signals. Then we will have to separate the sensor and the amplifier with a short length of cable to check out to see if there are any contributions by the piezoelectric or pyroelectric amplifier

and there is always a small effect there. But one of the problems is when we isolate it, separate it with a short length of cable, the cable introduces more effects than it eliminates. We get the same type of effects in a length of cable. So in these high shock environments there are multiple causes of zero shifts. One certainly is the pyroelectric effect in the electronics or in the material that encapsulates the electronics. But in our experiences that has been quite small. We are into a lot of things where zero shifts and off-sets really cause a problem when we are integrating the acceleration to get velocity or displacement and that is where it really shows up. One of the fields in that area now is pile driving, where they have gone into great detailed examinations of the causes of zero shifts. It gets down to even 1/10 of one percent zero shift, which is enough to upset a double integrating system. And when we get down into that level, one percent or below, we do see effects of the electronics. But the gross zero shifts like 30 or 40 percent, they are more attributed to what Pete talked about and Pat Walter talked about, due to clipping or nonlinearities in the electronics, or sometimes if it is ceramic crystals, to mechanisms in the crystal itself. Other times it is due to change in the residual stress patterns in the crystals, or in the pre-loading device on the crystals. If we do not come back to the same residual stress pattern as we started, it shows up as a zero shift, or if there is a slight interruption in the cable. With these built-in electronics, if a connector momentarily loses contact, we will get a gross zero shift. The effects he is talking about are present, but generally in our experience, even at very high G levels, are quite small.

JORGEN JENSEN

First of all, at the same time you put an amplifier inside the transducer you must lose something, and of course you will lose the lower frequencies. People normally talk about zero shifts with high G levels, and up to now I haven't seen zero shifts. I can recognize exactly what you are looking for, but if you are talking about high G level up to 100,000 Gs, normally, at the same time you have very high frequencies. If you have a very high rise time on your shock pulse you can very easily overload your preamplifier. This does happen a lot of times. Until now, all the customers I have visited I have shown them how to change the input to their amplifier. If they still have zero shift please call me. Until now, I have visited one and a half years in the United States, nobody has called me about zero shift. They have called me and told me they don't have zero shift anymore. I know you don't like the answer, but please if you can show me zero shift after I have visited you and we have changed the input to your chopped amplifier, I would be more than happy to come and visit you again.

RAY REED

Jorgen Jensen, when you are speaking of the preamplifier you are not speaking of the one internal to the gage, you are talking about the recording amplifier. I'm not speaking of any situation in which the signal was improperly recorded. We are well within band limits and we are within specification of the gage. I am not talking about our one-half or one percent shifts, I am talking about 30 or 40 percent, as you indicate Bob. But we are in the situation where we have to double integrate, and of course that causes severe problems.

AD-A137 304 TRANSDUCER WORKSHOP (12TH) HELD AT MELBOURNE FLORIDA ON 7-9 JUNE 1983(U) RANGE COMMANDERS COUNCIL WHITE SANDS MISSILE RANGE NM TELEMETRY GROUP L BATES ET AL. JUN 83

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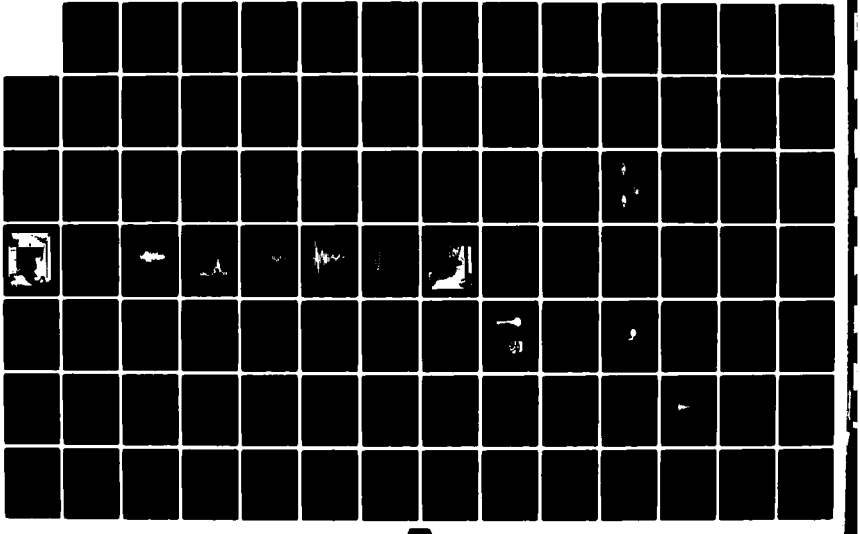

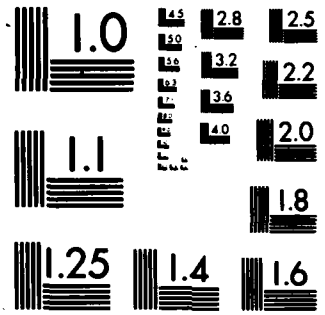

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

I am not talking about the difficulty showing up in the second integral. I'm talking about it showing up as residual amplitude in the acceleration record after a few milliseconds, a non-return to zero.

JORGEN JENSEN

I have seen photos of what you describe there, but if you can damp your input to your input chopped amplifier or voltage amplifier you don't overload it.

RAY REED

By overloading, you mean exceed the linear range?

JORGEN JENSEN

Yes.

RAY REED

This did not happen.

JORGEN JENSEN

It has happened 99 percent of the time, because if we are talking about 100,000 Gs, we are talking really very high frequencies.

RAY REED

We are talking now about the other 1 percent because these we have damped and they are not exceeding that level.

JORGEN JENSEN

Okay, if you can give me your address, you can put it in front of me when I come to visit you.

RAY REED

Okay, I would like to talk with you.

BOB LALLY

I have one more comment. There is a technique where you can put a series resistor in the front end of a charge amplifier and introduce a first order filter that may be overloading your electronics. That is fairly common in some of our transducers. We build the resistor internal to the transducers. The paper will be given tomorrow that shows an even more sophisticated and alternate way of doing that. Fred Schelby is giving the paper, so you can listen for that tomorrow.

SCOTT WALTON

If you look at the output signal, which is what you record, you see no problem there. I don't know of any way to look at the input of the charge amplifier without destroying it, and I'm quite sure that something indeed has happened on the input side of that charge amplifier but I don't know any way that I can monitor that to make sure that it's not overloaded on the input side.

JORGEN JENSEN

It is very easy to have external amplifier. We are talking about a linear system, so if you did decrease your amplifier 10dB the output of your amplifier would also decrease 10dB exactly. If you don't do it, something is wrong.

SCOTT WALTON

Oh, I agree with that, but that causes me a new problem. Namely, I get a much lower amplitude and my signal may be down in the noise.

JORGEN JENSEN

That was only to see if your amplifier worked perfect. And what happened for me is we have overload on all our amplifiers and it is sitting on the output of the charge amplifier so at the same time you overload your imput chart's amplifier, you have information you have overloaded. But still I would say it

has happened for me very very short pulses of about 100,000 Gs. The overload line was not fast enough or I couldn't see it. So I tried to damp the input signal and what we call 'zero shift' disappeared.

SCOTT WALTON

When you say damp it, are you talking about a resistor?

JORGEN JENSEN

Oh, I made a simple charge divider instead of a voltage divider.

SCOTT WALTON

A simple charge?

JORGEN JENSEN

Charge divider.

PETER STEIN

I think to summarize the discussion, what Dr. Reed asked is what's the penalty you pay for putting the microelectronics into the transducer, and I think the answer seems to be you lose the ability to check at first interface, which is

also what you're saying with potential penalties from which you cannot extricate yourself, which is what Scott just said; 'you can't check that particular boundary.' And that's your tradeoff.

DR. PAT WALTER, SANDIA NATIONAL LABS

I had something I might add that would be interesting and it's really a question for Mr. Hines and a comment to Kenny. Kenny was talking about the problem with cheap transducers and in temperature measurements in the last few years. Both Analog Devices and National Semiconductor have come out with integrated circuit type transducers that operate over a temperature range of a few hundred degrees and you can buy them out of a catalog for $8 or $10 apiece. And I have kinda the opposite problem. I see a lot of people weren't using them, and I'm ingrained to paying $1,000 for them and I'm looking for something bad about them. But they seem to work great and they cost very little, and if I were making resistance type thermometers, or whatever, today I'd be kinda concerned about what I see the semiconductor business coming up and doing to me. I just wondered if I could elicit any adverse comments?

FRANK HINES, RdF CORP

No, you're quite right. There are a great many developments in that line and they are quite good, many of them. One of the problems seems to be in uniformity sometimes, and calibration which won't match the standard RTDs. As a matter of fact we use some of National Semiconductor's transducers in our own

products, particularly in thermocouple reference compensation. In light of Kenny's question about cheap transducers, it is perhaps puzzling how .23¢ worth of wiring and film can be transformed into an $800.00 item. But one must remember that on the end of that .23¢ of material there's that special, specified, insulated, stranded, shielded, x number of conductor cables which $75 goes on each one. There is another specification which says we must clean it for LOX compatibility for which there is only one or two places in the country that can do this. So it must travel from coast to coast. There's another $50 for that particular thing. We must also remember that we have to have a full quality test program on the whole item. We must call in the inspectors at the appropriate time and wait for them while they decide when to come and observe all the testing that goes with it. And by the time one adds up all these things, the cost of the item itself is perhaps trivial to the whole end product. In fact that .23¢ worth of wire may have a little encapsulated case around it which is worth $4 or $5 all by itself. That's really my comment on the price of transducers. Yes, we can build transducers cheaply; we do. You'll get it out of the catalog with two inches of tin-copper wire on the end and that's it. If it doesn't work, we'll send you another one.

PETER STEIN

While Kenny's walking to the microphone, you know of course that you can get very high precision load cells commercially in quantity for something like $75.00, which is as close to throw away, as .1 percent, as you're going to get. But you have to buy what's in the catalog; no specials, no nothing.

KENNY COX

Well you'd be surprised how many we buy special and they come just like the item in that catalog. We don't get what we want. Anyway, we were led to believe some years ago - I haven't heard the nasty word strain gage mentioned here tonight, it's all been talk about crystal gages, but there's an awful lot of strain gage work being done yet in transducers - we were lead to believe that it costs a lot of money to develop these things and we were paying for that. Now I haven't seen anything new in the strain gage bridge transducer and we are paying more money for them. I don't understand that. The same guys are making them. They're not getting paid that much more, or at least that's what they're telling us. There is still a big difference there in the price. I used to buy them for $300.00; same transducer, same label, different company because the companies combined, you know, they keep adding together. There are two or three labels on the same transducer. A thousand dollars right now for that particular transducer. I won't name the company.

PETE STEIN

I'll let all the manufacturers' respond to the cost. How about going down the line?

LEE MYERS, SENSOTEC, INC.

I can make a simple comment to that. We're Sensotec, Inc., and we haven't changed our price list in seven years. We haven't combined with anybody.

I don't know who you're talking about at all. The only price increases are new products with added value, higher accuracy, higher temperature capability of 600° or lower temperature capability of -320°. These have been our advancements. We still make the same product that we always have and the prices have not changed. In some cases, they've lowered. Again, it's just accuracy. The higher prices you don't want are transducers that cost $300.00 anymore. You want our .05 percent. They've been the same price for two years now as long as we've had them and I suspect they'll be the same price for another five years, hopefully lower priced. By that time, hopefully, we'll also have a .02 percent transducer which will be more money. The only increases in prices are for our new products. We personally have not raised prices. I can go back five years with price lists and verify that.

PETER STEIN

One down for Sensotec.

PAUL LEDERER

Wilcoxon raised its prices for the first time in two years last fall by about 5 percent pretty much across the board. By coincidence they hired just before that, so draw your own conclusions.

JORGEN JENSEN

Yes, okay. I don't exactly know the price from 1964, but I'm quite sure B&K's have increased. I made the first transducer in 1964. I was very proud of the

transducer actions in 1964. Compared to what I made three years ago, I'm not so proud anymore from the 1964. First of all, we have really increased, or you can call it decreased because it was all the bad features; temperature transient and all the things we were talking about today. They are really decreased, in the new types, about three hundred times for some of the sophistication. At the same time you have over here a calibration standard of your own, NBS. You want it traceable to NBS so we cannot come out with the garbage. NBS, they also increased their price for calibration. You wanted also a better calibration. If you can accept a transducer without calibration of course you would have a lower price, but at the same time you buy a transducer from B&K it includes all tests including calibration charges and you must pay for that. Because we must pay the people. People in Denmark are not completely crazy, they don't work without salary. They want to get food on the table too. So if you want the calibration, you must pay for it. If you do not want the calibration, please call me but we can take only one at a time. It is not just for one piece. But still let us see what we can do. We cannot decrease the price if you still want all the other things. So it's up to you. You must pay and you will get what you have paid for.

WALTER KISTLER

As a slightly biased manufacturer, I also had to disagree with Kenny. I think what is now available are much higher performance transducers at relatively

lower prices compared to when I look back on my experience and my history of 30 years or so. As an example, in 1955, quite a while ago, we offered to the field a little transducer called a mini-gage for $380.00. Twenty years later in 1974 the thing was selling for $320.00. But really the value of the dollar had gone down considerably so it was a double decrease in price, and performance was high. Yet it was acceleration compensated, a more sophisticated instrument, and I think that's not a unique case. In general, instruments have become much more sophisticated, higher performance and the price as far as I can remember, 30 years back, is still on the same level, specifically, if you take into account the devaluation of the dollar which is worth 30¢ now compared to before.

BOB LALLY

I have a little bit different view of the pricing situation also. If the transducer technology and the research and development of transducers received the support from the Government that much of your work does, then we could sell transducers much more reasonably. A very large amount of the income from transducers goes in to research and development for improving the transducers for testing. It's kind of a bad situation in the country today, especially when I see Paul Lederer leave the Bureau because his pioneering work in the transducer field was scrapped or disbanded or whatever. There is just no, transducers are still kinda considered a necessary evil, real financial support available in this area for things like the weapons get. That's one of the significant factors in the cost of sensors, especially when they are ordered in smaller quantities.

MAX KOPP, VALIDYNE ENGINEERING CORP

For Validyne, I would like to say that we haven't changed our prices for three years on standard items. Only when the people come in with specials that we have to do some hand work and it's a very labor intensified type thing, they have to pay the price for what they want. I hope things stay the same. That's the way its gonna be I guess. If and when larger orders come in for the same type of an item, transducer, it's gonna be easier to get the price down. We have just recently bought a couple of American controlled mills to do this. We haven't had the orders yet to even start up the second machine, so let's get the orders in and we can get the prices down.

FRANK HINES

I sort of like to sympathize with Kenny that in our own experience we have changed prices. It seems like a perpetual kind of thing. But in products that have not changed over the last 10 years, where we used to pay $400.00 for special products, we now pay $2,500.00 as a minimum order and that's only half as much as we got for the $400.00 previously. Therefore, I would like to pass Kenny's comments on to your own suppliers and feed on them a little bit. But I don't know how to do it, because they tell you that's it. So there is no way of really avoiding that type thing. The second point is that the office computer has been a great thing in some ways. Now you push a button and it will tell you what your costs are. Years ago we didn't know what our costs were, we sorta spread it out over the whole product line. Now we can pinpoint which of those product lines are putting us in the red and which are keeping us in the

black and that is very important. Therefore, you may find some product lines that are increasing in prices where others may actually go down.

TOM ESCUE, SERVONIC DIVISION, GULTON INDUSTRIES

I would like to focus your attention to the viewgraph there. You can see what happens to transducers that cost less than $15,000. Having been on both sides of the fence, I have spend 25 years in Government, and the reason transducers don't get the proper attention as Bob Lally pointed out is they don't cost enough. If you'll stop and think, those items that are very expensive on the programs get all the attention and so maybe we ought to think about that.

PETER STEIN

Allen Diercks from Endevco will say a few kind words. While Allen is working his way to the mike, Kenny have you ever considered, as a private citizen, to ask the price? It might be less than as a government representative.

ALLEN DIERCKS, ENDEVCO

I think we have the reputation of raising our prices about every three days. I had the feeling that Pete was focusing in on me when he asked the original question here. All the prices that we are dealing with where we are the customer are increasing. The engineers that we have working for us make substantially more now days than they did a few years ago. I'm sure all of you gentlemen have received increases in the past 10 years. I know that our

materials cost substantially more. The customers are getting more sophisticated. They are asking piercing questions, unfortunately, occasionally to our embarrassment. We are having to spend a lot more effort in the answering of these questions and all of this costs us money, and we have to find some way to reflect that in our prices. We have, even though Kenny hasn't noticed it yet, we have spent some of our resources on R&D. If Kenny would join me in the suite after this little session I'll show him a new strain gage device which is a bit different from what he's seen in the past.

PETER STEIN

Kenny are you satisfied?

KENNY COX

I have to confess that the manufacturer that I was speaking of is not represented here in this room .... after all these guys defended themselves.

PETER STEIN

Now that the guilty parties have owned up, you can tell them that. Are there other topics that excite your fancy?

DAVE MILLER, SUNDSTRAND AVIATION

I'll go to a slightly related subject. Recently I spent a great deal of time trying to explain to a gentleman in our purchasing department the difference

in specifications between the two or three different pressure transducer manufacturers. He was trying to select a transducer for a blanket order for the year and spent quite a bit of time coming back to me wondering why one gave one specification and another gave another specification, and how that related to the specifications that I had written. So I was wondering if there is any effort going into trying to standardize specifications on transducers?

PAUL LEDERER

There are a number of transducer standards at ISA and ANSI. Specifically, the one I am thinking about now is for piezoelectric accelerometers that first came out in 1964. You must remember that these are voluntary standards and nobody really has to go by them. When we first wrote these things we felt that they were primarily a vehicle for better communications. We feel that these standards are called guides to specifications. You use them to describe the specifications in a language which hopefully everybody can understand. But remember they are voluntary, Nobody really has to follow them, and of late, less and less people seem to have followed these things. I don't know why.

JORGEN JENSEN

Oh yes, it's very nice to follow the standards because a customer can compare the two products from two companies, and I know B&K follows the ANSI standards. I know the ISO Group from Europe tried to make a new standard, and it is very close to what I consider the ANSI standard. So it looks like it could be a standard for the whole world.

PETER STEIN

Dave were you talking of common standards or common ways of expressing the standards?

DAVE MILLER

The specific example that I was referring to had to do with, number one, the temperature effects which were expressed. One manufacturer had combined span and zero effects, the other did not. So it was very difficult to make a comparison. This happened to be on pressure transducers. The other item was in over pressure specifications there were different languages used. Another example was inaccuracies; one had a combined accuracy the other one had separate linearity hysteresis, etc. In some cases I find that manufacturers of these pressure transducers define their linearity as best straight lines, some of them define it as end point linearity. So there are differences there that I have to find explanations for.

PETER STEIN

Well, there are enough pressure transducer manufacturers on the panel, how about it fellows? A comment, by Frank Hines? Did I read somewhere this organization, the RCC, does write standards of that type?

KENNY COX

We've been involved for many years in reviewing standards, and we've found that there are so many of them written that by the time we get them read they are revised. But if you pick up the 106 that we've been talking about, in the blue manuals, that 106 manual is put out by the TG group of the RCC. That's one of their major efforts. In that 106 is a chapter on transducers. We have spent hours reading specifications for transducers. ISA 37, I think, is the one for the strain gage. There is an ISA something for potentiometers, there's one for temperature, there's a B88 by ANSI that's another one. We refer to these, instead of rewriting the whole book again. We have taken the time to cast out some of them and recommend that you take the others. Now you can get the 106 from the RCC Secretariat at White Sands. Send for it and you can get a copy of it. However, I think it's $75 for one book. They don't come cheap, these standards. By the time you buy them you can have $500 tied up pretty easy. Of course, if you're writing $100,000 contracts, well, $500 isn't too much. Did I say enough Leroy? Leroy is chairman of our committee.

PETER STEIN

That wasn't the question though Kenny. The problem is how do you get the manufacturers to follow those standards. I think that was what Dave was driving at.

HARVEY WEISS

I think it's precisely because these are interrelated things. We talked about costs, the high costs, lack of standards, lack of customers like us, and the knowledge of what standards are being adhered to and the way we get around it. Unfortunately, we have to write a procurement specification which scares the heck out of the manufacturer because he sees a document that in essence is his catalog with a few things that we feel are quite important that he simply doesn't put in the catalog. He doesn't tell us what happens to the differential pressure at high static pressures. He doesn't tell us what happens to resistance to ground at temperature. He doesn't tell us what the variation and damping coefficient is with temperature and things that we have to know and is part of our measurement process to find out. He talks about accuracy which is about probably the vaguest terms, the most misunderstood terms. We ourselves within our own corporation have half a dozen different definitions from different departments and I'm sure it's the same thing within the field. So what happens is we put a spec together and they charge us for just looking at it, just coming up with something to meet it. And we're paying through the nose, and I would certainly be very much in favor of some sort of standard to emerge, something that the manufacturers can agree with. To give you an example, I wrote a Murphyism about how one of the manufacturers, who will be nameless, calibrates differential pressure transducers on one side only and meets the spec beautifully from 0 to positive full scale but doesn't meet the spec at all if you do it from minus to plus. And it's their technique. That's

the way they do it and they do it for everything that they make and they sell it to everybody that way and it's their standard.

PETER STEIN

I heard manufacturers discuss Grumman. You seem to know more about what you are doing and therefore you ask for more specs and that does run the cost up.

RICHARD PEPPIN , BRUEL & KJAER INSTRUMENTS, INC.

Talking about specifications, we frequently get manufacturers' data that essentially, as far as I know, we take their word for. Along these lines the National Bureau of Standards has the NVLAP Program, (National Volunteer Lab Accreditation Program) and they are planning to perhaps come up with a laboratory accreditation for calibration labs. I guess my question is what would you feel, each manufacturer, about participating or being accredited by an NVLAP Program; in some sense letting the consumer know that indeed the calibration specifications and so on are correct?

LEE MEYERS

As far as being accredited, our door is open for you to come in at any time and witness calibrations. I don't know that we would want a third party for no particular reason other than it's a third party. We don't lie to anybody. If it doesn't meet the specifications that we publish, we rebuild it. Again, we're

a manufacturing plant that doesn't need a lot of extraneous things to add to the cost. I don't know how costly it would be, I wouldn't say we would be totally opposed to it. That's more a corporate decision than my personal decision. Now we wouldn't be opposed to it, we would look into it. But, I would rather have the users come and witness our facility and witness our calibrations.

RICHARD PEPPIN

One of the reasons that promoted the question was that I'm involved in the NBS NVLAP program and I did some laboratory accreditation, not calibration laboratories, and what I found was that the laboratories, while they think they do everything correct, they don't always do things correctly. This is an inherent error that creeps in due to people teaching other people in the laboratory how to make measurements. Not having an outside accessor or somebody from the outside looking in critically often leads to inherent problems that remain. I found this in several labs whom I would call extremely competent labs, personnel and equipment, and yet it's very easy to find things wrong that can in fact lead to problems in their output which was test reports. So just people thinking that they have good labs doesn't make it so. A comment about having people come in and look at labs: I think that's fine as a consumer. Personally, I would say: 'gee I don't want to go to every lab and check it out, I don't have the time.' I'd want to see a lab and say: 'well, some third party approved it, I have trust in the third party whether it be Government or not and I think it would make life a lot simpler for people who buy things.'

JORGEN JENSON

I can give you an answer too. If you talk about ANSI standard I can guarantee you it absolutely will not increase the price because I follow the ANSI standard since I've been sitting in the development department. The first time we knew exactly what kind of test we should do. So it really made it cheaper and was easier for development. When you are sitting there you can do all kinds of tests, now you have a standard you can follow. Another thing is I don't believe a standard can increase the price for B&K because we follow, already, all kinds of standards. So all equipment and calibration are traceable back to the NBS and all kinds of standards in Europe. Therefore, it doesn't matter for B&K.

PETER STEIN

I'll tell a story to support what you just said. The National Highway Traffic and Safety Administration maintains throughout the country 13 different facilities that conduct car crash tests. It occurred to some bright guy to build a little black box that generates a standard transient very much like that which occurs in the car crash and to carry that to the 13 test facilities and to play that into their original data acquisition systems. Some were more than factors of two apart, and yet every facility is, if you look at the list of names, a well known respectable facility that traces all of their standards to NBS. And yet due to procedures such as you described that might appear to be totally irrelevant, there are these major differences. The kind of program you suggest might be very well carried out. Are there comments from the floor on that?

FRANK HINES

I am naturally more acquainted with temperature problems and others, and of course the temperature scale is very precisely defined. They've been working on that for years. They mess around with it every once in awhile to disturb you, but it's pretty well tied down. You would think that would be an easy thing to duplicate over the world too. There is plenty of activity actually in cost checking laboratories on that particular thing. We are participating in a round-robin procedure in which temperature sensors are calibrated in various laboratories. The results are then circulated among the whole group. And it gets very interesting sometimes, the answers that come back. Your own laboratory problems, I understand those, and there is largely a personnel and training procedure. The methods are probably well outlined, the procedures are specific, but the O rings are missing.

RICHARD HASBROUCK, LAWRENCE LIVERMORE LAB

This is a little bit apart from the calibration thing, but it's something I've been playing with over the years and escaped from my naivete into the realization that even with the specifications other subtleties change in any product, but transducers are the topic right now. You get a transducer, you work with the manufacturer. I've written several specifications. You find a qualified vendor, you place another order a year later and it doesn't work the same. It's a subtlety. If you're experienced, hopefully, you are constantly aware of it and if you haven't experienced it, beware. And you find, for example, that

your DC VC converter, the transformer manufacturer has changed something that the transducer manufacturer wasn't aware of and all of a sudden you've got noise all over the place and it fouls up your digital data acquisition system. There was no problem when you had a strip chart recorder, but now your computer is failing all over the place. Other subtleties: material changes; the manufacturer doesn't think that this change is significant; a small temperature change or process change makes his manufacturing process less expensive, more cost effective; and you as the user didn't realize that that was the one key thing that made that transducer work in your particular application. And, surprise, you buy another hundred of them and you suddenly wonder why they're all failing. So I don't know if this is a question or a statement, but I'd like some comment on how does the user assure himself that when he orders 100-AB16 whatever that might be a transducer today, and a year from now and three years from now that he is going to get truly the same product?

JORGEN JENSEN

I can give you an answer. At the same time you buy one transducer from B&K with one type number, if you buy it in about 10 years with the same type number you would have exactly the same product. But what happened, of course, is other things change in the world. So if we have found some bad things about a transducer, we change it to the new thing and take the old out. There it can be a problem so you cannot buy the old bad one. When they would decrease the specification, what I have seen a lot of times is some customers have bought, in my opinion, cheap transducers, and have asked B&K can you make it? B&K says: 'of course we can make it, what are your specifications?' It was $100,000, was the only specification we could get out of the customer.

PAUL LEDERER

I have been to a number of these sessions before and one of the things that always strikes me, maybe by virtue of the fact that we are sitting up here separated by the table from you, that there is sort of an adversary situation developing. And I think this is really regrettable because a manufacturer is in business to make money, it's an economic situation. He can do a certain amount of testing and calibration but he is limited in his resources that he can put into a very extensive evaluation. Therefore, I would like to urge you, if there are problems with transducers, let the manufacturer know. Don't just strike him off your list because most of your far more sophisticated equipment, your applications, are manifold in ways which we can't even predict. If you get peculiar test data you can help us by telling us about it and perhaps suggesting what might contribute to the operations and help us develop a better product. It's really basically a matter of dollars and cents.

WALTER KISTLER

In answer to Dick Hasbrouck's comments I would like to mention here that I am very much aware of the problems you people as users of transducers may encounter. But do not think for a moment that we don't have the same problems as manufacturers of transducers. I think we have the same problem even worse than you have. At least it's my experience that our vendors may change things as simple as aluminum wire. We were shut down for several months in our whole operation once because of aluminum wire we were buying. We had bought over the years certain specifications and we thought we should always get the same thing.

Suddenly it was completely different. A completely different proportion of silicon was in it, and when we built our gages the aluminum wire at the end just fell apart and we had to redirect whole batches. Another example - the silicon material we used to buy over the years, and we thought we would always get the same, and we bought it in large quantities. Then for the test we were sure it worked fine and suddenly our whole production of semiconductors was down the drain. It didn't work. It took us again a long time to find out at very great expense, suddenly it was N material instead of P material. All the rest was similar. You could make all the other tests and it sounded fine. Only N instead of P and that makes quite a difference in the output. So we too have our problems ourselves exactly along these lines. I think it's in the nature of things. Things change, people change, and suddenly a process that was under control for many years is for some reason or more gone. Maybe the guy who used to run it retired or died, and somebody new came up and the whole works falls apart. So it's a unique problem.

TOM LITHGOE, SERVONIC DIVISION, GULTON INDUSTRIES, INC.

Paul, one of the things we do at Gulton to try to discourage the adversary relationship, and one thing that I really haven't heard much tonight is an interest in the manufacturers' engineering to work with the user engineering. One thing we do in Gulton on our product, and we really don't have a standard product, we have a list of capabilities that we usually call out just in general in our brochures, but to prevent these kinds of problems what we try to do is get with the user, understand exactly what his application is, try to see what kind of problems could come up, and try to devise the correct kind of final test

procedure to prevent these kinds of problems. In addition to preventing problems where a different supplier, a subsupplier, changes a product or process, we call out a source control on our drawings. Many of those requirements could be instrumental in changing these parameters. So whether it is a special requirement for using the transducer in a certain application or whether its common mode or a certain definition, to that respect we try to devise the test procedure exactly as close as we can around the user application. But let me say that this increased the cost. I think it would be better, we would much rather have a transducer making the proper measurement as opposed to having a more expensive misapplication of the transducer and perhaps jeopordize some very expensive testing.

CHUCK BELENSKY, GRUMMAN AEROSPACE CORP

I think one of the problems we have is when something is made and changed and we're not told about it. There may a subtle change that you can get by with, but I can remember some problems we've had particularly with pressure transducers on the engine inlet testing of wind tunnel models. In particular, when a strain gage type deposition is done on the back side of the diaphgram, and has been done that way for many years, and there were no particular problems but then when it switched around to the front side and then the wires have to be brought back around the diaphgram, I know you have a particle inpingement problem and the wires get hit by small pieces of dirt or whatever. If it wasn't used in a wind tunnel you'd never know it, and 99 times out of 100 it may not be. But the manufacturer, when he was originally making it, may not even have thought about, or he thought about it and didn't think it would be

a problem, but certainly didn't tell us about it and the model number doesn't change but the problem all of a sudden becomes a problem that never existed before. Those are the kind of things that bug us. And you said before Grumman may be kind of tough in their specifications, but it is because of things like that. Another area would be, for instance, if you're buying an accelerometer and you try to think of every possible thing to ask or compare specs to. One of the problems we've had in the past is buying an accelerometer and hoping somebody doesn't blink at it a little too hard because it might be overranged, say for instance, 0-150 g and you drop it two inches and it is no longer working. So you go to somebody and they'll say they have an overrange device, mechanical stop, and it will always keep it from breaking no matter what. The problem happens if you use two or three in conjunction. Now you have a phase differential problem that you never thought of before. If you don't think enough to ask this ahead of time, you've spent a lot of money needlessly. There are just too many things that if you don't think to ask, if you don't know about, you get fooled. So it forces you as a user to be much tighter in your specifications and worrying about them. I'm not looking at it as an adversary thing. I'm just saying as a user we have budgets to work under and we hope to get as much as we can out of our money. We just hope not to be fooled.

PETER STEIN

In terms of oscilloscopes and strain indicators I have two case studies where absolutely major performance changes were made in the design of the hardware but the model number changed only by the addition of the letter A. Both manufacturers I approached at the time, and I told them, these are absolutely major

performance changes that affect the entire measuring system. Why do you just differentiate it by the letter A? The answer I got in both cases, and I don't know if it applies to other manufacturers was this: If we change the model number all of our customers would now have to change the model number in their specifications. If they do that, the competition is going to be there and say: 'hey while you're changing model numbers we also got some model numbers.' If you simply add the A you preclude this possibility of changing vendors at the same time as you're changing model numbers. So there is possibly a self-defense mechanism in that particular area of major changes in performance without major changes in model numbers. I think this group is perhaps the least adversary group in terms of users and vendors. It is only tonight because of the table, Paul, that we appear to be adversaries. But I have heard other people comment during the meeting that they come to these conferences because there is such an intense mixture of users and vendors and they can talk in a friendly manner and get their problems sorted out and listen to papers by manufacturers. And there are some on the program at this conference that have been just downright excellent in imparting information that users need to know that they couldn't get from the catalog and they are now getting from a technical presentation. And the vendors are picking up from the users all sorts of useful hints and bits and pieces. I know, myself, that when I find out when in 1985 the next conference will be, my year will be organized around those dates. I want to thank Kenny Cox, General Chairman of the Conference, for inviting me back here, and Steve Kuehn, who organized the Manufacturer's Panel. This is the seventh time I have had the privilege to be the moderator. I would like to thank the manufacturers for being so patient and coming down and laying themselves wide open to your bullets, which you really haven't fired too violently tonight.

SESSION V

VIBRATION AND SHOCK

Lawrence Mertaugh, Chairman

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ADP002690

A Systems Approach to Measuring Short Duration Acceleration Transients

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Test Measurements, Facilities and
TM Mechanical Design Division
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Albuquerque, N.M. 87185

Introduction

It is common for failures to occur when attempting to acquire acceleration structural response measurements during crash, impact, and pyrotechnic testing. The structural response of a mechanical system to severe transient loading is commonly measured by accelerometers which are less than ideal. In particular, their amplitude-frequency response has one or more resonant peaks so that the output of the accelerometer may not be an exact replica of the input. If the transient input stimulus contains frequencies near these resonant peaks, signal distortion, over-ranging of signal conditioning electronics, or even failure of the sensing element may occur (Reference 1). These and other problems have spurred the development of a new acceleration-measuring system (Reference 2) which incorporates the following features:

1. Transduction Element.

   Quartz: Extremely rugged, high yield stress, piezoelectric constant holds over very wide stress range.

2. Connectors.

   Solder pins: Mechanically simpler and more rugged than coaxial connectors.

3. Mounting.

   Integral Stud: Simpler and more rugged than separate stud, allows transducer to be smaller.

4. Electronics.

   Integral Amplifier: Low impedance output allows coaxial connector elimination, no cable noise, high signal levels.

5. Transducer Resonance.

   Filtered: Low-pass filter between quartz crystal and internal amplifier reduces effect of induced ringing in transducer element. (Only frequencies below 10,000Hz are typically of value for structural modeling.)

PCB Piezotronics was the successful bidder to a development specification (Appendix A) containing these features and placed by competitive bidding by Sandia National Laboratories. The accelerometers developed to this specification use the basic seismic system of the standard PCB 305A shock accelerometer. Probably the most interesting design feature is the two-pole active Butterworth filter between the quartz element and internal FET amplifier. A block diagram of the internal electronic configuration is shown in Figure 1. A photograph of the accelerometer is shown in Figure 2.

Performance Verification Program

Standard accelerometer performance properties, such as thermal shift, base strain sensitivity, etc. were measured and are listed in Appendix B for completeness. These properties are peripheral to the shock-related characteristics that are to be discussed here.

The design criteria for the filtered accelerometer, designated Model 305M23 and ranged for 20,000g, required that the frequency response be flat to 10kHz and roll-off at 12dB per octave thereafter. This indicates that the -3dB point should occur at about 17kHz. In fact, the -3dB breakpoint occurs at

approximately 25kHz as shown in Figure 3. Figure 4 shows the amplitude portion of the frequency response of an unfiltered 305A to 50kHz. There is a minor resonance at about 38kHz in this accelerometer. Figure 5 superimposes the responses of Figures 3 and 4 on a linear vertical scale and makes the comparison between these two accelerometers more vivid.

The phase response of the filtered Model 305M23 was measured from 60Hz to 21kHz and found to be linear within this frequency region corresponding to the 0.7 damping of the Butterworth filter.

Shock testing was next performed to introduce high frequencies and high acceleration levels into the test accelerometers and to compare their output with that obtained from conventional shock accelerometers. In particular, a piezoresistive accelerometer having a 50,000g range and a PCB Model 305A piezoelectric accelerometer were used as standards for comparison. Two series of shock tests were performed. In the first series an 18"x18"x2" aluminum plate was suspended by a cable and one and two pound projectiles were fired at it from an airgun. Impact was at the center of the plate. The test accelerometer was mounted on the side of the plate opposite the impact and near the edge of the plate. The piezoresistive accelerometer was mounted one inch from the test accelerometer. Although the two mounting locations will not provide identical results, the plate response should be similar for each set of measurements. A photograph of the test equipment is shown in Figure 6.

The output from both transducers was recorded at various impact velocities. Figures 7 and 8 are time histories of one such event recorded respectively by a PCB 305M23 and the piezoresistive accelerometer. It is evident that the time histories of these two transducers are not comparable: that of the piezoelectric accelerometer having a maximum amplitude of about 40,000g compared to 6,000g for the filtered device. Figure 9 represents the Fast Fourier Transform of the output of the piezoresistive accelerometer and shows a large resonance at about 170,000Hz. This is the resonance of the transducer seismic system which has been excited by corresponding frequencies in the input impulse. The magnification produced at the resonant frequency of the seismic system of the transducer effectively masks the structural response and can also overrange the data channel.

Since the two-pole filter built into the accelerometer being reported on has a -3dB point at about 25,000Hz, digital filtering of the time history of Figure 8 with a filter of the same character should extract information similar to that shown in Figure 7 if the two transducers see nominally the same acceleration stimulus. The result of digital filtering using a two-pole filter having its -3dB point at 25,000Hz is shown in Figure 10.

Figure 11 superimposes these two filtered time histories and clearly demonstrates the similarity of the two responses. The

shaded area of this figure emphasizes the region of primary interest. Exact correspondence could not be expected considering the slightly differing locations of the transducers and the many high frequency vibrational modes possible in the plate.

Another overlay (Figure 12) - this time of the Fast Fourier Transforms of the two outputs - demonstrates the very close correspondence in frequency content at frequencies below 10,000Hz.

Further experiments were made with a Hopkinson bar consisting of a 2"x2"x48" bar of aluminum. The test and reference transducers (usually a PCB305A) were mounted on one end of the bar and the device was impacted by a projectile at the other end. The bar was also instrumented by strain gages at the center. A photograph is shown in Figure 13. The Hopkinson bar has several virtues for shock testing these devices: a) it permitted survival testing at 100,000g; b) the high frequency content of the shock pulse was low enough that the reference accelerometers could make a measurement of the pulse amplitude without being excited at resonance; and c) the relatively uncomplicated bar motion allowed better comparison with the reference accelerometer output. The strain gages provided further corroboration of the shock levels reached.

The PCB Model 305M23, developed to Sandia's specifications, has proved cabable of obtaining data comparable to that of standard piezoelectric and piezoresistive accelerometers when high frequencies are absent. In the presence of high frequency stimuli, the accelerometer has obtained data without over-ranging its data channel and without introducing error signals from excitation of the resonant frequency of its seismic system. It should, therefore, be especially useful for impact and pyrotechnic measurements.

These shock accelerometers are in the process of being fielded in earth penetrator vehicles; in shale rubblization experiments, and in flyer plate tests. Final results from these experiments will soon be available. It appears this joint development effort and test program has greatly enhanced the probability of acquiring successful structural measurements in harsh mechanical loading environments.

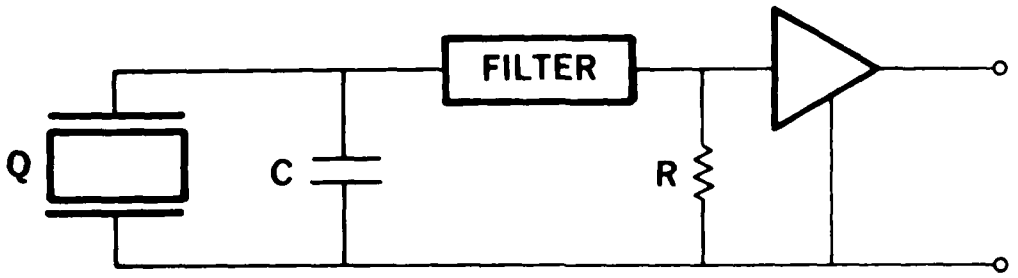


FIGURE 1. BASIC INTERNAL ELECTRONIC CIRCUIT OF INTERNALLY FILTERED ACCELEROMETER (PCB 305M23)

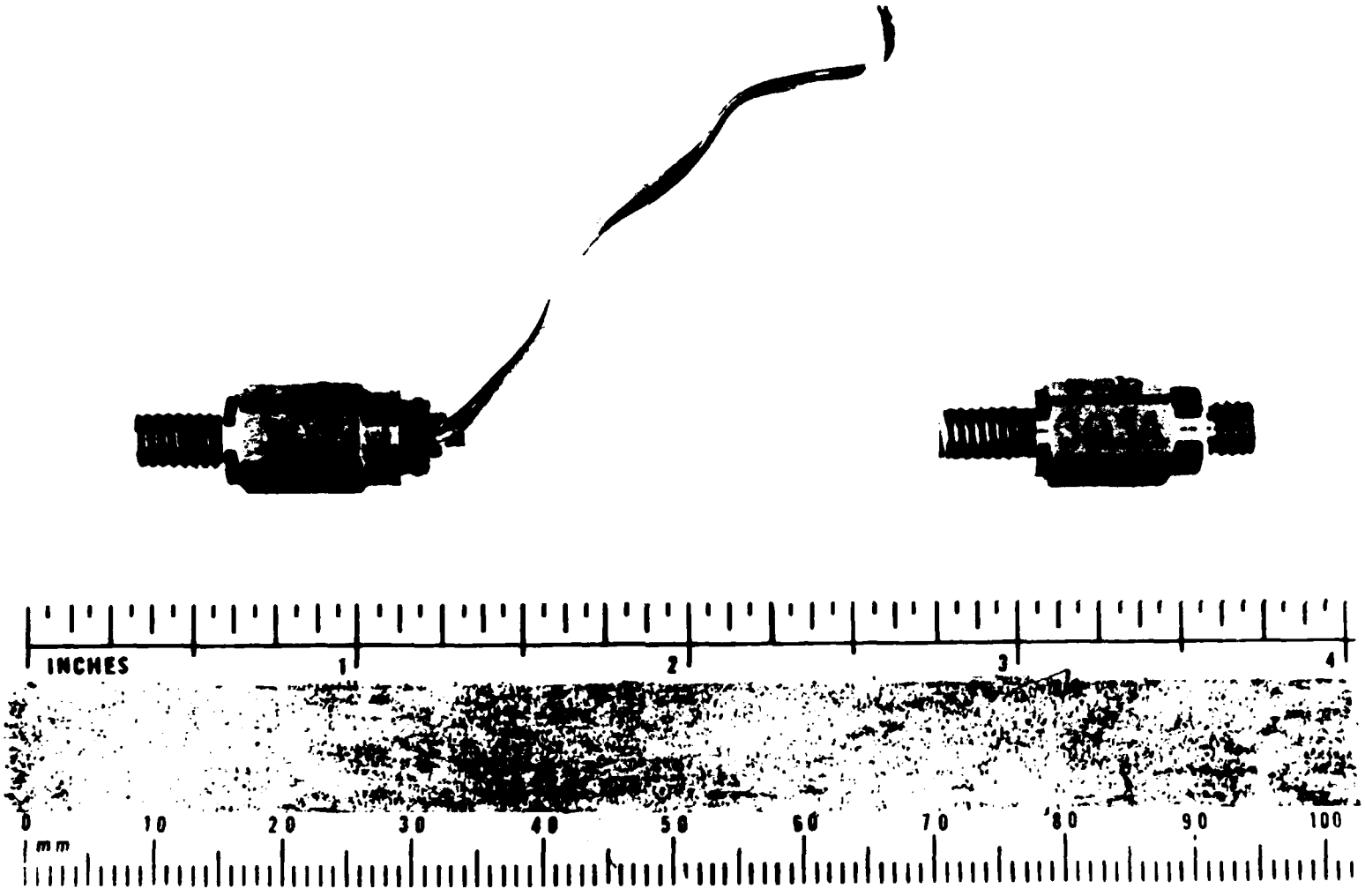


FIGURE 2. INTERNALLY FILTERED ACCELEROMETER (PCB 305M23), LEFT, AND UNFILTERED ACCELEROMETER (PCB 305A), RIGHT

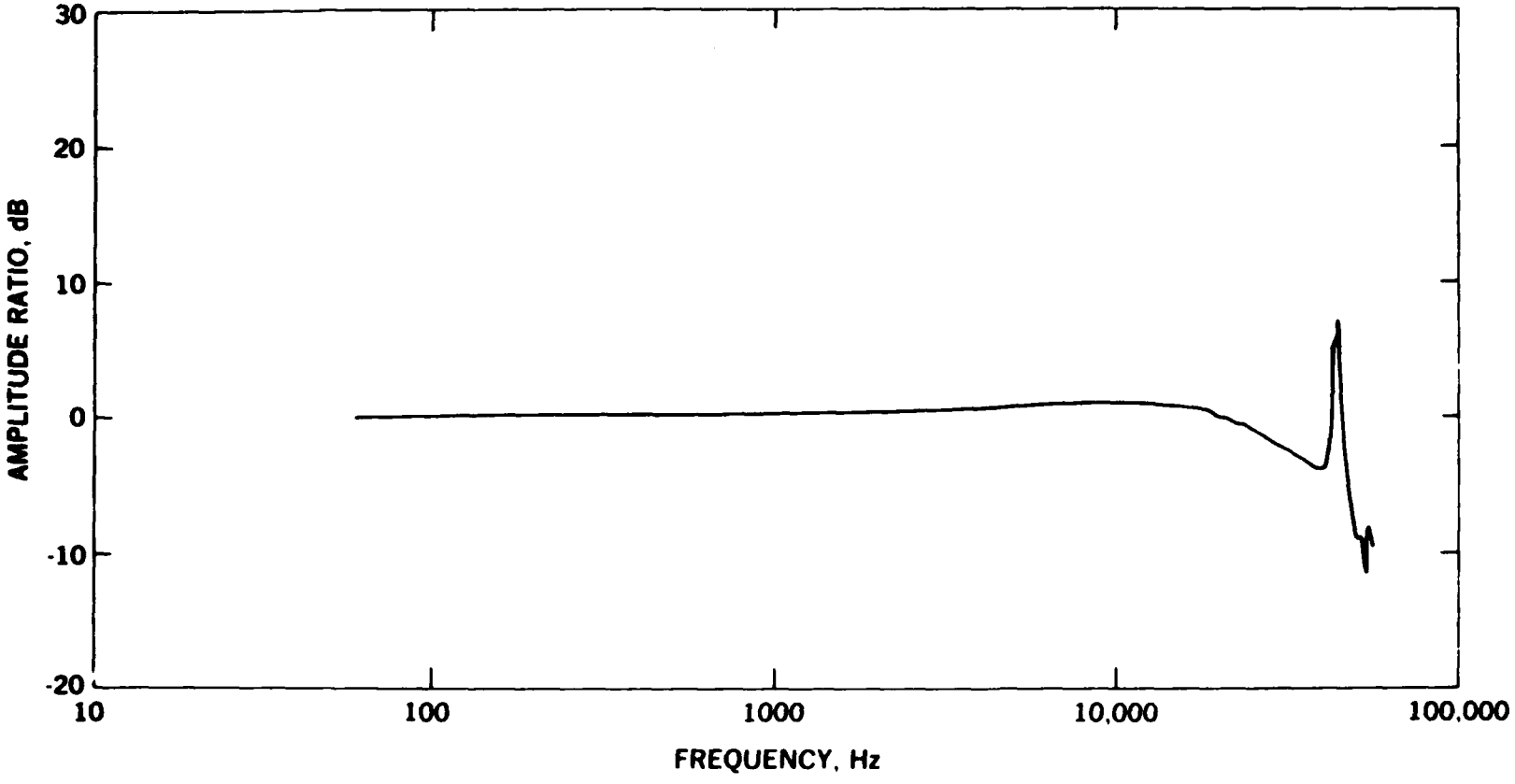


FIGURE 3. FREQUENCY RESPONSE OF INTERNALLY FILTERED ACCELEROMETER (PCB 305M23)

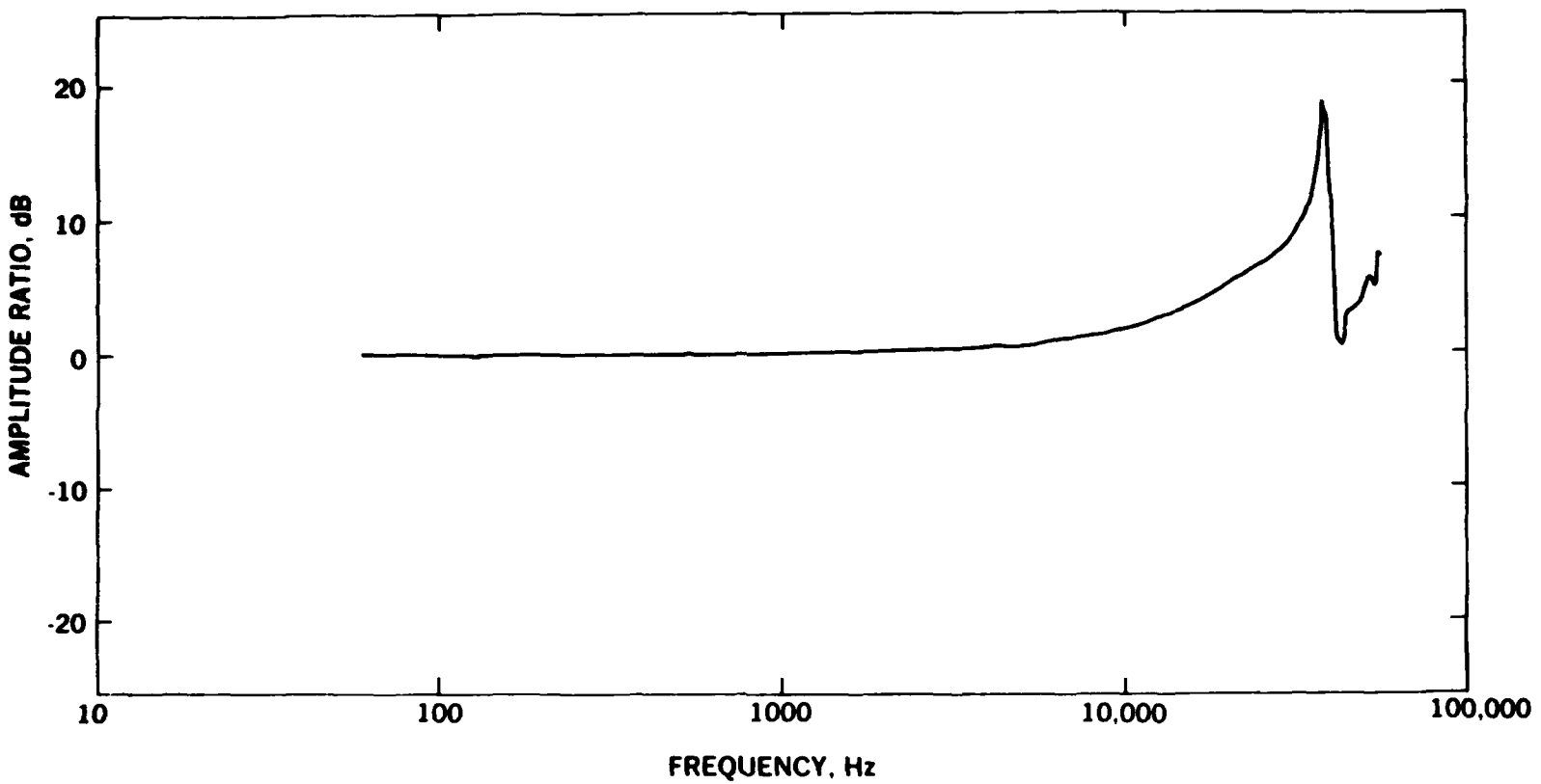


FIGURE 4. FREQUENCY RESPONSE OF ACCELEROMETER WITHOUT AN INTERNAL FILTER (PCB 305A)

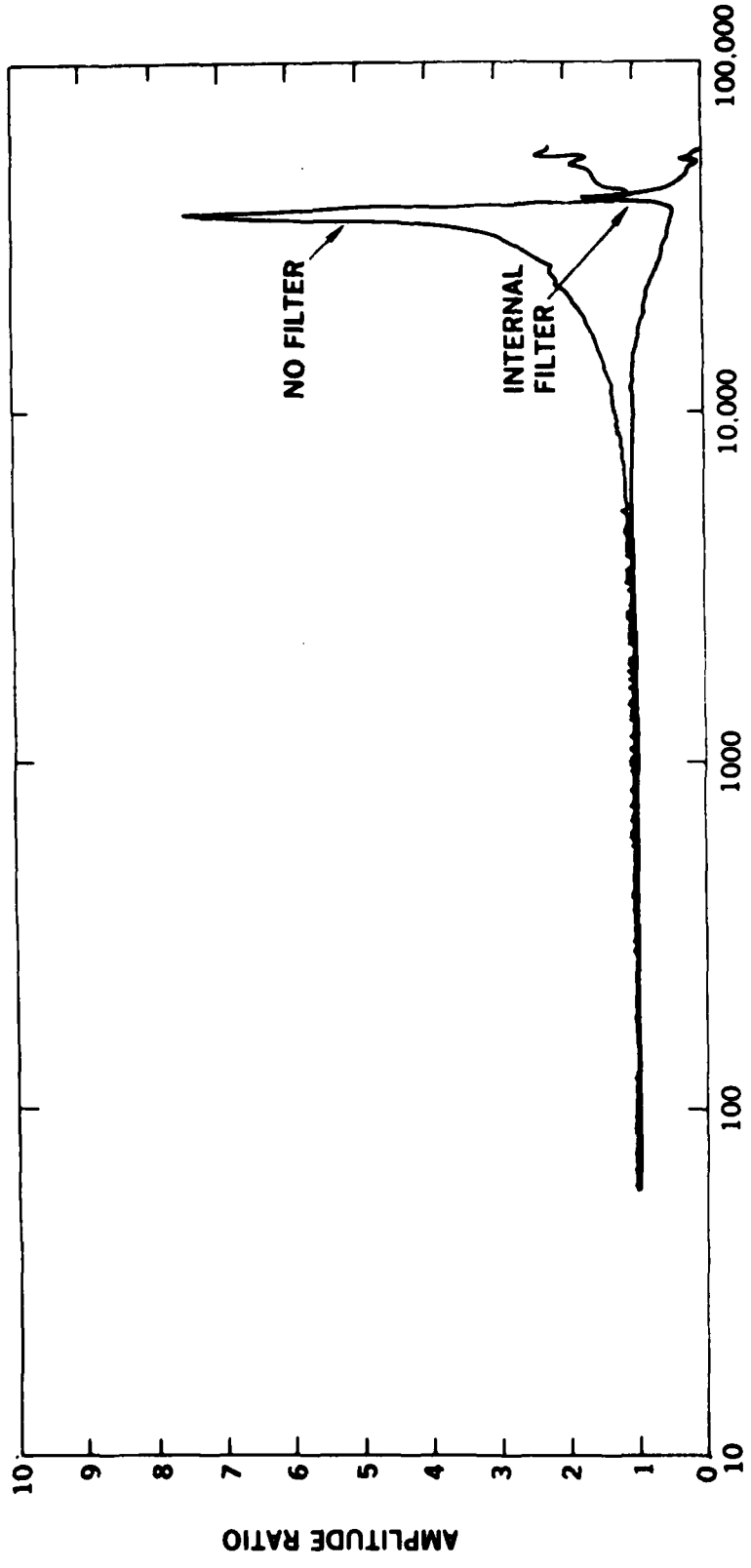


FIGURE 5. ACCELEROMETERS WITH AND WITHOUT AN INTERNAL FILTER USING A LINEAR AMPLITUDE RATIO VERTICAL SCALE (PCB 305M23 AND PCB 305A)

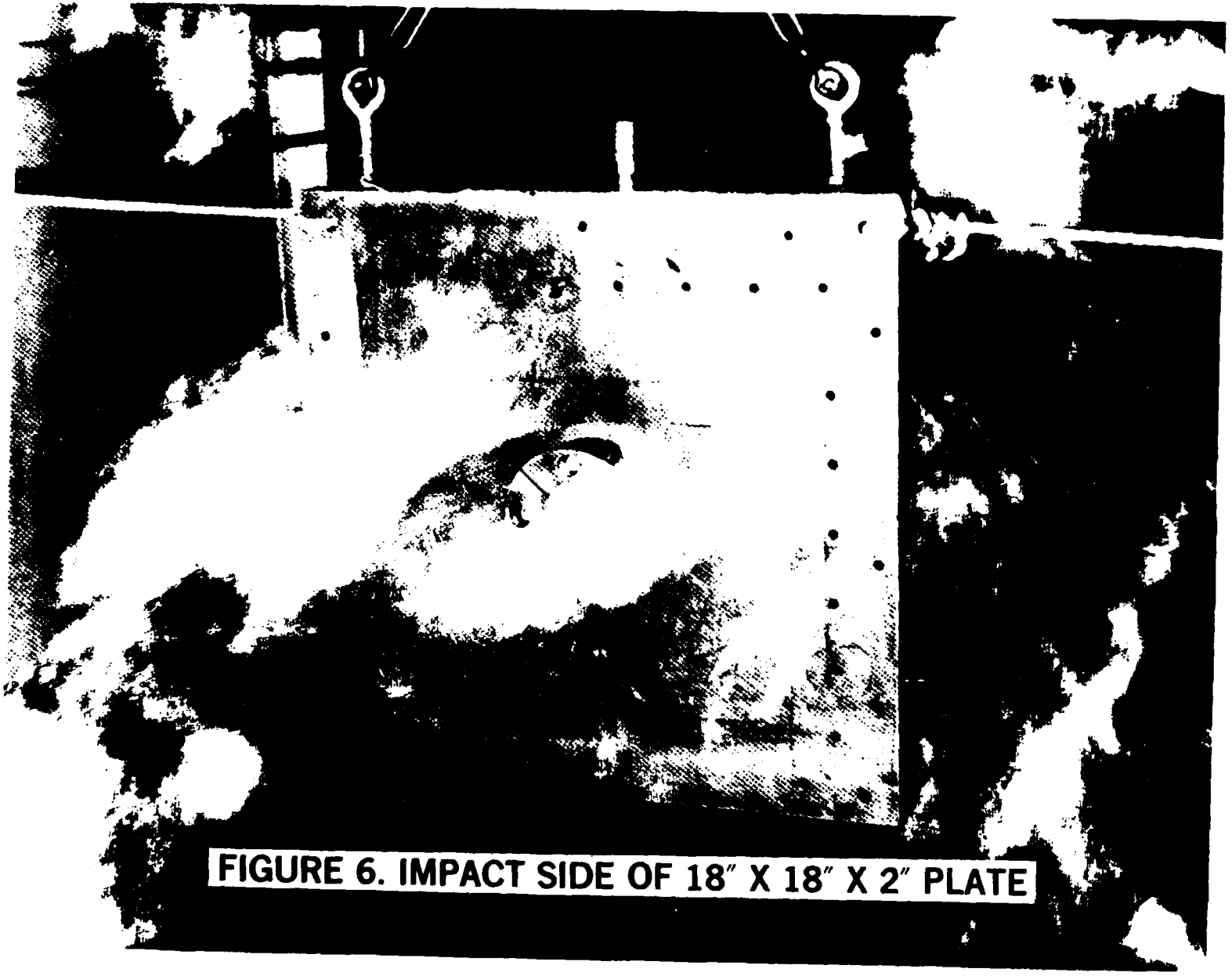


FIGURE 6. IMPACT SIDE OF 18" X 18" X 2" PLATE

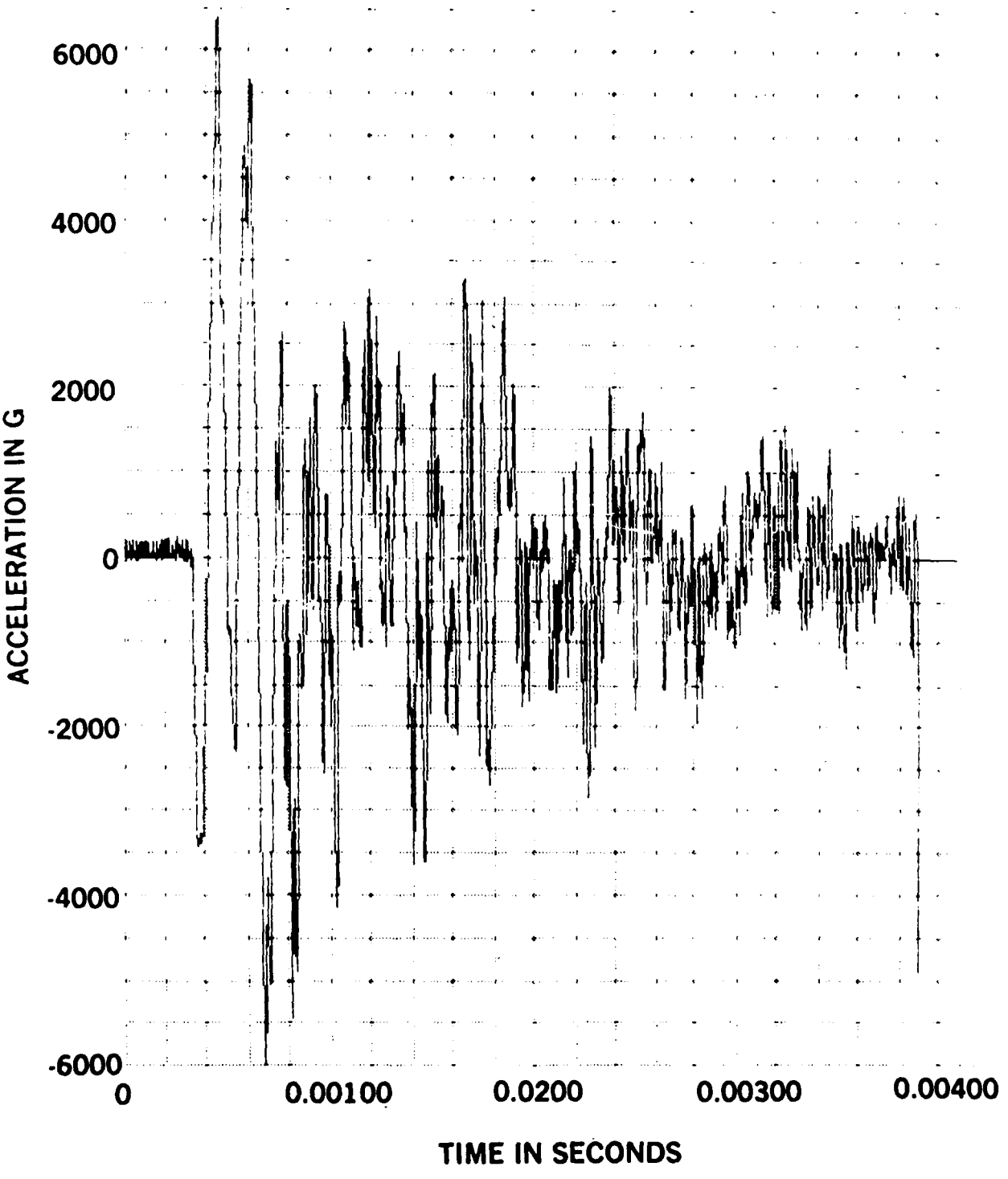


FIGURE 7. RESPONSE OF ACCELEROMETER WITH INTERNAL FILTER (PCB 305M23) TO VIBRATING PLATE

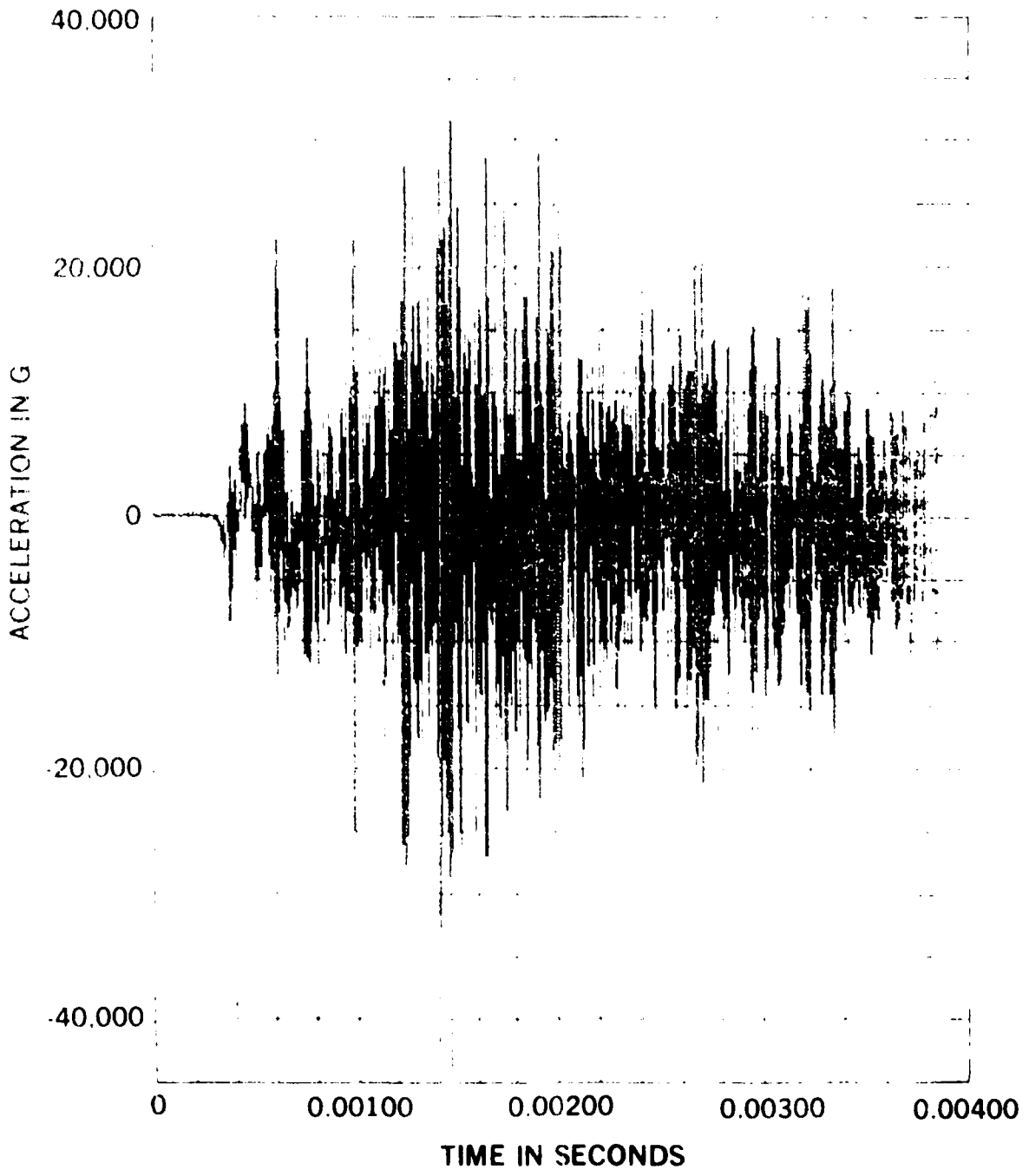


FIGURE 8. RESPONSE OF UNFILTERED PIEZORESISTIVE ACCELEROMETER TO VIBRATING PLATE

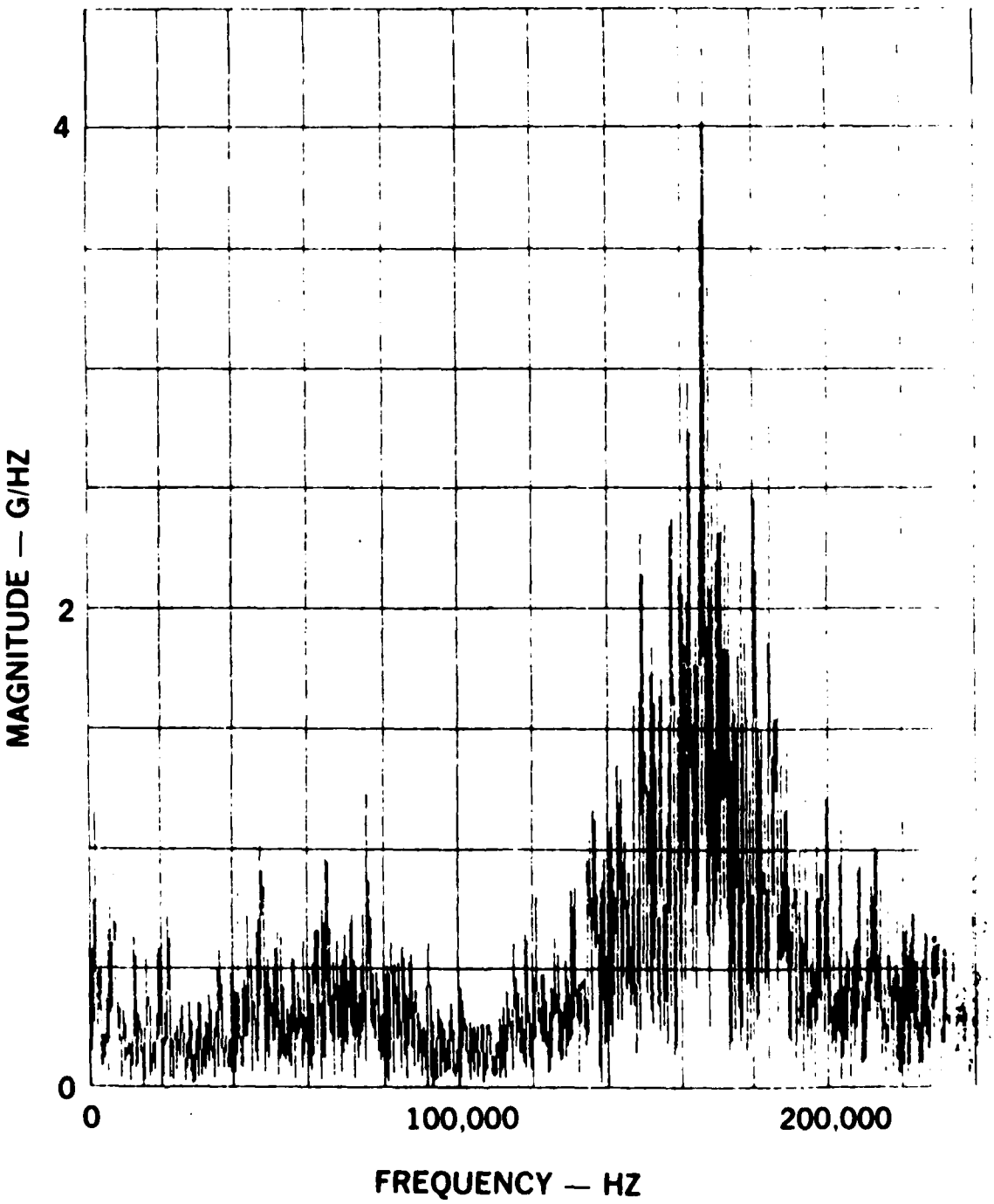


FIGURE 9. FAST FOURIER TRANSFORM OF THE RESPONSE OF UNFILTERED PIEZORESISTIVE ACCELEROMETER TO VIBRATING PLATE

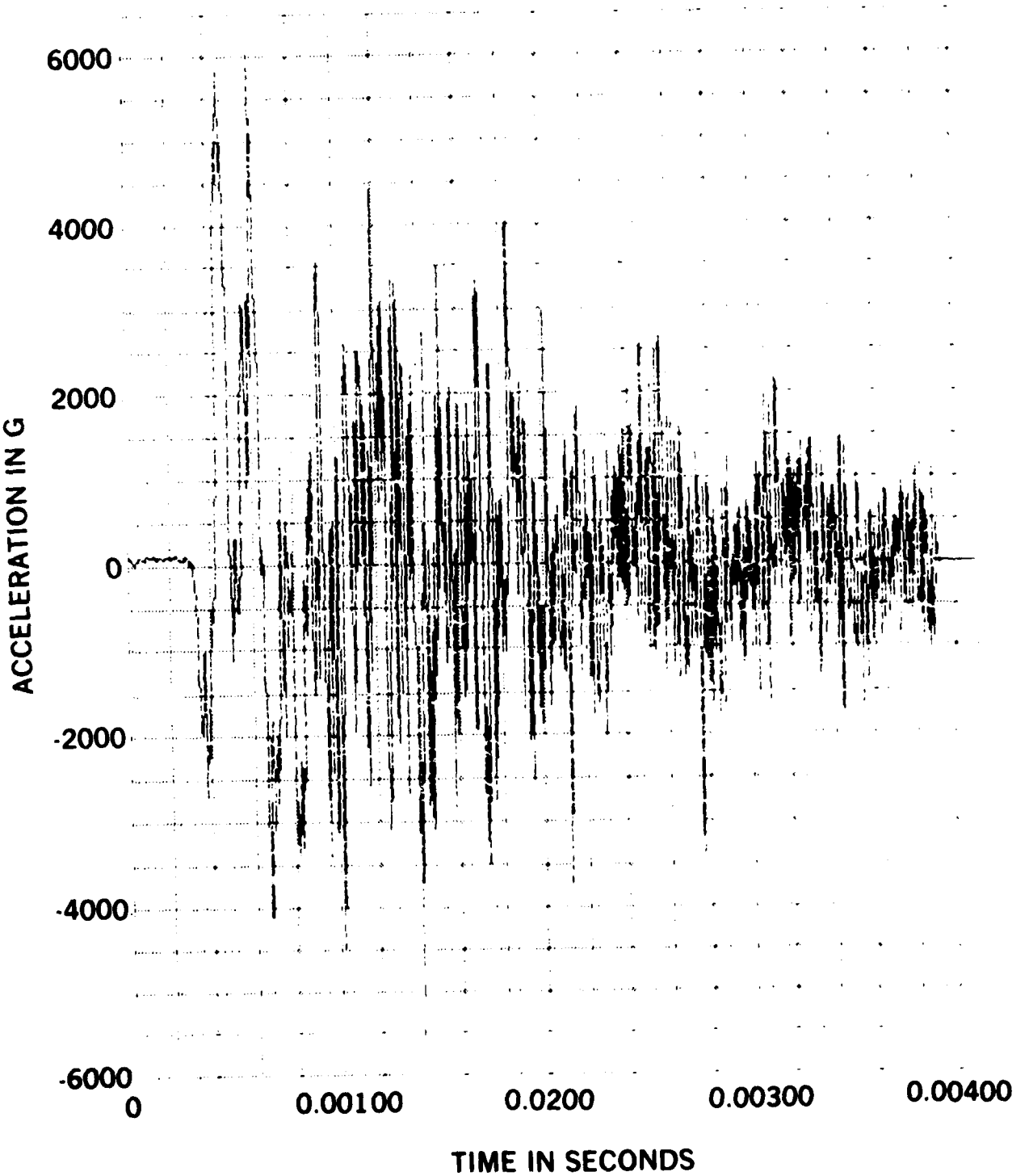


FIGURE 10. RESPONSE OF EXTERNALLY FILTERED PIEZORESISTIVE ACCELEROMETER TO VIBRATING PLATE

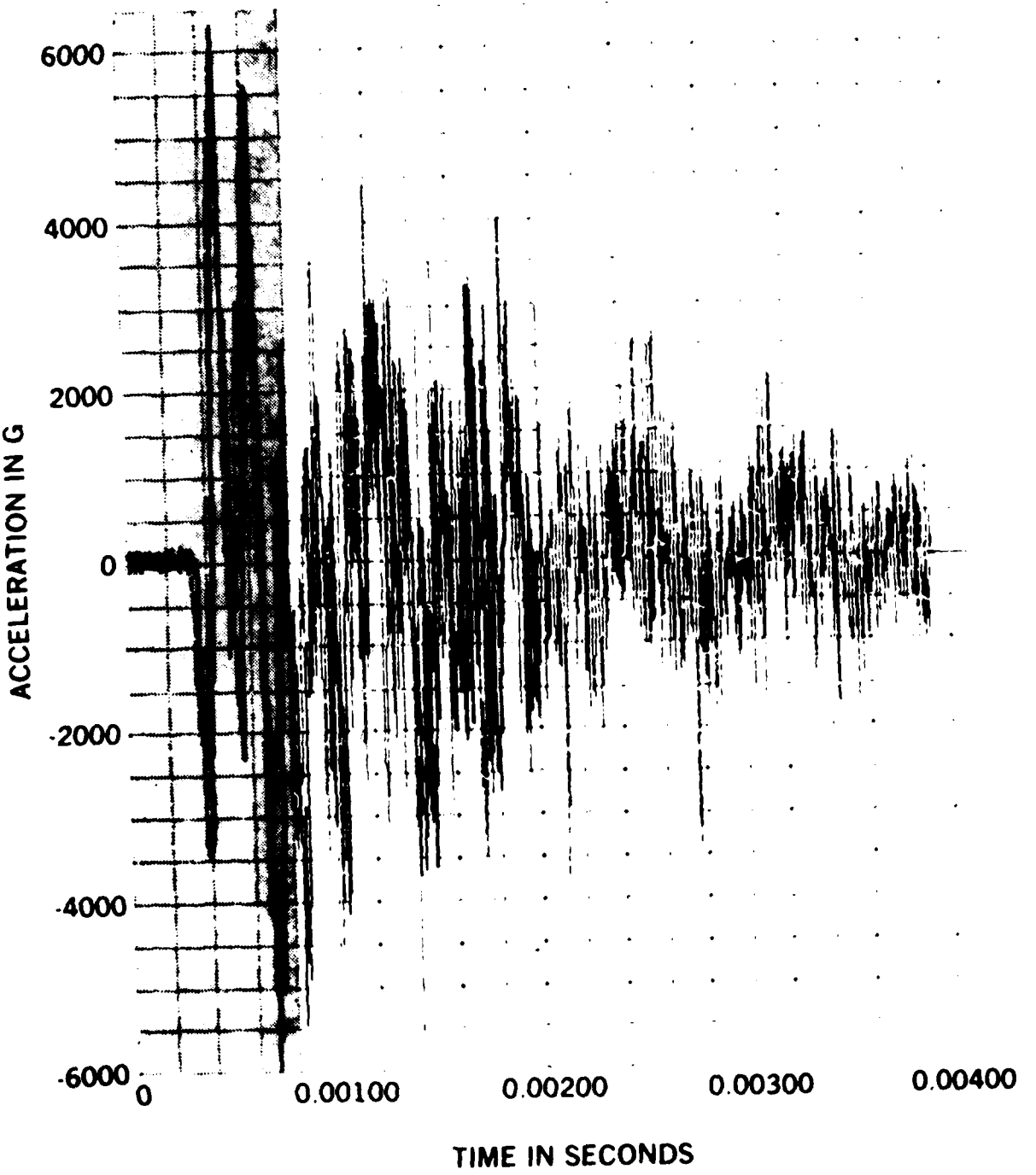


FIGURE 11. RESPONSE OF ACCELEROMETER WITH INTERNAL FILTER (PCB 305M23) SUPERIMPOSED ON RESPONSE OF EXTERNALLY FILTERED PIEZORESISTIVE ACCELEROMETER. VIBRATING PLATE TEST

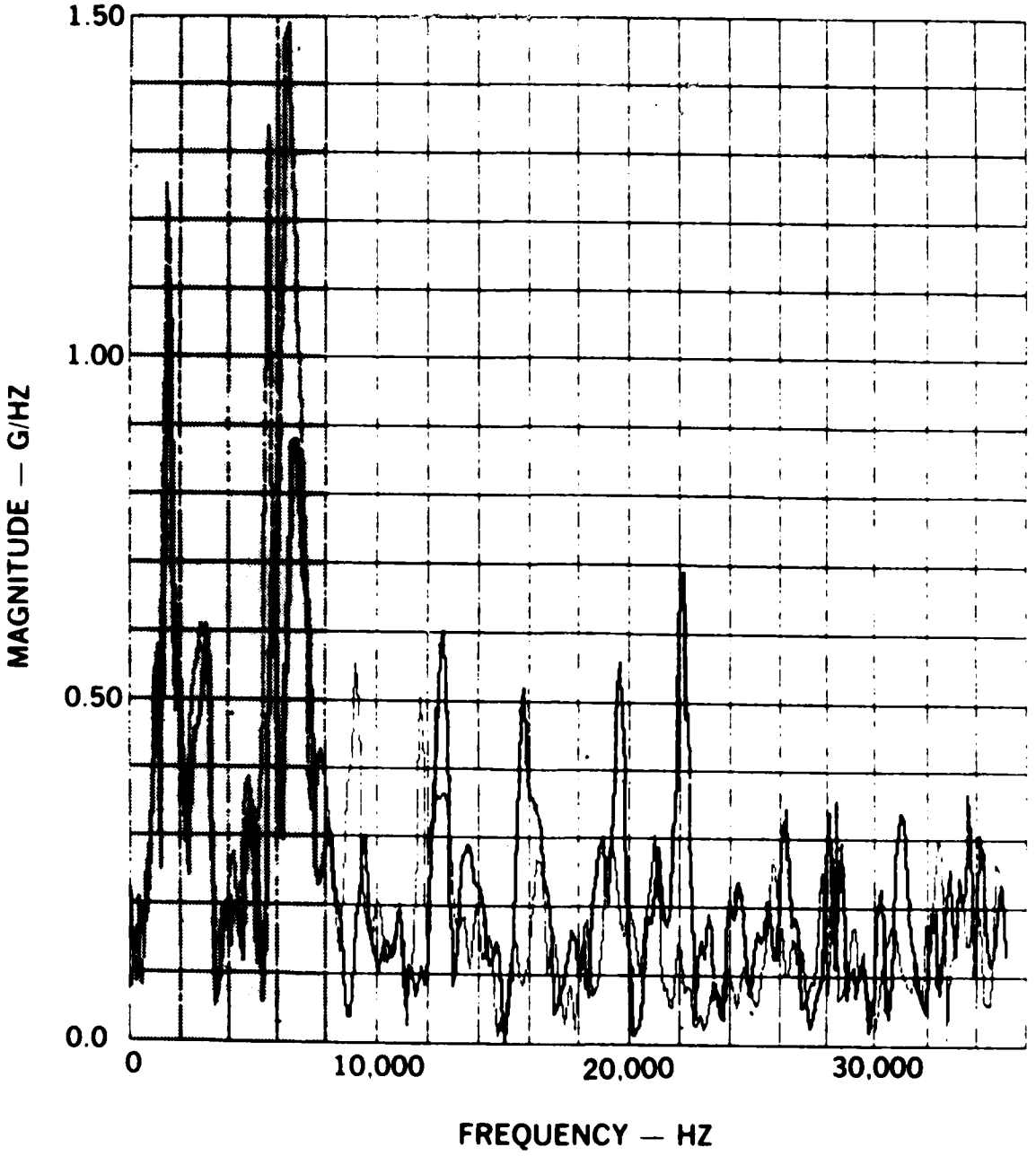


FIGURE 12. FAST FOURIER TRANSFORM OF ACCELEROMETER WITH INTERNAL FILTER (PCB 305M23) SUPERIMPOSED ON FAST FOURIER TRANSFORM OF PIEZORESISTIVE ACCELEROMETER. VIBRATING PLATE TEST

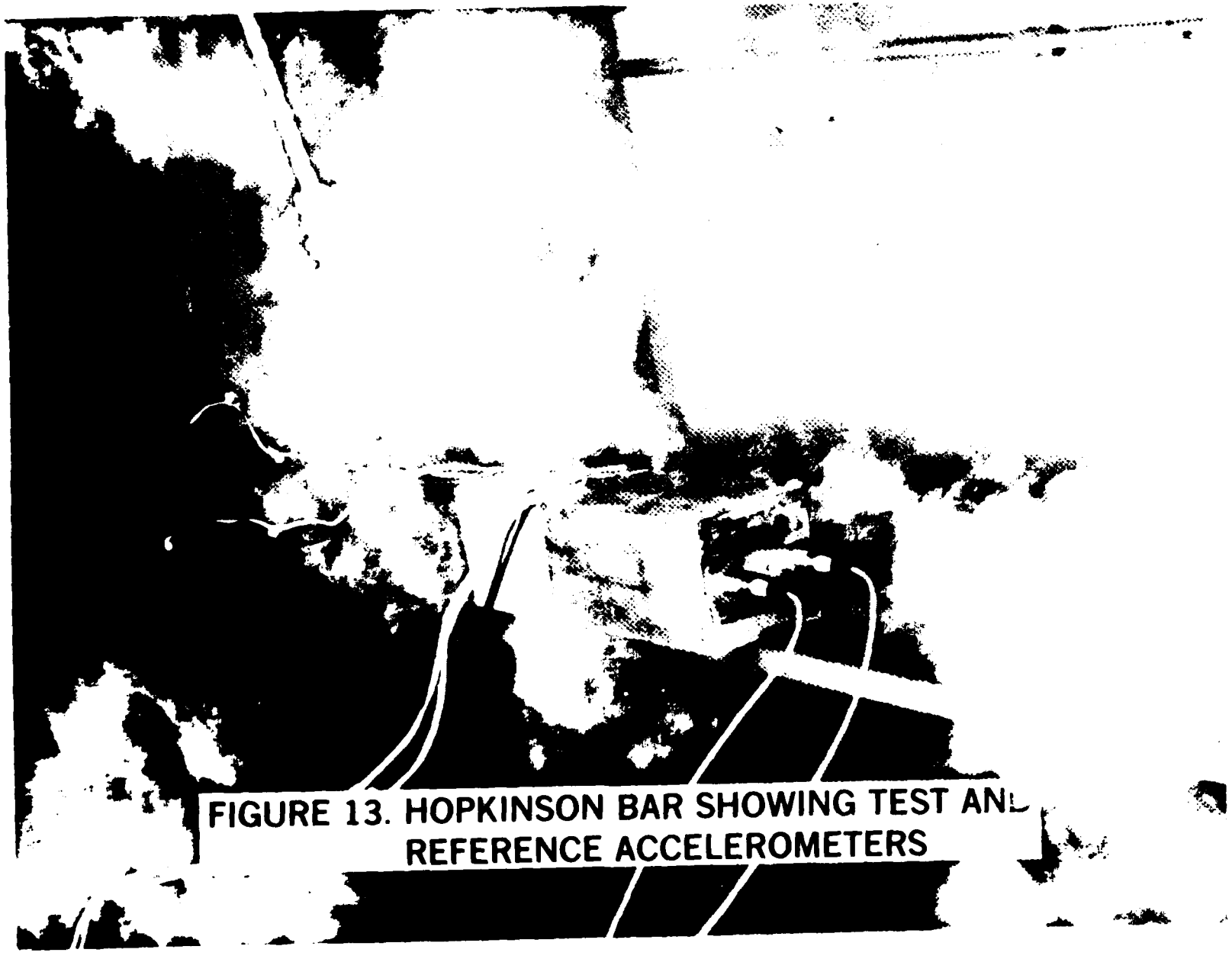


FIGURE 13. HOPKINSON BAR SHOWING TEST AN[illegible]
REFERENCE ACCELEROMETERS

Figures 14 and 15 show the results of one high level test on the Hopkinson bar. From Figure 14, the maximum amplitudes were 90,000g for the compression pulse and slightly more than 100,000g for the reflected pulse. This data is from the reference accelerometer and was confirmed by strain gage data. The test accelerometer which was ranged to produce ±5 volts at ±20,000g clipped before these extreme levels were reached, as shown in Figure 15, but did survive this environment.

Lower amplitude pulses of about 25,000g peak are shown in Figures 16 and 17 for the reference and test accelerometers respectively. The outputs of the two accelerometers are within 6% of each other indicating that under these conditions of moderately long pulses (about 0.7 milliseconds) and moderate peak amplitudes both transducers are capable of producing consistent, verifiable amplitude data.

Conclusion

A shock measurement system has been developed in which the quartz seismic system, two-pole active filter and an FET source follower are incorporated in a transducer housing measuring 5/16"hex.x5/8". Tests have shown that the system will survive ±100,000g without damage. Although the results reported here are for accelerometers ranged to ±20,000g, there is no reason to limit the accelerometers to that range and PCB can supply different ranges as required.

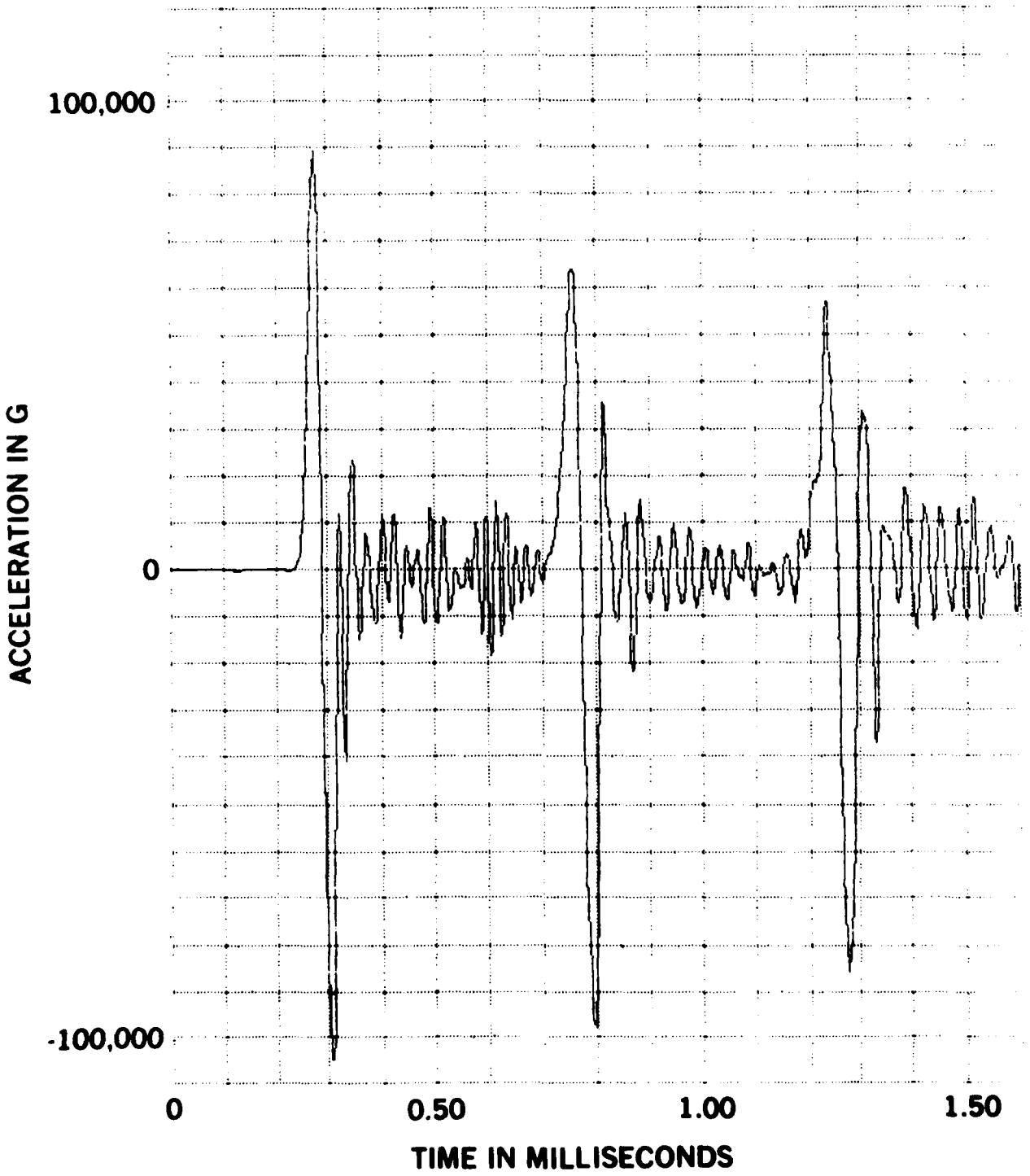


FIGURE 14. RESPONSE OF UNFILTERED PIEZOELECTRIC ACCELEROMETER (PCB 305A) TO HOPKINSON BAR IMPULSE

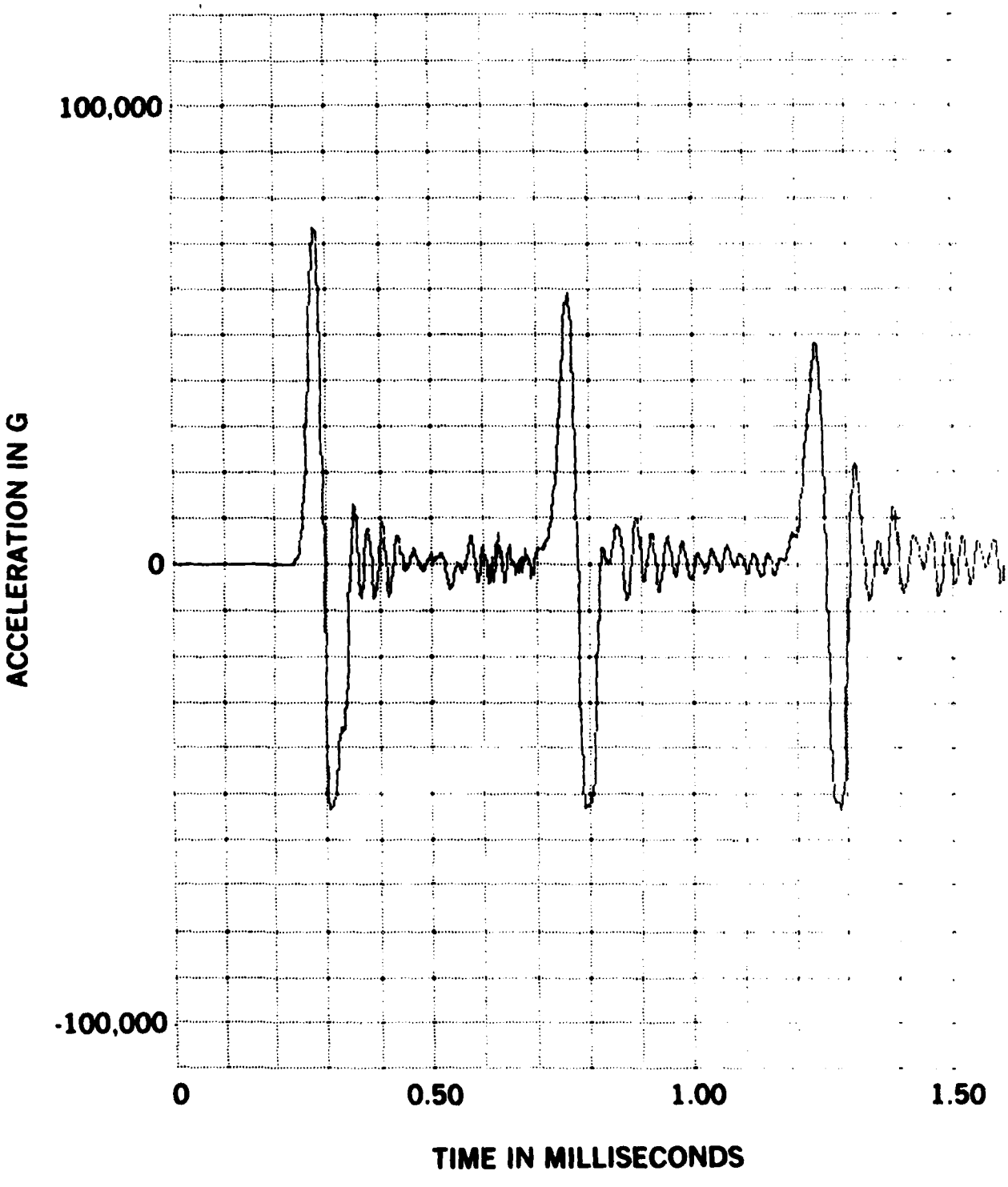


FIGURE 15. RESPONSE OF FILTERED PIEZOELECTRIC ACCELEROMETER (PCB 305M23) TO HOPKINSON BAR IMPULSE

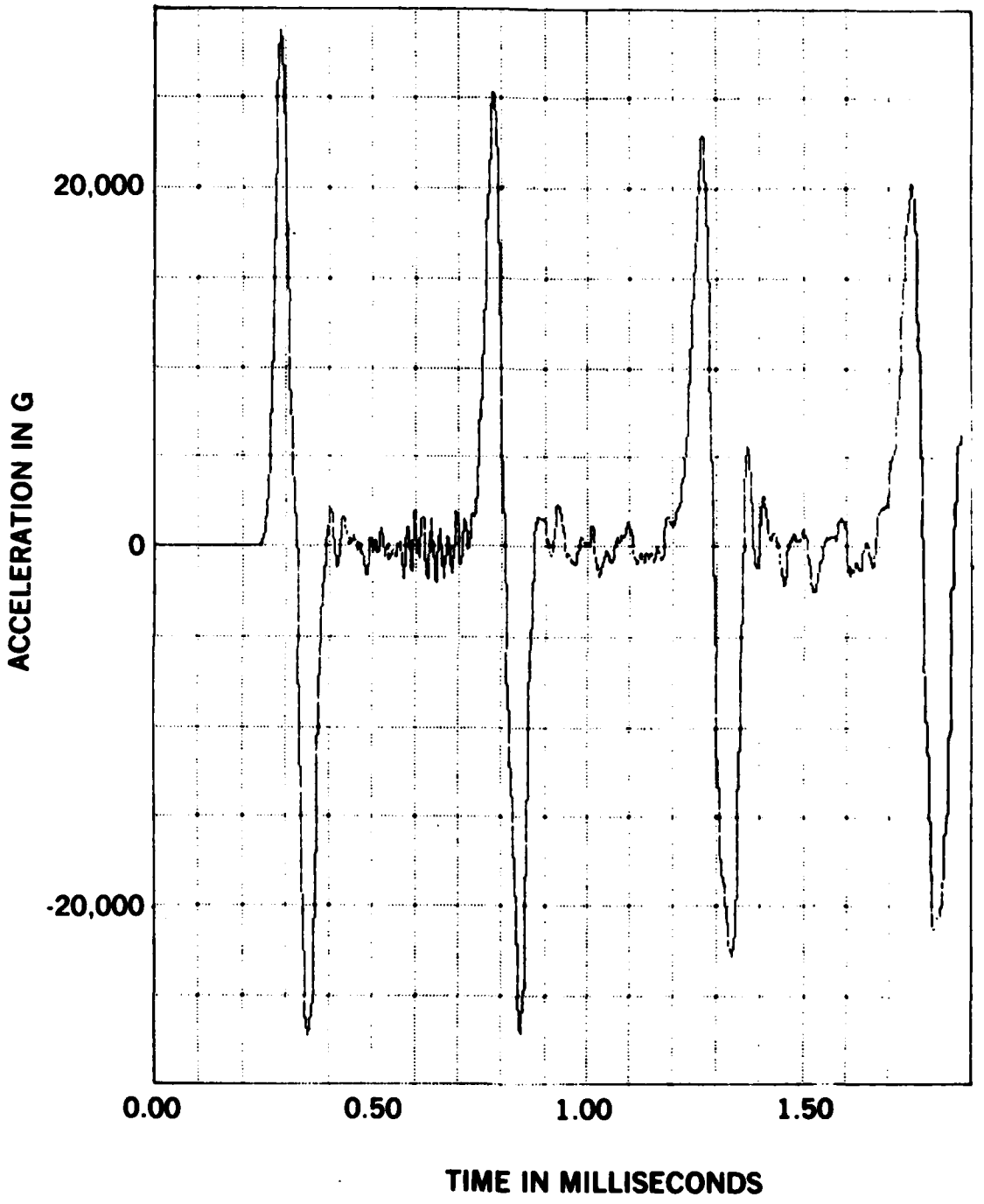


FIGURE 16. RESPONSE OF UNFILTERED PIEZORESISTIVE ACCELEROMETER TO LOW LEVEL HOPKINSON BAR IMPULSE

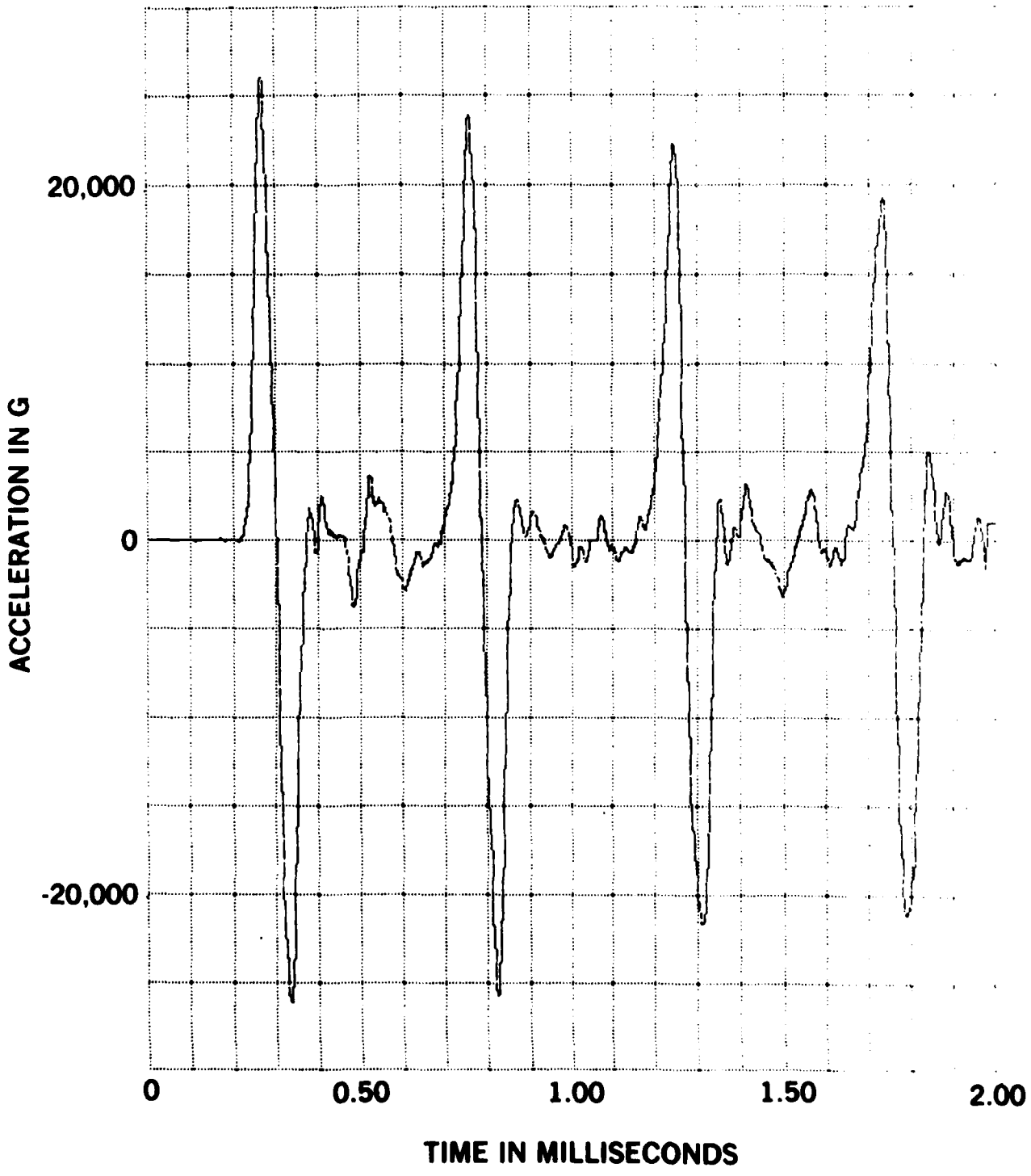


FIGURE 17. RESPONSE OF FILTERED PIEZOELECTRIC ACCELEROMETER (PCB 305M23) TO LOW LEVEL HOPKINSON BAR IMPULSE

Bibliography

1. P. L. Walter and H. D. Nelson, "Limitations and Corrections in Measuring Structural Dynamics," Experimental Mechanics, 19 (9) 309-316, Sept. 1979.

2. F. Schelby to Distribution, Internal Memo, "Developments in High g Shock Measurement at SNLA," Oct. 14, 1982

Appendix A

Specification for High G Shock Accelerometer

These specifications define a high-g shock accelerometer using a quartz crystal transduction element followed by an internal filter section and internal amplifier. It is required that the filter precede the amplifier in order to preclude electrical overload due to high frequency "ringing" of the crystal. These devices are intended for use in crash, impact, and explosive environments and are subjected to very harsh treatment. A family of transducers of various ranges are envisioned but even the lowest ranges may see, and must survive, up to 20,000g transverse shock.

Short duration precursor stress waves present in the vehicle at impact may cause the crystal to "ring" and, therefore, it is conceivable that as much as 100,000 equivalent g's may stress the transduction element even though the base input is much lower.

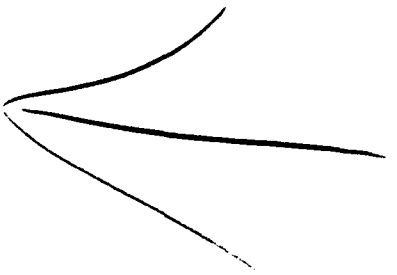
Range (FS)	$\pm$2000 g to $\pm$20,000 g
Output	$\pm$5 v FS
Sensitivities (10%)	2.5 mv/g to 0.25 mv/g
Time constant	2 seconds minimum
High frequency response	flat within $\pm$5% to 10,000 Hz with roll off commencing so as to achieve as much attenuation as possible of the accelerometer resonant frequency
Filter	2 pole, Butterworth response
Amplitude linearity	$\pm$1% FS
Transverse sensitivity	$\leq$5%
Transverse limit	20,000 g
Polarity	positive output for acceleration directed into base
Signal ground	either case or solder terminal
Seal	hermetic

Operating Temperature Range	-40deg.F to +200deg.F
Power Supply	4 ma constant current
Size	as small as possible, comparable to Kistler 805A or PCB305A
Mounting	integral stud

Appendix B

Measured Standard Performance Properties

Range (for ±5v output)	±20,000g
Time constant	2 seconds
Sensitivity	.19 mv/g
Transverse sensitivity	5.3%
Thermal sensitivity shift	.02%/deg.F
Temperature range	-40 to 250deg.F
Frequency response	flat within ±5% to 25kHz
Base strain	0.2 eq.g/microstrain



AD P002691

CALIBRATION OF VIBRATION PICKUPS AT HIGH FREQUENCIES

B. F. Payne

National Bureau of Standards

Washington, D. C. 20760

INTRODUCTION

Improved design of vibration pickups by several accelerometer manufacturers has resulted in low-mass or miniature accelerometers with extended frequency response. This paper discusses methods for measuring the frequency response (calibration) of this type of miniature accelerometer. By using a calibration system composed of a Michelson interferometer with a helium-neon laser as a light source, absolute displacement measurements can be obtained over the frequency range of approximately 2 to 30 kHz. Using techniques developed at NBS, measurements can be obtained at amplitudes of 121 nm and 193 nm. Since the vibration exciters have limitations in amplitude, the 121-nm technique enables higher frequency measurement cabability. These measurement techniques and the experimental measurement apparatus are discussed in this paper. An example of a measurement on a miniature accelerometer over the frequency range of 10 Hz to 30 kHz is discussed.

ELECTRODYNAMIC SHAKERS FOR LOW FREQUENCY MEASUREMENTS

Electrodynamic shakers are most useful for frequencies up to about 5000 Hz, the range for which these shakers have relatively low distortion and low cross-axis motion. For frequencies from about 5000 to 10000 Hz the NBS standard electrodynamic shakers are still useful but have decreased accuracy due to a slight increase in cross axis motion.

For frequencies from about 1 Hz to 100 Hz, a fringe counting interferometer is used at NBS to establish the sensitivity of an internal servo-accelerometer[1] built into a low frequency shaker. This shaker with a built-in calibrated accelerometer is then used to calibrate accelerometers in this low frequency range.

For frequencies of 10 Hz to 10000 Hz another type of electrodynamic shaker with a built in acccelerometer is calibrated by a reciprocity method [2]. These shakers are then used to calibrate accelerometers in this mid-frequency range.

PIEZOELECTRIC SHAKERS FOR HIGH-FREQUENCY MEASUREMENTS

For frequencies above about 2 kHz , piezoelectric ceramic shakers are well suited to generate sinusoidal motion along a single axis with low distortion and over a wide range of frequencies (fig. 1) [3]. Piezoelectric shakers are suitable for use with the optical method using laser interferometry. Their stiff construction minimizes unwanted motion of the shaker table relative to the shaker base, in contrast to the soft suspension of electrodynamic shakers. This soft suspension

allows the shaker table to be agitated by low-frequency mechanical and acoustical noise. This ambient noise makes the electrodynamic shakers unsuitable, for the most part, to optical methods of calibration, except at the very low frequencies (below 100 Hz) where the displacement is so large that the ambient noise is small relative to the large sinusoidal vibration. Piezoelectric shakers have long been an important component in our optical calibration systems. The work of Jones [3] extended the useful frequency range of such shakers to provide the increasing frequency range needed for government, industrial, and defense laboratories. These NBS shaker designs provide a more nearly uniaxial motion at higher frequencies, thus minimizing the errors due to transverse motion and harmonic distortion.

These piezoelectric shakers are well suited to vibration measurements of accelerometers, including the type shown in figure 2 which have a mass of about two grams. Accelerometers of this size are especially suitable for high frequency measurements in the range of 10 to 30 kHz whereas some larger accelerometers may be beyond their useful range because of structural limitations. The small accelerometers such as shown in figure 2 can be attached to the shaker table by fast drying cement and can be easily removed. The following sections of this paper will describe the optical and comparison measurements on a typical miniature accelerometer of this type.

THE OPTICAL INTERFEROMETRIC MEASUREMENT SYSTEM

The optical measurement systems shown in figures 3 and 4 are used for absolute displacement measurements needed to calibrate the accelerometer [4]. The accelerometer to be tested is usually mounted in the center of the shaker table and a small mirror is glued to the shaker table in close proximity to the accelerometer. For the minature type accelerometer, the diameter of the accelerometer may be too small to cover the mounting hole in the center of the shaker table, in which case the accelerometer is mounted just to one side of the mounting hole with a fast drying cement. Since the mass of the small accelerometer is about two grams, the off-center mounting does not create unsymmetrical loading problems encountered with heaver pickups. A Michelson interferometer is used for the optical measurements of displacements, as shown in figure 3. A 3 to 5-mW helium-neon laser is used as the optical source. The beam splitter directs one half of the light to the fixed mirror and one half to the small mirror on the shaker table. These light beams then recombine at the beam splitter and are reflected to the photodetector. By electrically analyzing the signal from the photodetector, the accelerometer can be calibrated at either 121 or 193 nm.

MEASUREMENT AT 121 nm

For this case the fixed mirror is mounted in an optical mount designed so that the mirror is mounted on a small piezoelectric driver (fig. 3). The mirror is free to move along the axis of the incoming light beam. The signal from a sine wave oscillator is amplified to about 30 to 50 volts peak to peak. This amplified signal is then used

to excite the fixed mirror at a frequency of approximately 0.3 Hz, producing a variation in the current I by a variation in the Δ as shown in eq. 1 below. The current is also varied by the forced vibration of the shaker.

To facilitate discussion, an expression for the output current of the photodetector is reproduced below.

$$I=A+B\ (\text{Cos}\ 4\pi\Delta/\lambda).J_0(4\pi d/\lambda)-2J_2(4\pi d/\lambda)\cos 2(\omega t+\phi)+\ \ldots$$
$$-B(\sin 4\pi\Delta/\lambda)\ .2J_1(4\pi d/\lambda)\ \cos(\omega t+\phi) \qquad [1]$$
$$-2J_3(4\pi d/\lambda)\ \cos\ 3\ (\omega t+\phi)+\ldots\ ,$$

where A and B are constants; d,ω,ϕ, represent the amplitude, angular frequency and phase, respectively, of the displacement being measured; Δ is one half the optical path length difference of the two beams; λ is the wavelength of the light source; and t is time. The quantities Jp(x) are Bessel function of the first kind of order p.

If the d-c component of the current (a function of Δ and d) is considered, it may be observed that for any fixed value of d, the range of variation of I is

$$I(\text{max})-I(\text{min})=2BJ_0(4\pi d/\lambda)=\text{Delta(I)}$$

since the cosine function varies from 0 to 1. This difference decreases as d approaches a value which makes

$$J_0(4\pi d/\lambda)=0.$$

For a laser with λ = 632.82 nm, this value of d is equal to 121.1 nm. To implement this method, the current I is modulated by a periodic variation of Δ resulting from the movement of the fixed mirror, as discussed above. A computer controlled, programmable digital synthesizer systematically varies the amplitude of vibration of the shaker, while a digital voltmeter reads Delta(I) and stores it in the computer memory. The synthesizer voltage is varied in small increments until Delta(I) reaches its lowest level or Delta(I)=Delta(Min). The d-c current then remains constant at I= A regardless of any changes brought about by Δ. Some recent work has focused on techniques to determine the lowest level of Delta(I). The precision of this calibration method depends to a great extent on the accuracy of determining this term, and it will be discussed in greater detail in a future report.

Having arrived at the precise amplitude of vibration which corresponds to Delta(Min), or the fringe-disappearance condition corresponding to 121.2 nm, the accelerometer output is measured at this point. The acceleration level, referred to the standard acceleration of free fall, g, is computed from:

$$\text{Acceleration}=(2\pi f)^2 d/g \qquad [2]$$

where d=121.2 nm, and f is the frequency (Hz). The sensitivity of the accelerometer is computed from the following equation:

$$\text{Sensitivity} = \sqrt{2}\ E \ /\ \text{Acceleration} \qquad [3]$$

where E is the rms voltage of the accelerometer output.

MEASUREMENT AT 193 nm

This measurement technique is similar to the 121 nm measurement described above. In this case the fixed mirror is not excited but held in a fixed position. The signal from the photodetector is processed by the wave analyzer shown in figure 4. The wave analyzer is tuned to the fundamental driving frequency of the shaker. By thus filtering all but the fundamental frequency term in eq. 1, only the following term remains:

$$I = -B(\text{Sin}\ 4\pi\Delta/\lambda)\ 2J_1(4\pi d/\lambda)\cos(\omega t+\phi).$$

At discrete amplitudes of vibration corresponding to nulls of the Bessel function, the above equation reduces to:

$$J_1(4\pi d/\lambda) = 0$$

This is accomplished reasonably well by mounting the interferometer apparatus on an air suspension table in order to hold Δconstant.

In practice, using current shakers, only the first null is measured in the frequency range of 2-20 kHz due to limitations in the drive of the shakers. The null is determined precisely by varing the drive voltage from the oscillator until the wave analyzer can be tuned to a precise null (minimum). At this null the displacement is precisely 192.96 nm for a He-Ne laser source of 632.82 nm. Having obtained this precise amplitude, the acceleration is computed from eq 2 and the sensitivity of the accelerometer is computed from eq 3.

COMPARISON AND DISCUSSION OF THE TWO METHODS

The two methods discussed above are limited to discrete amplitudes. Table 1 lists the acceleration levels for the two methods corresponding to the first null of the Bessel function. In the case of the 121-nm test, the procedure is automated using a desk-top computer. All of the test and measurement procedure is controlled by the computer and the data is recorded automatically. In the case of the 193 nm measurements, the procedure requires a wave analyzer which in our case is not under computer control and therefore requires manual balancing to obtain the null condition.

EXPERIMENTAL MEASUREMENTS FOR A MINIATURE ACCELEROMETER

A miniature accelerometer of the type shown in fig. 2 was calibrated using these two methods for frequencies starting at 3 kHz and extending to the limit of the drive amplitude of the shakers. Comparison

measurements were also make from 10 Hz to 10 kHz using electrodynamic shakers as described above. Figure 5 shows the results of these measurements. In the case of the 121 nm measurements the data were obtained up to 29 kHz, while in the case of the 193 nm measurements data were obtained up to only 20 kHz. The drive limitation of the shakers determined the upper frequency limits. The two methods show good agreement over the frequency range where both methods can be used. The roll-off in the frequency response of this accelerometer is due to the signal conditioner which has a compensating network to reduce the response at higher frequencies. Since the accelerometer and signal conditioner are designed to be used as a unit, the signal conditioner could not be easily replaced by one with a flatter responce. The estimated errors are +/- 2% from 2.5 to 10 kHz, +/- 3% from 11 to 15 kHz, and +/- 4% above 15 kHz.

SUMMARY

Optical interferometric measurement methods can be used over a wide frequency range for accelerometer characterization. By using carefully designed shakers, the amplitude measurements have been made over the frequency range of 3 to 29 kHz. Measurements were made at 121 nm and 193 nm displacent (zero to peak). The 121 nm measurements were extended to 29 kHz with the present NBS shaker model S93 while the 193 measurements are limited to about 20 kHz because of the greater amplitude requirements. For the case of the 121 nm measurements, the experiment is completely automated with the use of a small desk top computer. Care should be exercised in the use of these methods at extended frequencies, to be certain that the shaker used has uniaxial, undistorted motion over the frequency range of interest.

REFERENCES

1. R. S. Koyanagi, "Development of a Low-Frequency-Vibration Calibration System," Experimental Mechanics 15, No. 11 (1975): 443-448

2. B. F. Payne, R. S. Koyanagi, C. Federman, and E. Jones, "Accelerometer Calibration at the National Bureau of Standards," ISA ASI 75255 (May 1975).

3. E. Jones, W.B. Yelon, and S. E. Edelman, "Piezoelectric Shakers for Wide-Frequency Calibartion of Vibration Pickups, " J. Acoustical Soc. Amer. 45, no. 6 (1969): 1446-1559.

4. B. F. Payne and M. R. Serbyn, "Absolute Calibration of Accelerometers at the National Bureau of Standards, "Proc. Tenth Transducer Workshop, 136-144 (Range Commanders Council, White Sands Missile Range, NM, 1979).

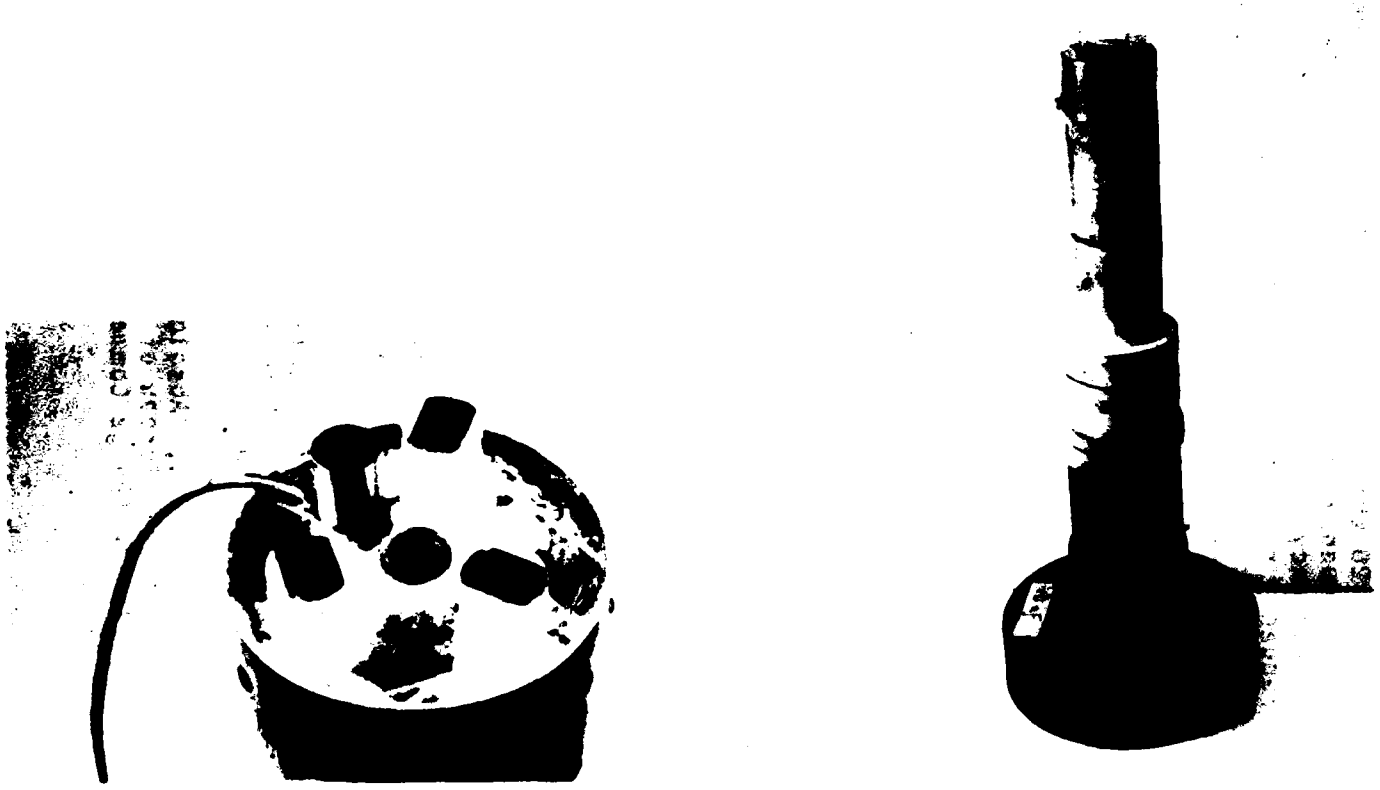


FIGURE 1. PIEZOELECTRIC SHAKER FOR HIGH FREQUENCY DISPLACEMENT MEASUREMENTS.

TABLE 1. Acceleration levels for 121 nm and 193 nm

FREQ. (kHz)	Acceleration (in g units) d=193 nm	d=121 nm
1	.78	.49
2	3.11	1.95
3	6.99	4.39
4	12.42	7.80
5	19.41	12.19
6	27.95	17.56
7	38.04	23.90
8	49.69	31.22
9	62.89	39.51
10	77.64	48.78
11	93.94	59.02
12	111.80	70.24
13	131.21	82.43
14	152.17	95.60
15	174.69	109.74
16	198.76	124.86
17	224.38	140.96
18	251.55	158.03
19	280.28	176.08
20	310.56	195.10
21	342.39	215.10
22	375.78	236.07
23	410.72	258.02
24	447.21	280.94
25	485.25	304.84
26	524.85	329.72
27	566.00	355.57
28	608.70	382.40
29	652.95	410.20
30	698.76	438.98

FIGURE 2. MINIATURE ACCELEROMETER FOR HIGH FREQUENCY APPLICATIONS.

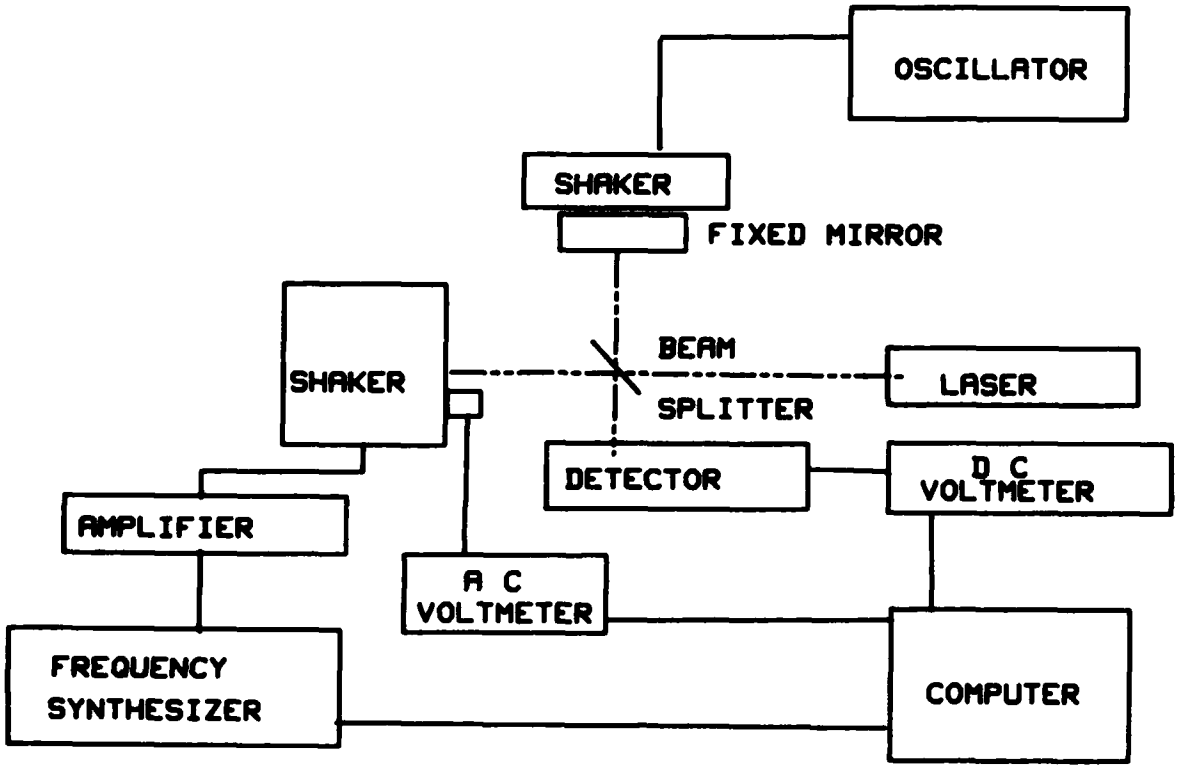


FIGURE 3. OPTICAL MEASUREMENT SYSTEM FOR 121 nm.

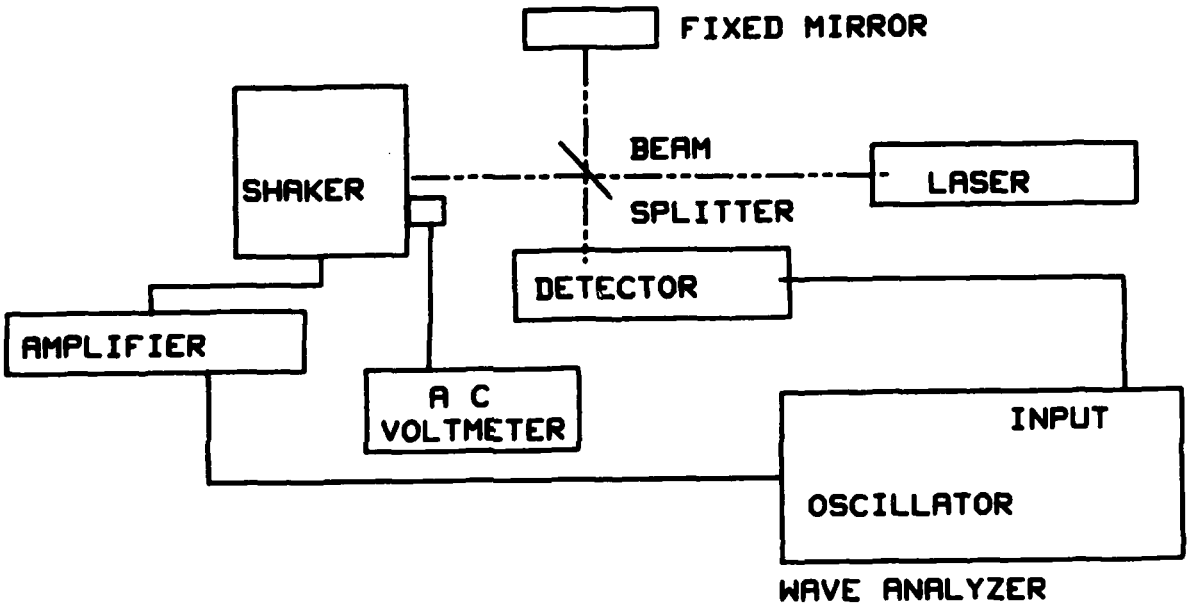


FIGURE 4. OPTICAL MEASUREMENT SYSTEM FOR 193 nm.

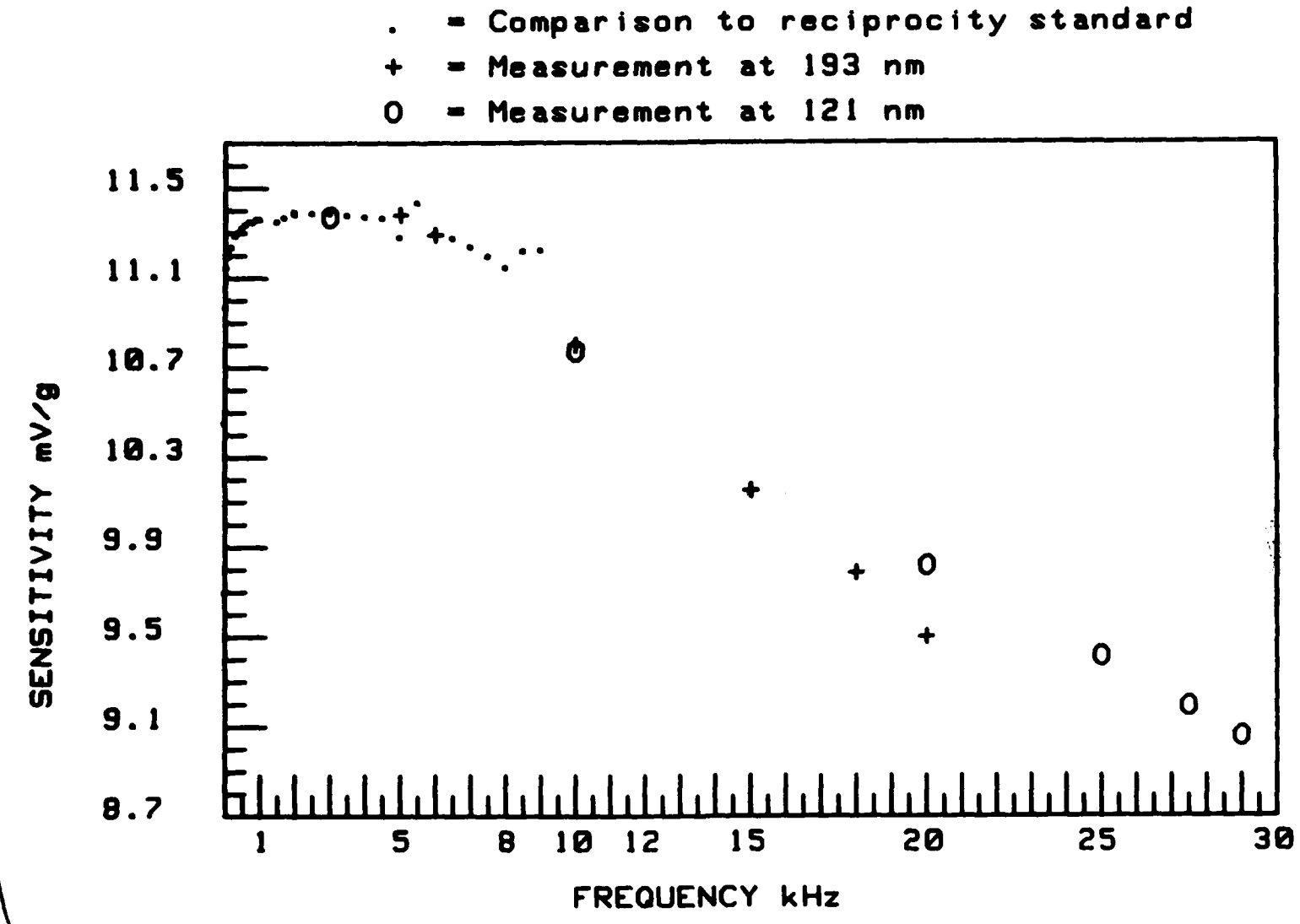


FIGURE 5. SENSITIVITY OF A TWO GRAM ACCELEROMETER

AD P002692

SSS-IR-83-6141

SHOCK ISOLATED ACCELEROMETER

by

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(This work funded under Contract DNA001-82-C-0271)

ABSTRACT

This paper presents a novel concept for isolating an accelerometer from large, potentially damaging, transient accelerations. It consists of a piston, bore, and a preset frictional force between the two. The accelerometer is mounted on the piston. The piston will displace relative to the bore when the input force to the bore is equal to or greater than the frictional force. By knowing the total piston mass and frictional force between it and the bore, an upper limit to the transmitted acceleration is defined. This "clipping" acceleration level can then be set to protect the transducer from overranging. Initial tests have successfully clipped 80kg, 70 μsec duration, input accelerations down to an average level of 20kg.

It is shown that once the piston stops sliding within the bore, the integrated accelerometer signal will give the true velocity of the "gauge package," and the doubly integrated accelerometer signal will give the true displacement minus the relative displacement between the piston and bore.

Methods of controlling the accelerometer and gauge package resonances, excited through shock input, are being developed.

INTRODUCTION

A constant and ever-present problem of shock experimentation has been the damage or destruction of sensors due to an input overrange with the subsequent loss of meaningful data. This problem is a particular nuisance in shock-induced ground motion measurements where it is difficult to predict parameters, such as acceleration and local media inhomogeneities or poor gauge coupling, which may result in short duration, high amplitude signals. As a consequence, S-CUBED has developed a promising technique for the protection of acceleration sensitive transducers to shock-induced overrange.

BACKGROUND

Consider the two blocks in Figure 1. A normal force, N, acts across the boundary resulting in a friction force along the contact surface. If a force is applied to the lower block, it is transmitted through friction to the upper block. This static friction force, f_s, is defined by the static friction coefficient, μ_s, at the contact surface and the magnitude of the normal force:

$$f_s = \mu_s N \tag{1}$$

The two blocks will accelerate as a unit until the force acting on the lower block is greater than or equal to the maximum force of static friction.

Relative motion between blocks then occurs; the kinetic friction force, f_k, is constant and dependent only on the coefficient of kinetic friction μ_k and the magnitude of the normal force.

$$f_k = \mu_k N \tag{2}$$

An upper limit to the force (and acceleration) acting on the upper block is now defined and is given by:

$$f_{s\ max} = \mu_s N = M_2 a_2 \tag{3}$$

or

$$a_2 = \frac{\mu_s N}{M_2} \geq \frac{\mu_k N}{M_2} \qquad (\mu_k \leq \mu_s)$$

Once the external force is removed, the internal forces are equal and opposite and produce equal and opposite changes in momentum; the difference in kinetic energy being lost to friction. Both blocks then cease relative motion and come to the same final velocity.

Clearly, if an accelerometer (or velocity gauge) is mounted on the upper block, it will respond accurately to the external force, unless such a force exceeds that due to the static friction at the contact surface, then the transducer sees only the kinetic friction force. Therefore, the maximum acceleration of the transducer can be adjusted by varying:

1. The coefficients of Friction (μ_k and μ_s).
2. The normal force (N).
3. The combined mass of the upper block and transducer.

FIXTURE DESIGN

In order to make use of this system, it is assumed that the external force will exceed the static friction force for a relatively brief time compared to the total duration of the signal and that the direction in which the external force acts is known.

The problem then is to design a fixture on which to mount the transducer(s). A number of constraints apply to the configuration, size, and material from which it is made.

We chose a piston and split bore schemes (Figure 2). Adjustment screws traverse the gap in the bore allowing the normal force between the piston and bore to be adjusted over a wide range. The transducer is mounted on the end of the piston. The overall size of the fixture was made as small as possible, being transducer limited, in order that the gauge perturb the media under investigation as little as possible. Worst case assumptions about the input signal were made so that piston length could be specified; in our case, it was 10^6g for 10μsec with a desirable "clipping" acceleration of 2×10^4g. Since, by definition, the relative motion between the piston and bore must cease while the piston is still in the bore, the time integrals of acceleration for the piston and bore must be equivalent. In other words, the piston and bore come to the same final velocity. Then the total displacement between the bore and piston can be obtained from the above values using:

$$a_1 t_1 = a_2 t_2 \tag{4}$$

$$\ell = \frac{1}{2} a_2 t_2^2 \tag{5}$$

$$\ell = \frac{a_1^2 t_1^2}{2a_2} \tag{6}$$

For $a_1 = 10^6 g = 1 \times 10^9 \frac{cm}{sec^2}$

$a_2 = 2 \times 10^4 g = 2 \times 10^7 \frac{cm}{sec^2}$

$t_1 = 10 \mu sec$

$\ell \approx 2.5 cm$

So, the total piston legnth is 2.5cm plus the bore length.

Several different materials were investigated for use in the test fixture: aluminum, plastic, steel, and stainless steel. Stainless steel was picked for construction because of its strength and resistance to corrosion. It is used for both the piston and bore so that thermal expansion will be matched and the clamping force on the piston will not change with temperature.

The contact surface between the piston and bore has an eight-microinch finish, and the surfaces are lubricated with a high pressure lubricant, Fel-Pro C5A anti-sieze compound.

The fixture is calibrated by varying the clamping screw torque and measuring, with a load cell, the force necessary to cause displacement between the piston and bore. Figure 3 is a plot of such a calibration and shows linear relationship between the clamping screw torque and the equivalent "clipping" acceleration of the piston (measured force divided by piston mass).

EXPERIMENTATION

Initial testing revealed that with impulsive loading the fixture would "ring"; the acoustic vibrations of the test fixture were being recorded by the accelerometer and confusing the signal of interest. A composite piston utilizing wave dispersion and viscoelastic damping was constructed to reduce the interference caused by the vibrations. Figure 4a and 4b compare the response of the solid piston and composite piston to an impulse generated by dropping a 1/8" steel ball onto the fixture from a height of 30cm. The amplitude of the ringing was reduced roughly by a factor of three in the composite piston.

The real test of such a system is to subject the fixture to an impulsive force. This was done, initially, on the S-CUBED drop bar calibrator diagramed in Figure 5. Elastic collision between the drop bar or ball is assumed, and the final gauge velocity and average acceleration during impact can be calculated through conservation of momentum equations. Figures 6a and 6b compare the fixture's response to the impact of an aluminum sphere (130gm, 4.5cm diameter) dropped from a height of 1 meter. The dotted trace represents a test where no piston-bore slipping occurred, and the solid trace shows a test where slipping did occur. The initial peak on the clipped trace represents the peak static friction force, and the average acceleration (approximately 800g) is indicative of the kinetic friction force, the ratio is approximately 1.5. The final velocity is the same for both, acceleration and velocity versus time is lost only while the piston is sliding. This means that the error in displacement (double integrated acceleration) is limited to transducer response and the relative displacement of the piston and bore, which might be several millimeters. This is small compared to typical shock-induced ground motion displacements of several tens of centimeters or so.

The maximum drop height obtainable on the S-CUBED drop bar facility is nominally 4m. This limits peak gauge velocities to approximately 4m/sec and average accelerations to 10kg.

In order to obtain higher accelerations (approximately 100kg) and velocities (approximately 50m/sec), a smooth bore, 75mm, howitzer was employed. It was used to launch a 1.5kg aluminum projectile with a muzzle velocity of about 70m/sec. In addition, an independent measurement of the test fixture velocity versus time was made with a VISAR (laser velocity interferometer). Figures 7a-c show the data obtained from a test where the piston "clipping" acceleration level was set to approximately 20kg.

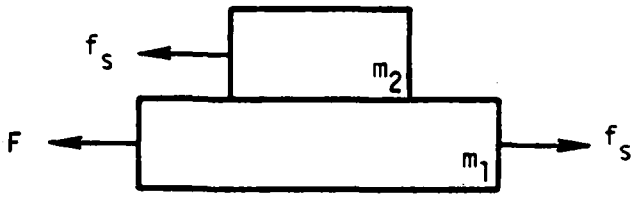
The bore mounted accelerometer shows an impact duration of approximately 70μsec with a peak of 80kg or so. The sudden rise of the signal at 115μsec was attributed to an intermittent connector (the transducer was tested after the shot and found to be undamaged).

The piston mounted transducer (Figure 7b) shows an initial peak of 60kg with an average clipping acceleration that starts at less than 20kg and climbs to over 90kg. The mean value lies in the range of 20kg to 30kg, which is very close to what was desired. The duration of the piston slip is 172μsec. The numerical integration of the bore signal, the piston signal and the VISAR data are plotted in Figure 7c. The VISAR and bore signal show very good agreement.

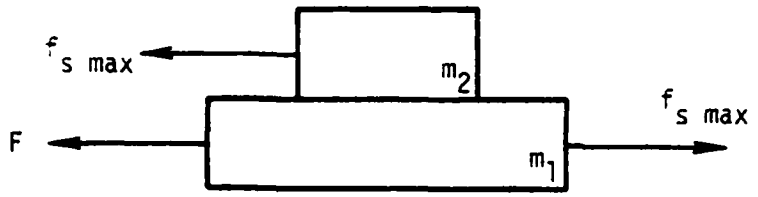
CONCLUSION

The true solution to the problem of transducer overrange damage is to use a sensor with adequate dynamic range; often this is not possible. In those cases where the signal cannot be predicted

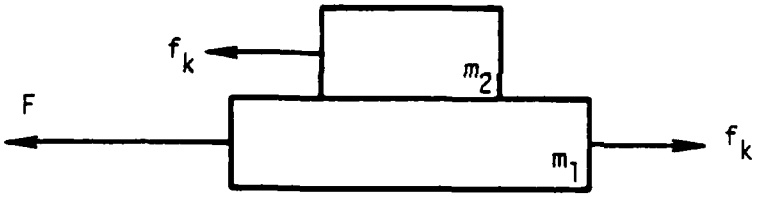
with sufficient accuracy, protection of the transducer from overrange needs to be pursued. The technique just described offers such protection to acceleration sensitive transducers without affecting their normal operation. The main limitation of the friction-coupled shock isolator is its inability to offer protection for off-axis overrange inputs. It therefore requires precise alignment along a predetermined axis of motion.



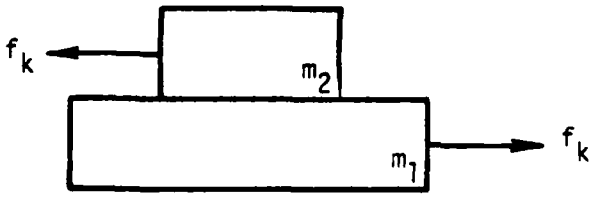
no relative motion between blocks.



relative motion just starts when $F=f_{s\ max}$.

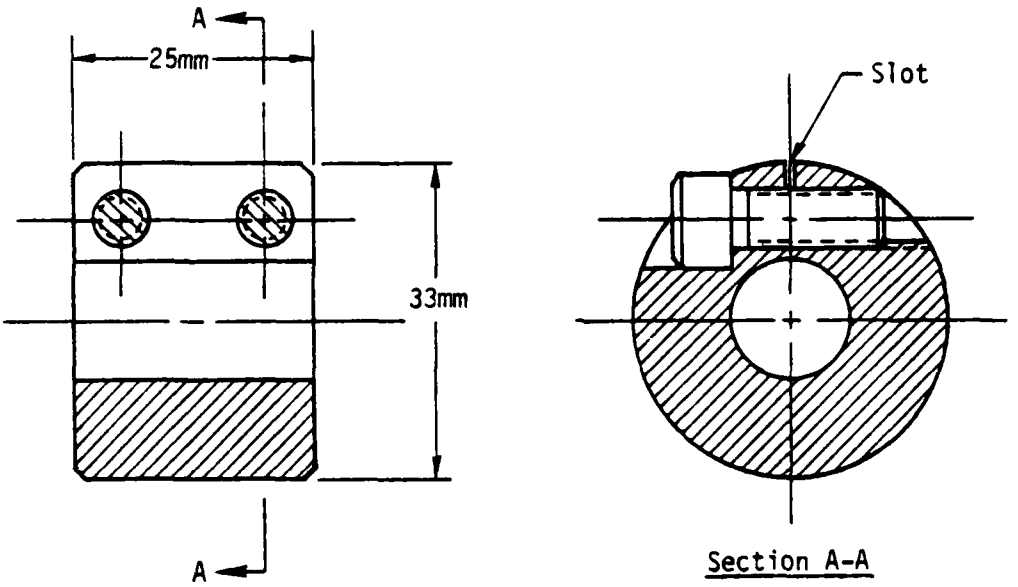


when $F>f_k$, the net force acting on the lower block is, $F-f_k=m_1a_1$, and on the upper block it is $f_k=m_2a_2$



if the external force, F, is removed, then only the friction force, f_k, acts on the two blocks. Slipping occurs until the frictional force has reduced the relative motion to zero.

Figure 1. Friction coupled blocks.



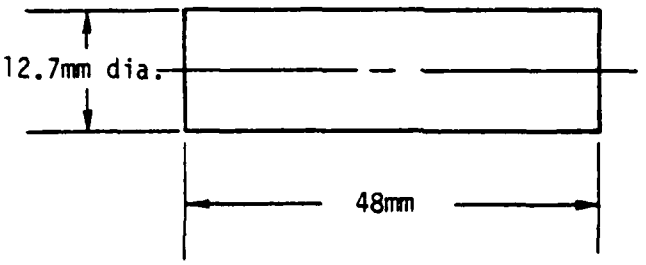


Figure 2. Shock isolated accelerometer.
Bore and Piston

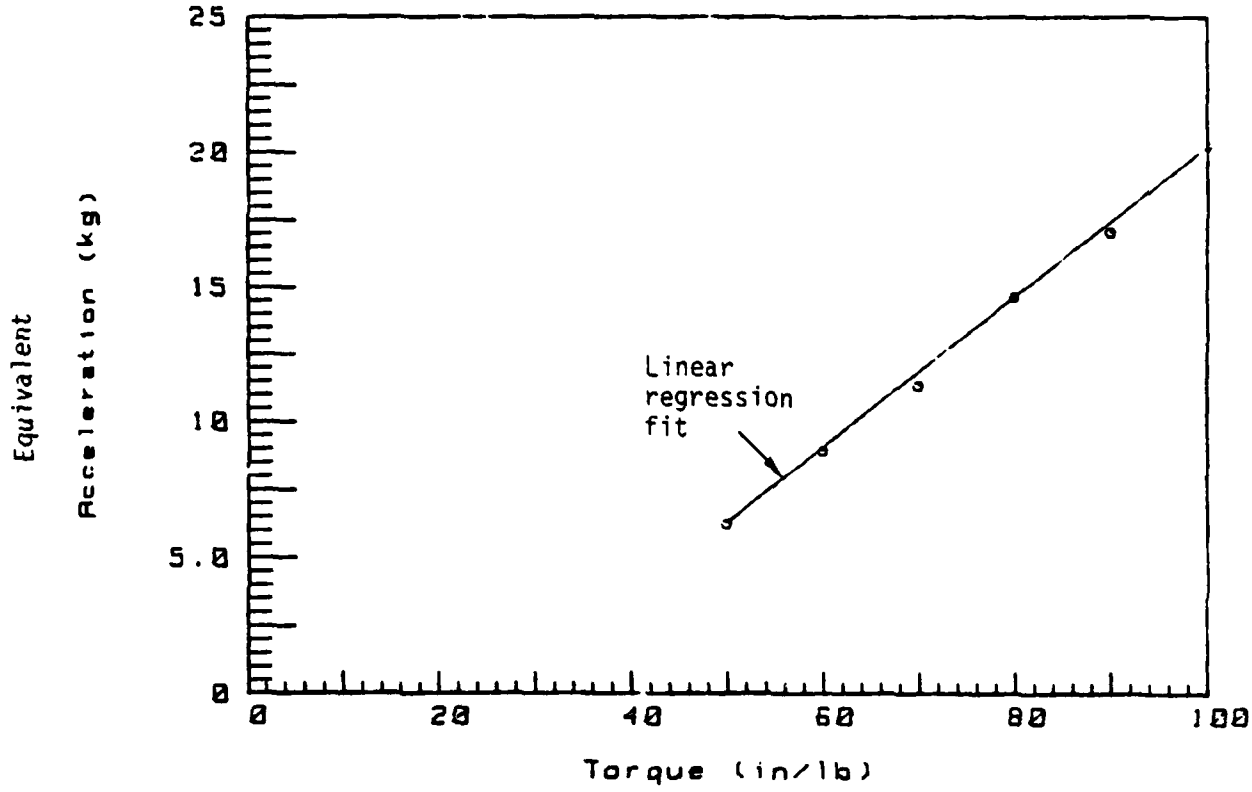


Figure 3. Load cell calibration of test fixture.

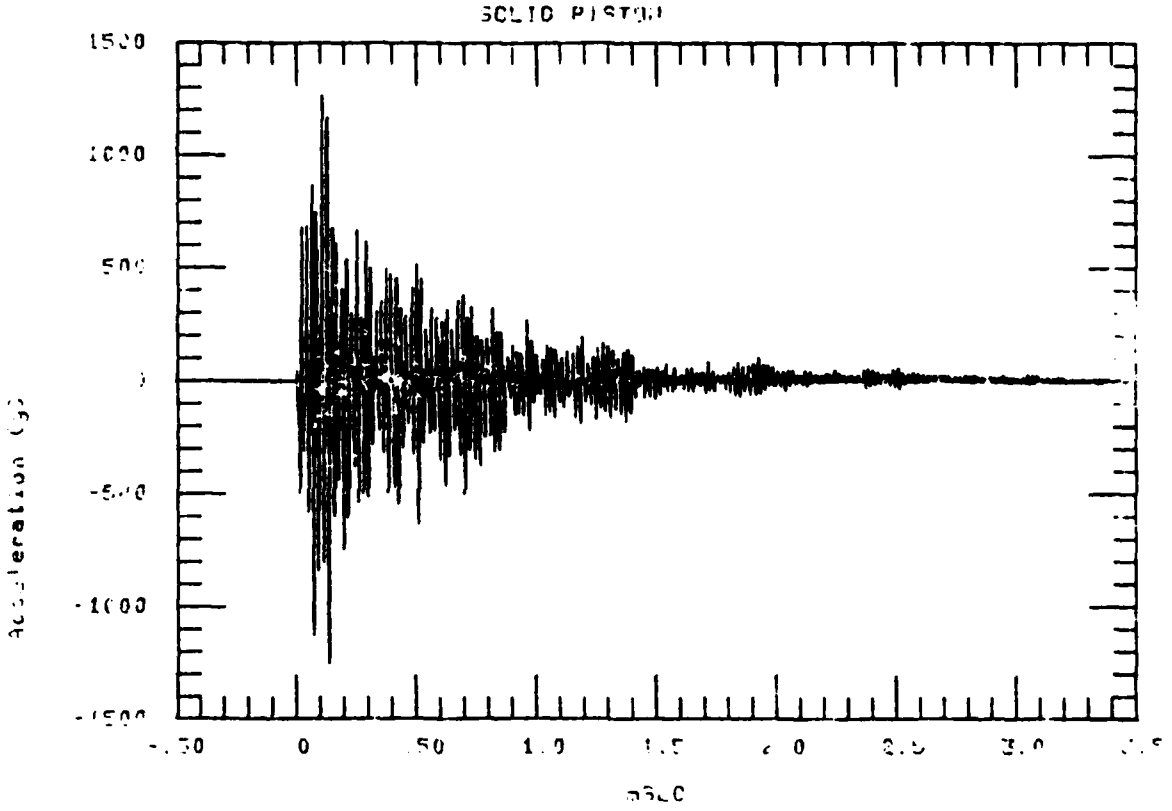


Figure 4a. Response of solid piston to a small impulsive force.

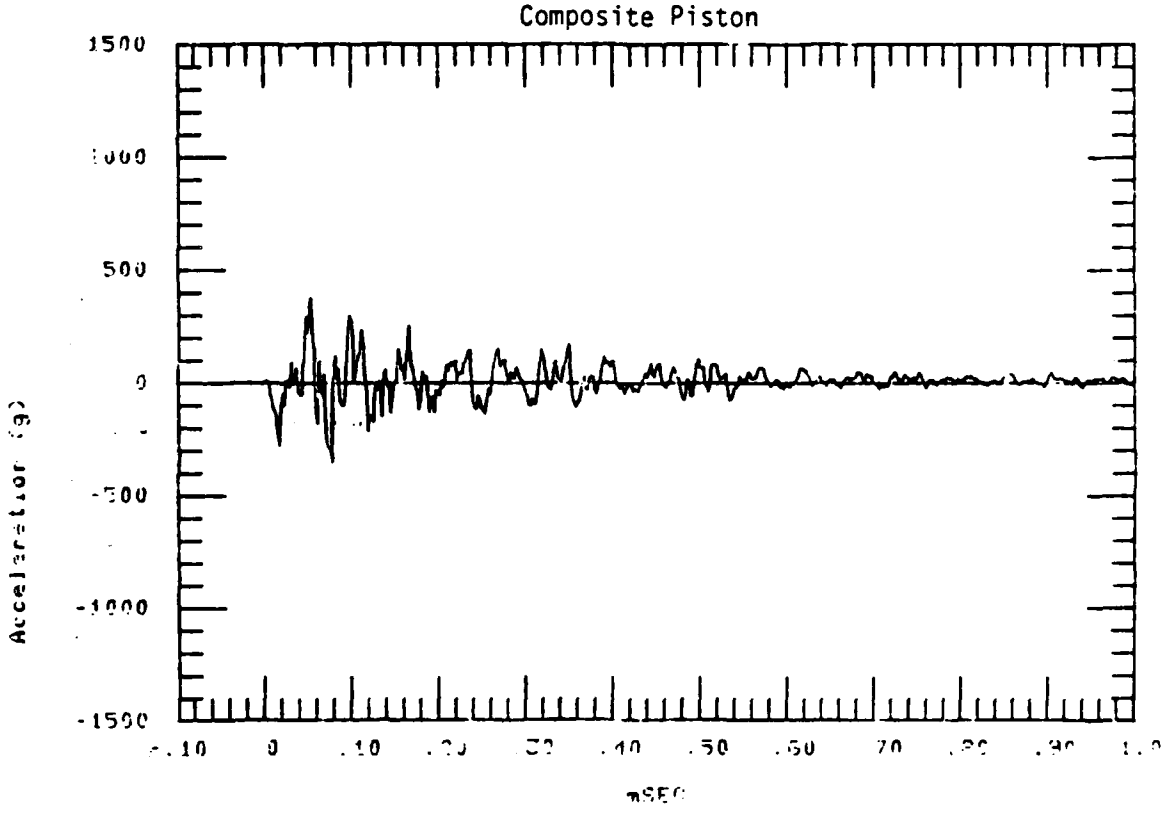


Figure 4b. Response of composite piston to a small impulsive force.

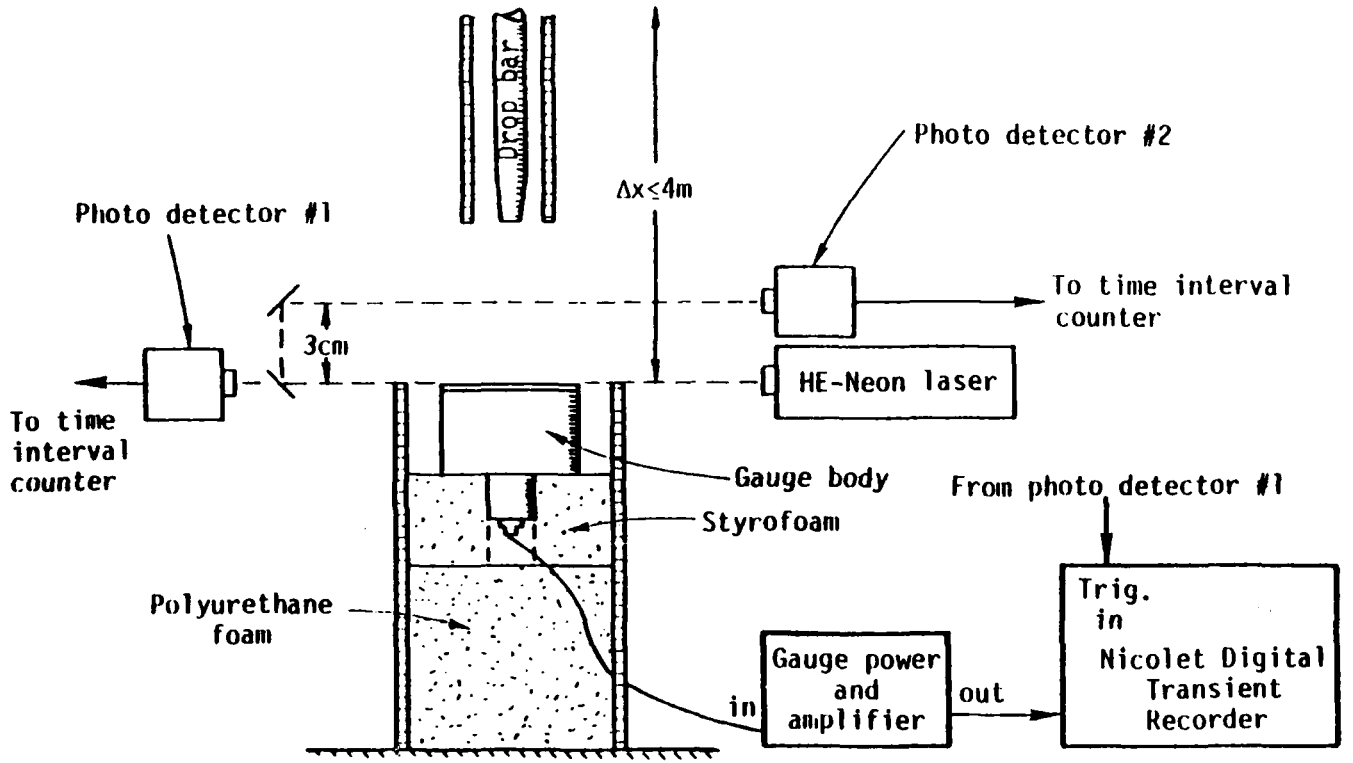
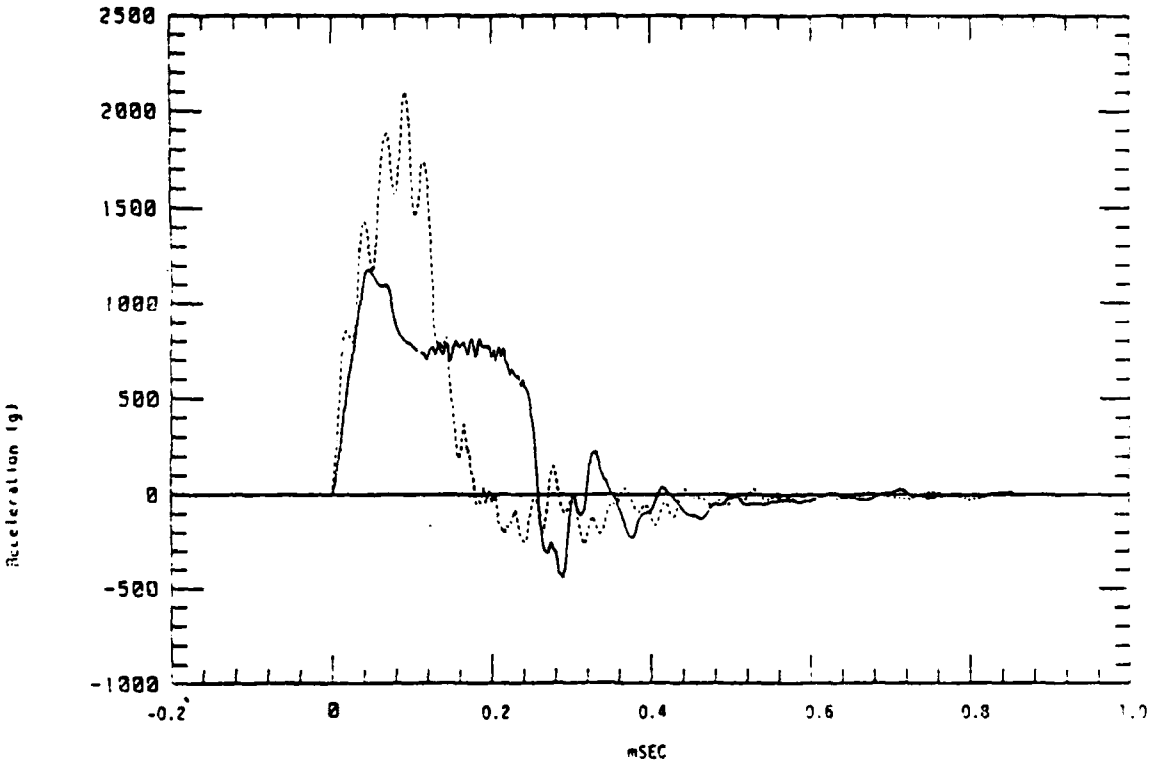
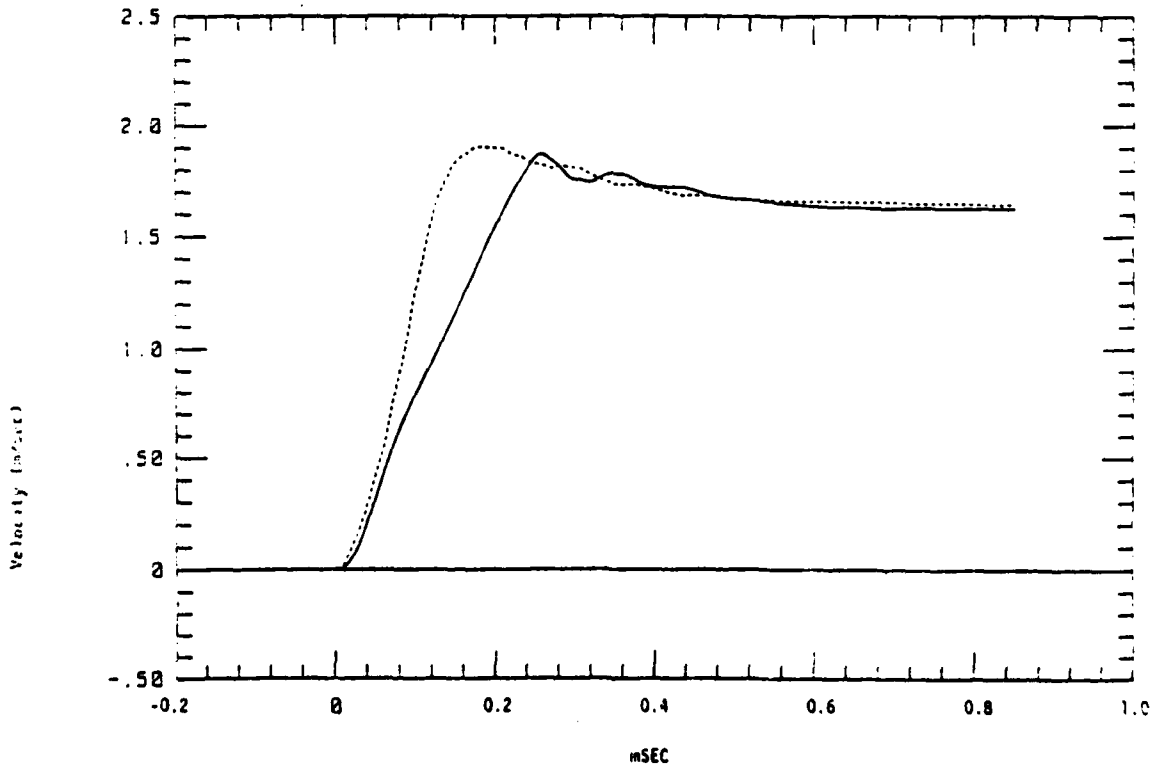


Figure 5. Drop bar.





Figures 6a and 6b. Drop ball test.

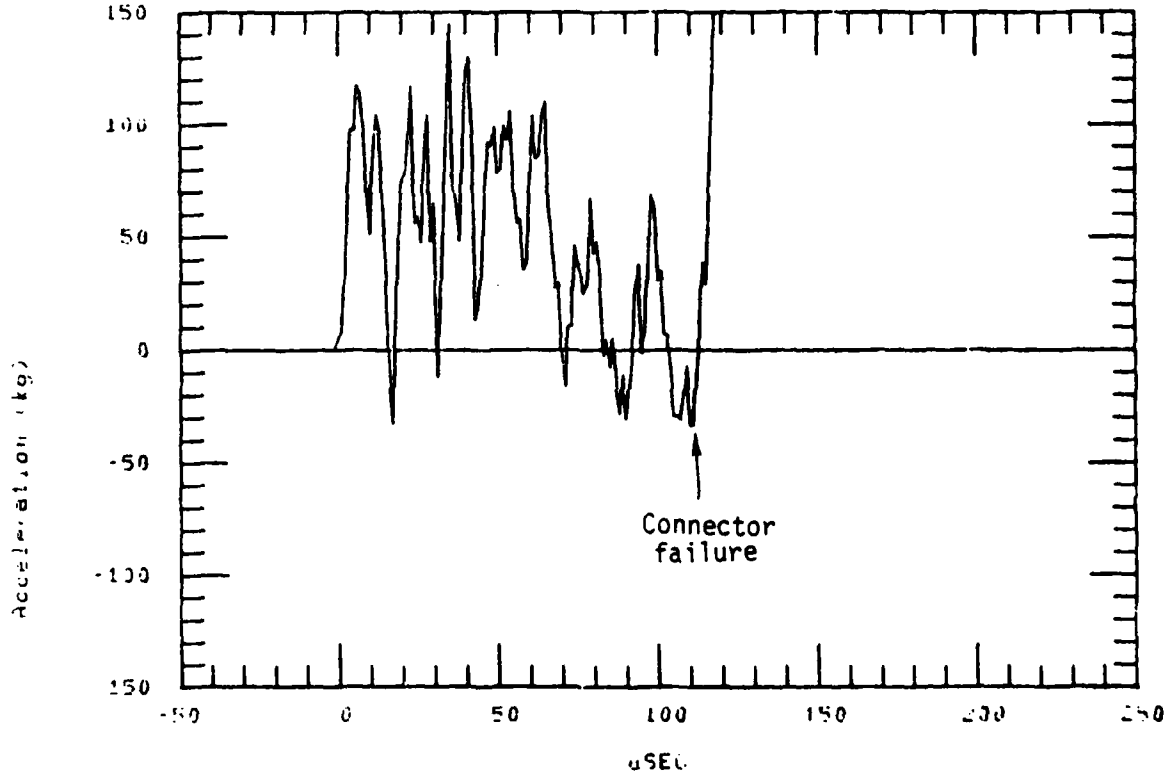


Figure 7a. Bore mount accelerometer.

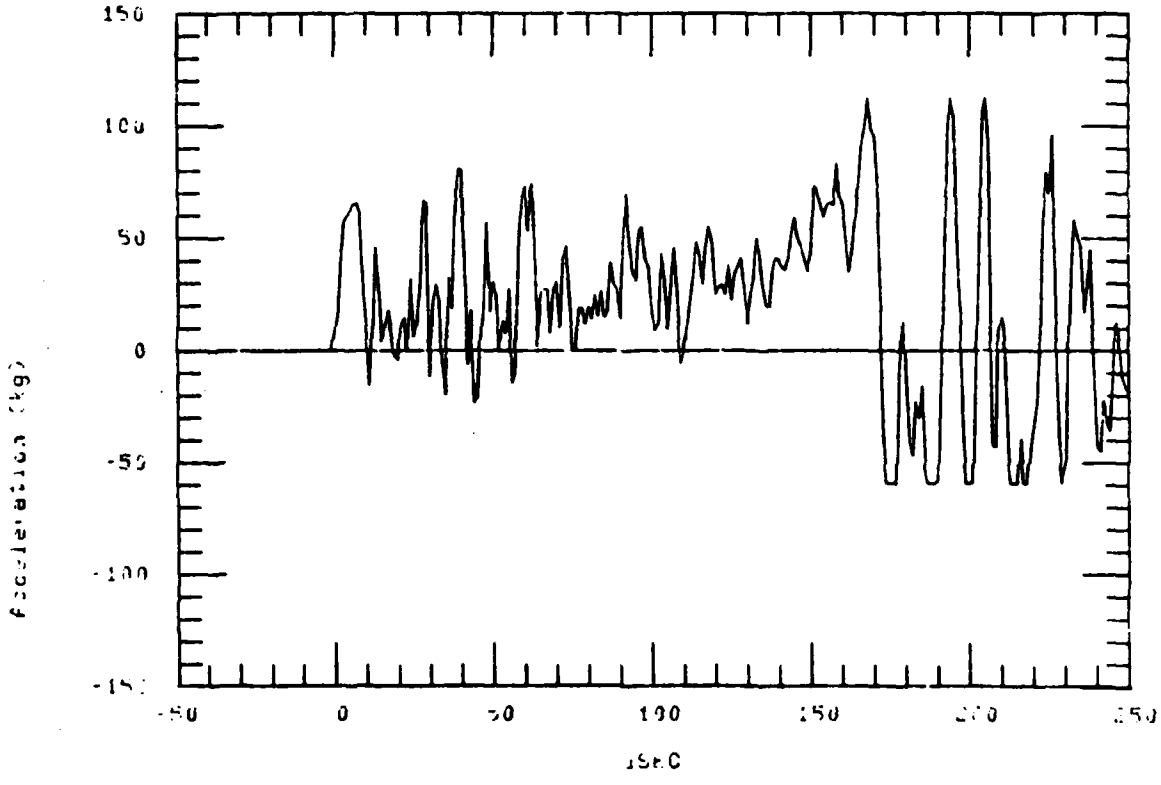


Figure 7b. Piston mount accelerometer.

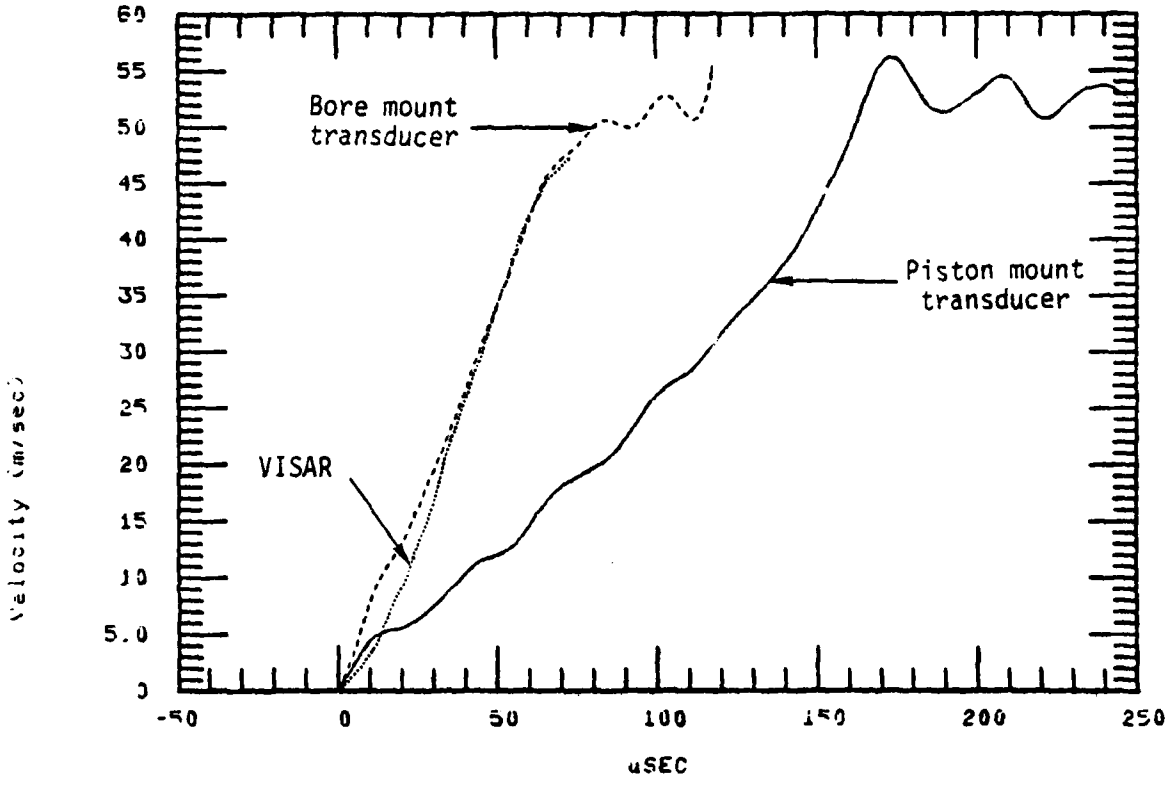


Figure 7c. Numerical integration of acceleration and VISAR.

ADP002693

TESTING TECHNIQUES INVOLVED WITH THE DEVELOPMENT OF HIGH SHOCK ACCELERATION SENSORS

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INTRODUCTION

This paper describes testing techniques and equipment used in the development of the Endevco Model 7270 Shock Accelerometer, having a range beyond 100,000 g and a mounted resonant frequency on the order of a megahertz. Conventional testing techniques proved inadequate for thorough evaluation. A new calibration system based on the Hopkinson bar has been developed to give rigorous and accurate tests to determine sensitivity, amplitude linearity and zero shift due to accelerations beyond the transducer's designed full scale acceleration level. A related but smaller apparatus was developed to determine resonant frequency and also, although to a very rough degree, the frequency response of the accelerometer. It provided the means to create sub-microsecond rise time strain waves to excite an accelerometer's resonant frequency.

THE TRANSDUCER

It is instructive first to discuss the transducer to illustrate the need for new testing techniques. Inside the transducer's rectangular steel case is the sensing element, depicted in Figure 1 (patent applied for). The chip of silicon, one millimeter square, incorporates the entire spring, mass, and four-arm piezoresistive strain gage bridge assembly. It is sculpted from single crystal silicon using anisotropic etching and microelectronic fabrication techniques. Strain gages are formed by a pattern of dopant in the originally flat silicon. Subsequent etching of channels frees the gages, and simultaneously defines the "masses" as simply regions of silicon of original thickness. The monolithic structure and extremely small size

assures large strength-to-weight ratio; the freed gages maximize linearity and sensitivity. The structure's megahertz resonance and linear range of more than 100,000 g promise to severely challenge (and appear to exceed) the limits of amplitude and precision of the historical methods for calibration and test of shock accelerometers.

THEORY OF CALIBRATION USING THE HOPKINSON BAR

The short pulse durations associated with high acceleration shock cause errors in calibration when using back-to-back standard and test accelerometers. Relative motion between the test and standard accelerometers becomes significant when the pulse wavelength approaches the fixture/accelerometer dimensions. Reducing these errors by increasing pulse duration or by decreasing dimensions is not always practical, thus the alternate approach of the Hopkinson bar becomes attractive.*

In contrast to the short fixtures of comparison techniques, a mounting fixture in the form of a Hopkinson bar (a long and slender elastic cylindrical bar) is deliberately made longer than the wavelength of the pulse. The entire pulse becomes embodied as a compression wave which travels toward the accelerometer mounted on the end. This allows measurement of the wave free of reflections and distortion. That is, provided that the assumption described in the next paragraph is true.

A one dimensional theoretical model of such a bar of constant cross-sectional area results in the prediction that the pulse travels without distortion or attenuation. A one-dimensional model is fairly simplistic, however. Analysis of cylindrical bars using Pochhammer's equations, which take into account radial displacements due to Poisson's expansion, show that

* Comparison techniques suffer other difficulties, not the least of which is establishing the linearity of the standard transducer [1,2]. The technique is most often used at acceleration levels below about 15,000 g.

a wave travels essentially unchanged as long as the wavelength is long compared to the diameter of the bar.[3,4] This condition can be fairly easily met. Dispersion and attenuation generally occurs to very high frequency components of a wave. Production of high frequency components in a test pulse is therefore to be avoided, and those that are created are allowed to decay, hopefully to have negligible contribution to the total wave after a few diameters of travel.

By using strain gages mounted near the middle of the bar, the wave at that point is well established and will change little thereafter. It can be monitored in full, free from reflections as it travels toward the accelerometer provided that the bar is sufficiently long. Thus the pulse is known, and the sensitivity of the accelerometer can be derived by comparison of its output to the strain gage output.

The fundamental relation for the calibration is:

$$a = 2c \frac{d\varepsilon}{dt} \qquad (1)$$

where acceleration a, as experienced by the accelerometer mounted on a free end, is proportional to the propagation velocity c and $d\varepsilon/dt$, the time rate of change of strain. More useful is the integrated form of the equation, in which the integrated accelerometer output is compared to the magnitude of the strain.* This is the basis of the calibration using the Hopkinson bar. The measurement of a high level acceleration pulse is reduced to the straightforward strain measurement at levels well within the verifiably linear regions of strain gage operation.

CALIBRATION APPARATUS

Figure 2 shows the schematic of the apparatus, which is described thoroughly in Reference 5. In summary, a projectile with a parabolically pointed tip (based on the work of Brown and Drago[6]) is propelled by air pressure when a paper diaphragm ruptures. It impacts an aluminum mitigator on the end of

* This provides an averaged sensitivity value over the acceleration levels of the pulse. If the accelerometer is nonlinear, correction factors are necessary to determine amplitude linearity.[2,5] Such correction factors are negligible for the small degree of amplitude nonlinearity observed in the tests described in this paper.

the compliantly supported titanium bar, which is 5 feet long and 5/8" in diameter. A compression wave is established and travels to the accelerometer mounted on the other end of the bar, monitored on the way by the two strain gages. Usually the accelerometer is mounted on a "breakaway", allowing it to fly free from the bar so that any zero shift occurring to the transducer output would be visible during that period of zero-g flight. The waveforms of the strain gages and the accelerometer are stored in a Nicolet 4094 Digital Storage Oscilloscope. Digital integration of the accelerometer output is possible using Nicolet-supplied software. Figure 3 shows the capabilities of the system, where peak acceleration and corresponding pulse widths are shown as a function of projectile shape and driving pressure.

CALIBRATION RESULTS

Extensive calibrations at "low" acceleration levels (10,000 g) were performed on several models of shock accelerometers on both the Hopkinson bar and on the comparison-based Endevco 2965C Shock Calibrator (described in Reference 1). Agreement in sensitivity values from the two radically different systems was good: a bias between the two of less than a percent and a standard deviation of two percent in the data from the Hopkinson bar. Figure 4 is an example of the waveforms in a test of sensitivity on the new system. Note that the acceleration pulse occurs 150 μs after the strain gages detect the pulse, since it takes that long for the wave to travel the distance between the gages and the accelerometer. Note also that the integration is performed over the first positive acceleration pulse, and that the several strain gage signals after the initial pulse are from reflections of the strain wave in the bar which the accelerometer does not experience because it is flying free.

Figures 5 and 6 are examples of how zero shift is measured. The lower waveform of Figure 5 is the output of the Endevco Model 7270 to 150,000 g; the upper waveform is the same output digitally integrated. In this figure the integration is extended over a millisecond for determination of zero shift. This is a typical result for the 7270. The near-zero slope during free flight corresponds to a shift less than 0.1 percent of the peak value of 100 mV. Figure 6 shows the effect of integrating a 0.3 percent shift which occurred in a more conventional accelerometer due to a 100,000 g shock.

In the study of amplitude linearity, it was found that the sensitivity of five 7270 accelerometers at 150,000 g differed from sensitivity as measured at 10,000 g, (using the comparison technique) by a maximum of 4 percent. Calibration uncertainty on the Hopkinson bar is calculated to be approximately 6% in the realm of 100,000 g.[5] It appears from these and many other tests that the amplitude linearity of the 7270 exceeds the capabilities of the calibration technique.

SHOCK SURVIVABILITY

Besides calibration of shock accelerometers, the Hopkinson bar can be used to a limited degree to study shock survivability. Although the high frequency content of pyrotechnic shock cannot be well simulated, high acceleration levels can be attained fairly easily and with safety. Another bar was manufactured to this end, tapped so that the accelerometer could be mounted directly. As the strain wave reflects from end to end the attached accelerometer is subjected to repeated couples of positive and negative accelerations.

Figure 7 shows the output of a 7270, subjected to a pulse causing an indicated 250,000 g and 150,000 g in the positive and negative directions, respectively. The decay of the pulse is due to the rubber suspension system holding the bar. Admittedly this pulse is less severe than some pyrotechnic shocks. Were the bar of smaller diameter and shorter, and had the projectile had a ragged point rather than the smoothly sloping tip that was used, the pulse would have had higher frequency content. Each of these possible variations, however, would make support of the bar difficult.

A short small diameter bar has had application in the transmission of pulses of high frequency content, as described below, but at very much lower acceleration levels.

DETERMINATION OF FREQUENCY RESPONSE

Just as with sensitivity, the determination of frequency response of the 7270 required a transient method, since with no continuous motion could signals of sufficient amplitude or bandwidth be generated.

The first consideration was to determine the resonant frequency. Although fast rise time impacts can be used to excite the resonance of a conventional shock accelerometer, in most cases it was exceedingly difficult to excite the 7270's resonance with impact.

Figure 8 depicts the apparatus with which the resonance of all 7270's has been readily excited, by breaking 2 millimeter diameter glass capillary tubing against the end of an 18" long, 1/2" diameter high purity alumina rod. The breakage includes sub-microsecond steps, since resonances of 1.6 MHz and higher have been excited.

The glass is broken when in static compression. Ideally, the load would be released in a single step. From equation 1, the resultant step strain wave would correspond to a negative impulse acceleration for the accelerometer mounted on the end. With an ideal impulse input, by taking the Fourier Transform of the response, the frequency response could be obtained.[7]

Instead, the breakage is probably a series of smaller steps, causing trains of impulses. The actual shape of the strain wave is not known, since strain levels are too low to measure accurately. Despite this fact, the fast rise time causes accelerations of thousands of gs, and the output of the acceleration can be readily captured and analyzed by FFT. An example of this process is shown in Figure 9. The result shows major features of the frequency response: a 1.34 MHz resonance and minor resonances between 500 and 800 kHz probably associated with the thickness of the case.* Using results such as this, the performance of the 7270 can be summarized in Figure 10, a plot of the resonant frequency versus each unit's sensitivity from a family of prototype 7270's. All have the basic geometry shown in Figure 1.

* The variability in the low frequency response is the result of poor resolution of the fast digitizer used for this test.

CONCLUSION

Two sets of apparatus were built to evaluate and calibrate a new model of shock accelerometer. For the determination of accelerometer sensitivity and amplitude linearity, a Hopkinson bar was incorporated to create pulses at accelerations to greater than 100,000 g. Strain gage measurement of the pulse provides a standard for calibration of the accelerometer.

Zero shift due to accelerations greater than the designed full scale is measured by integration of the output of an accelerometer allowed to fly free from the bar after the initial positive pulse.

Resonant frequency is measured by performing an FFT of the output due to a submicrosecond rise time stress wave in a smaller version of the Hopkinson bar. Breakage of glass capillary tubing provides the pulse. The wave is not monitored, so the resultant "frequency response" is only approximate.

The calibration techniques described in this paper provide accurate and versatile means to evaluate the performance of shock accelerometers at levels to 100,000 g and above, a task not possible with conventional techniques. The quality of performance of the accelerometer with the extremely small monolithic silicon sensing element was found to be excellent.

REFERENCES

1. "Comparison Shock Motion Calibrations", Technical Paper No. 240, Endevco Corp.

2. Dove, R., Butler, R., and Duggin, B., "Calibration and Evaluation of Accelerometers in the 10,000 g to 100,000 g Range", 20th ISA Conference and Exhibit, October, 1965, Los Angeles, Print 17.3-1-65.

3. Kolsky, H., Stress Waves in Solids, Oxford University Press, 1953, pg 87.

4. Redwood, M. Mechanical Waveguides, Pergamon Press, 1960, pg. 143.

5. Sill, R.D., "Shock Calibration of Accelerometers at 100,000 g Using Compression Waves", 29th International Instrumentation Symposium, ISA, Albuquerque, New Mexico, May 1983.

6. Brown, G. and Drago, G., "Shock Calibration of Accelerometers Using Hopkinson's Bar", University of California, Berkeley, College of Engineering, No. 77.3, March, 1977.

7. Eller, E. "Response of Transducers to Fast Transient Motion Inputs", Tenth Transducer Workshop, Telemetry Group, Inter-range Instrumentation Group, Range Commander Council, White Sands, New Mexico, June, 1979, Colorado Springs, Colorado.

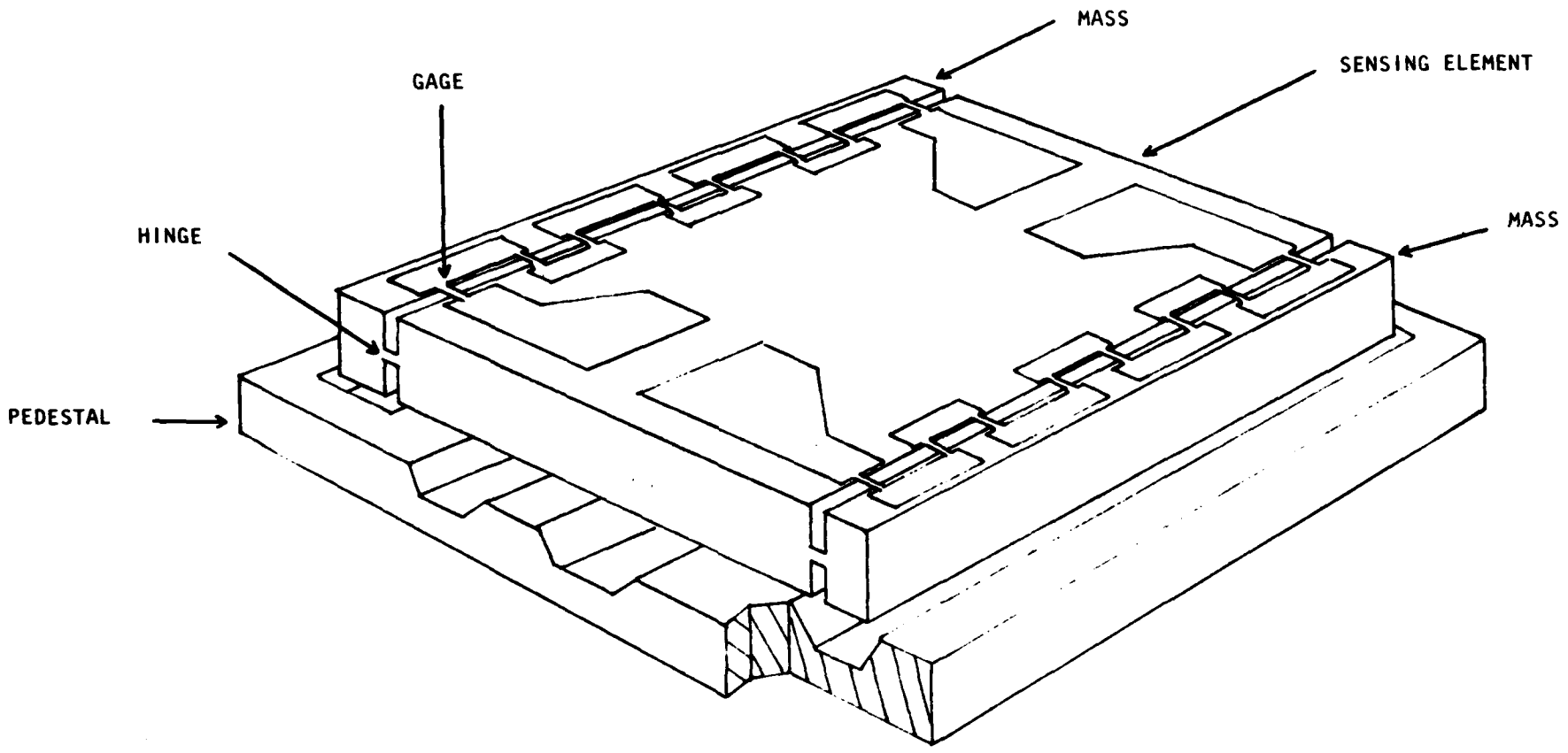

Figure 1. Monolithic silicon sensing element for Endevco® model 7270 accelerometer.

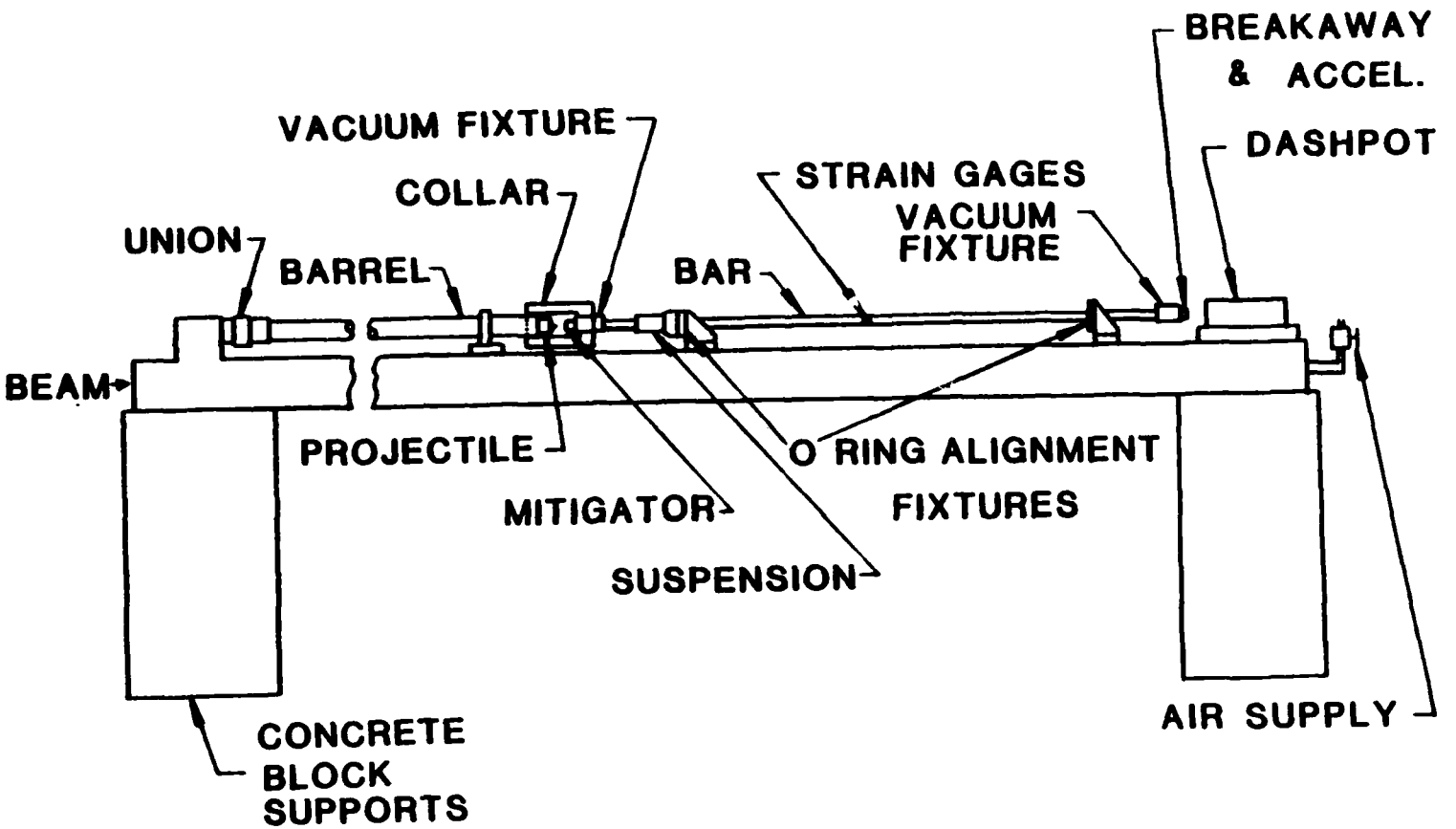

Figure 2. Schematic of apparatus.

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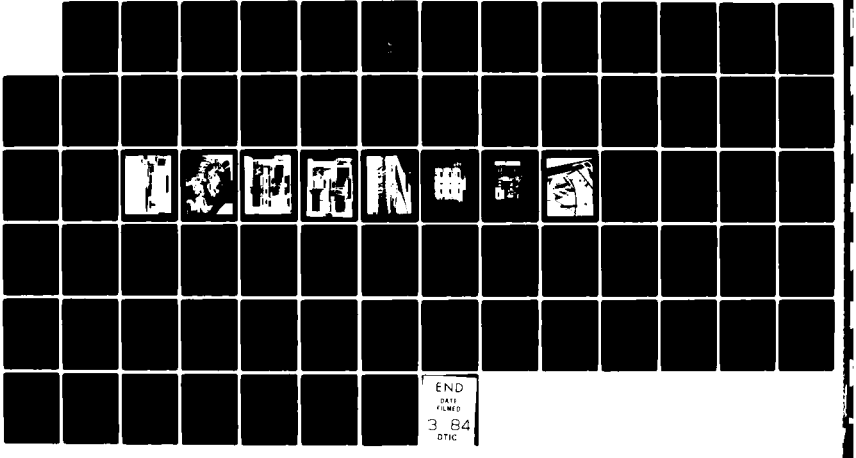

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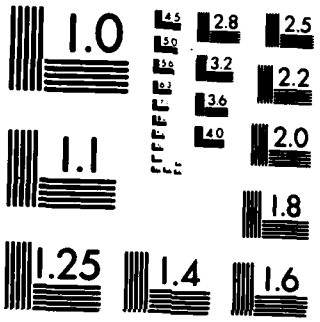

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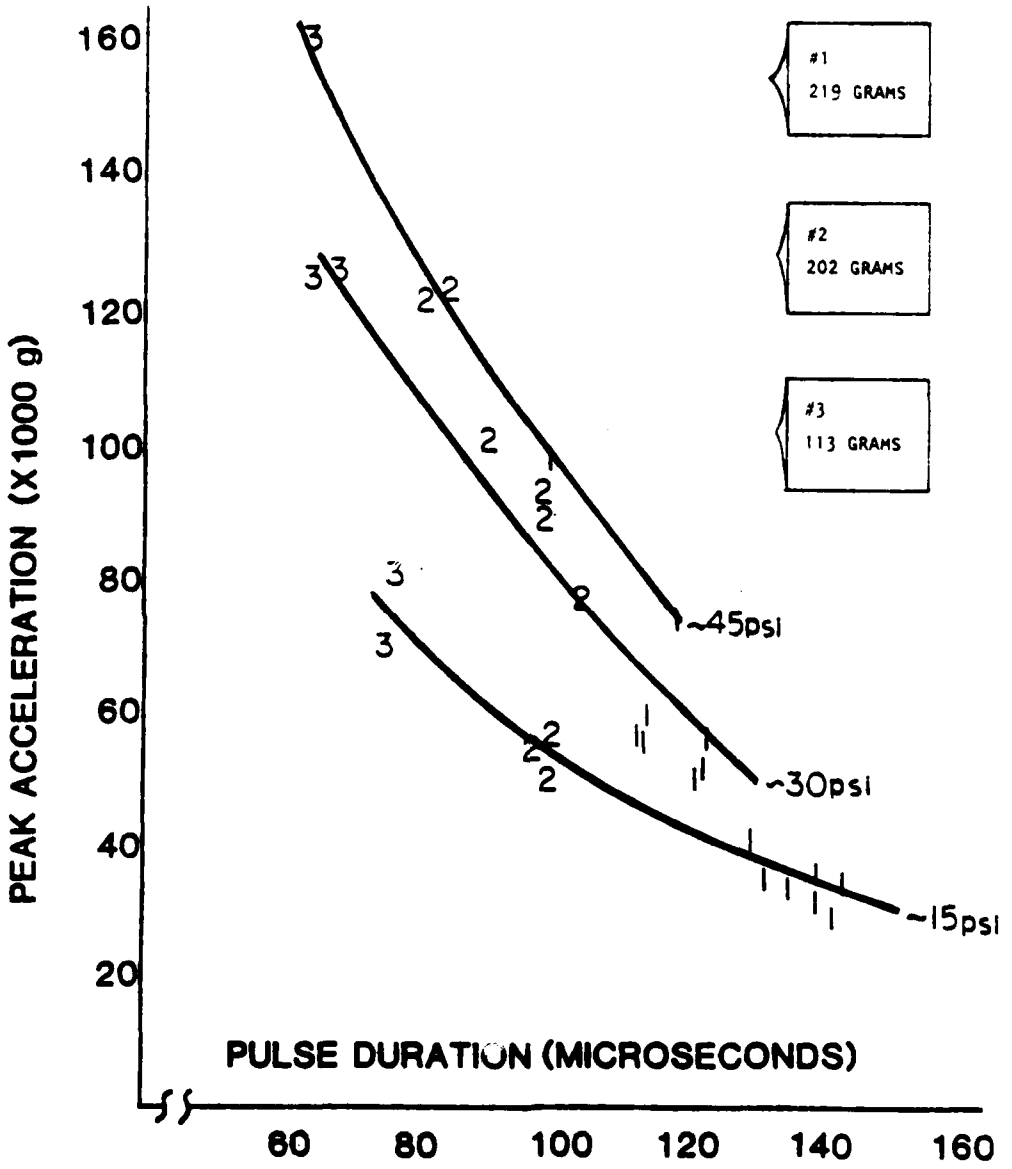

Figure 3. Peak acceleration vs pulse duration using each of three projectiles at three driving pressures.

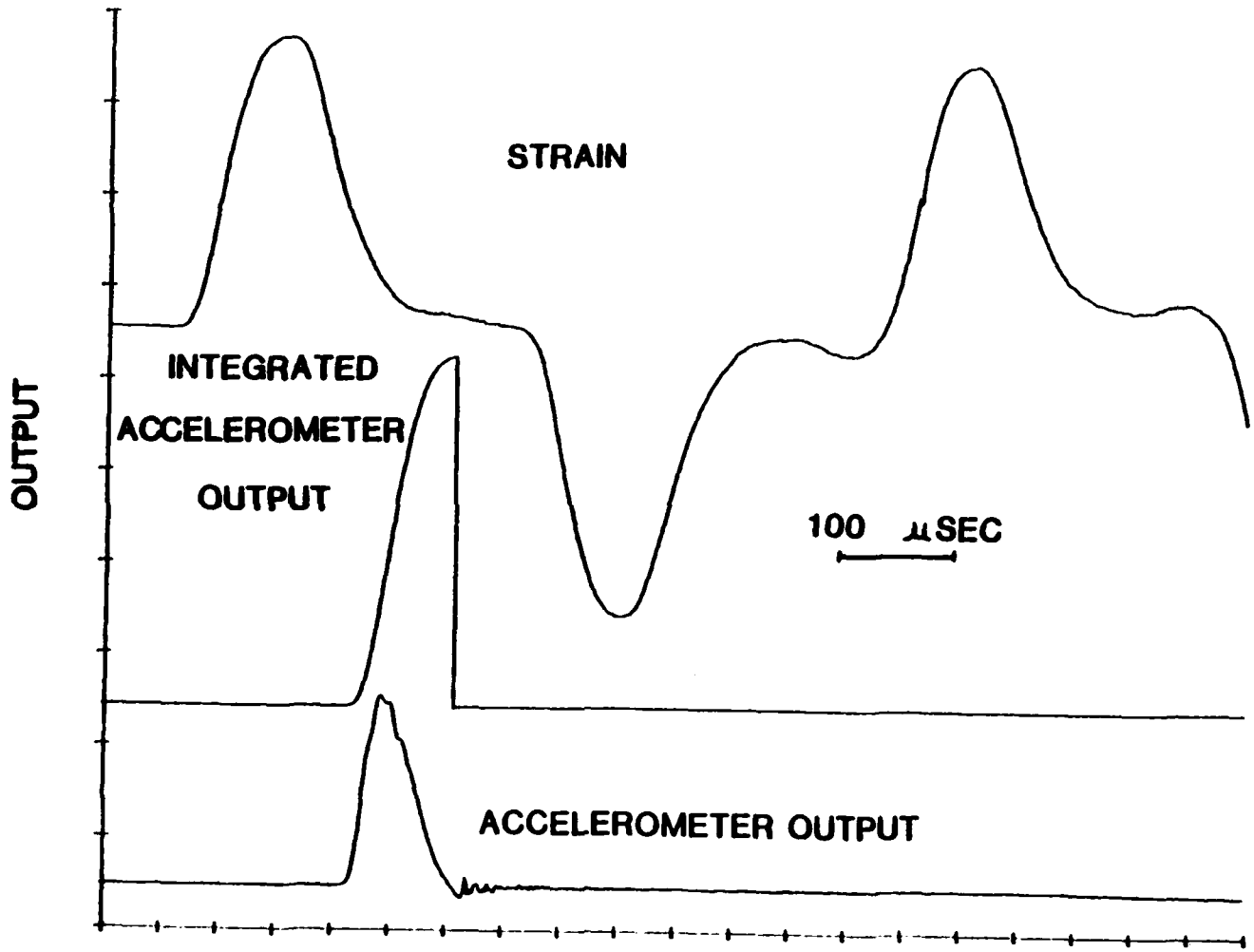

Figure 4. Test waveforms.

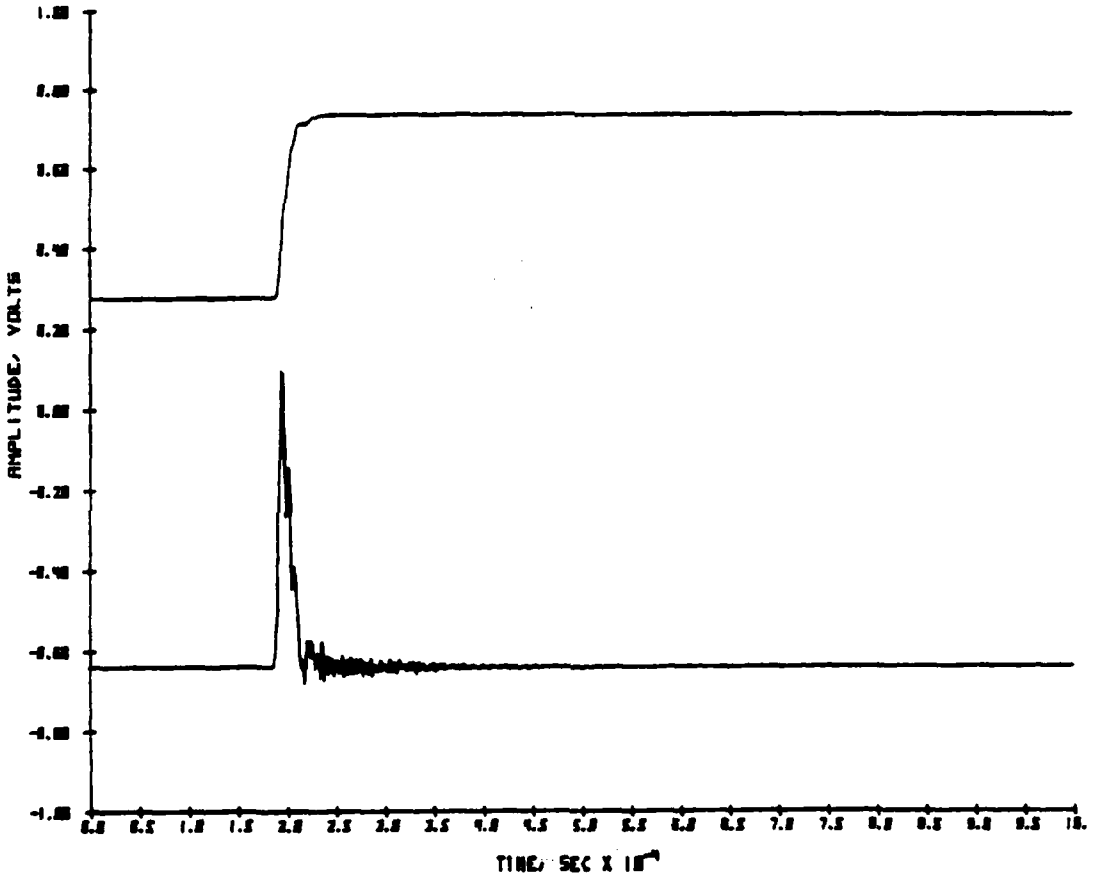

Figure 5. Output of 7270 from 150,000 G, lower waveform, integrated output, upper waveform.

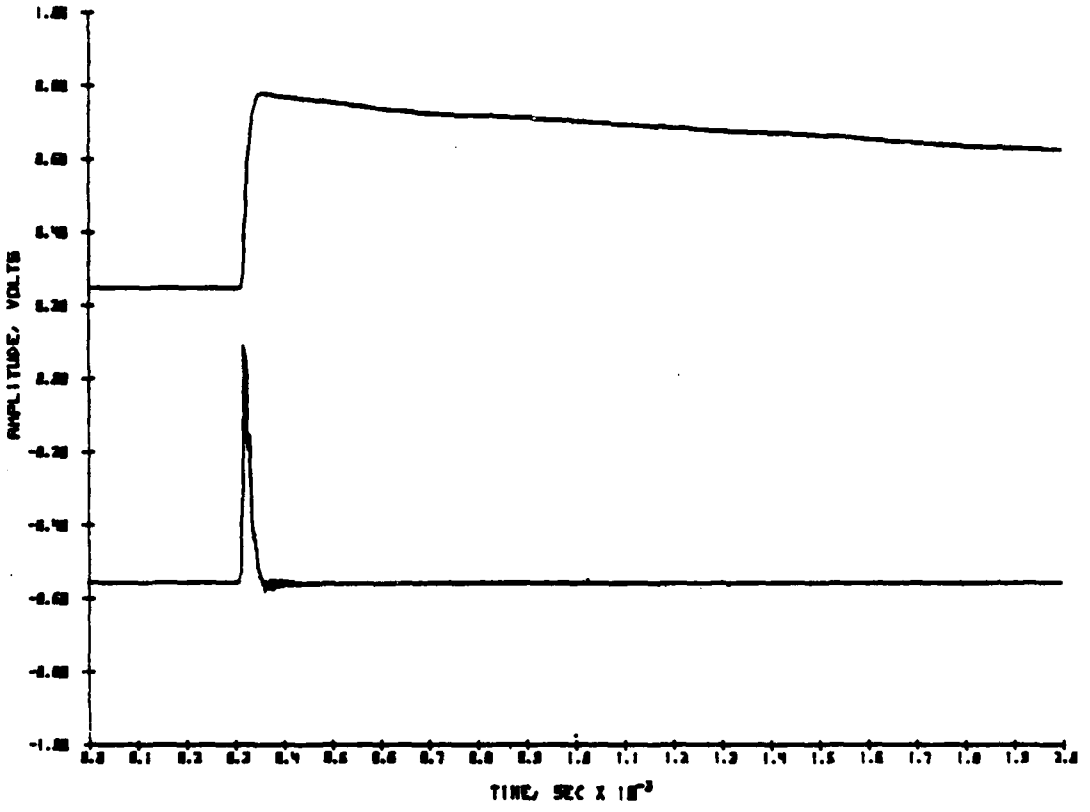

Figure 6. Output of conventional accelerometer to 100,000 G, lower waveform: integrated output showing 0.3% zero shift, upper waveform.

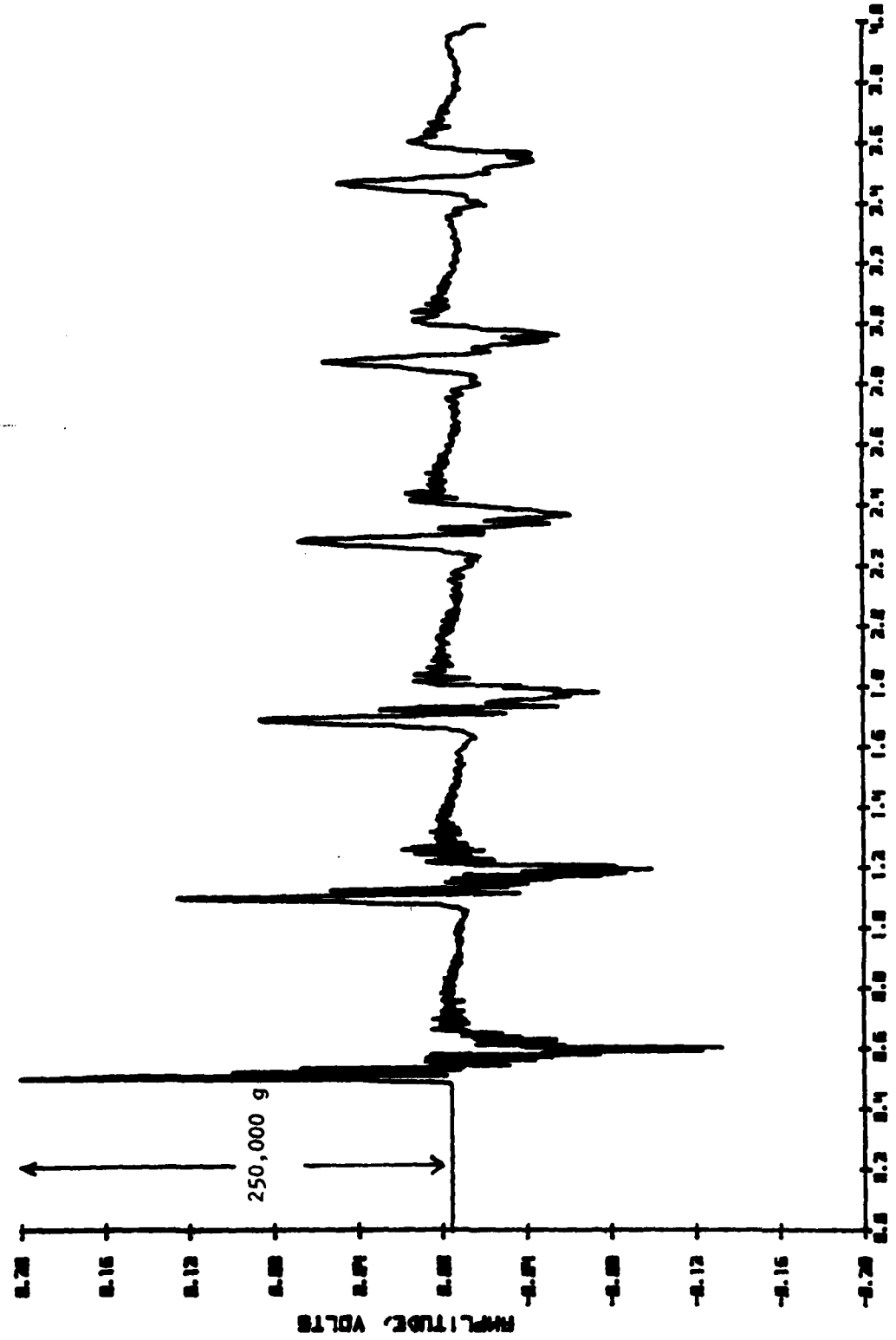

Figure 7. Accelerometer output when attached to Hopkinson Bar.

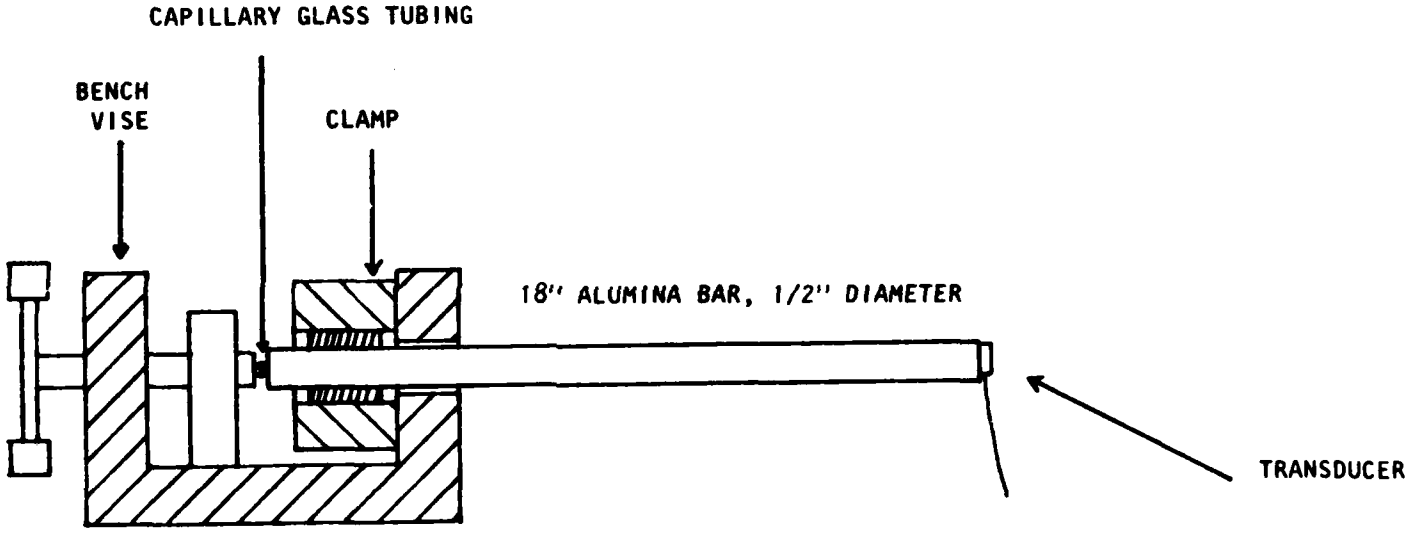

Figure 8. Apparatus for determining mounted resonant frequency.

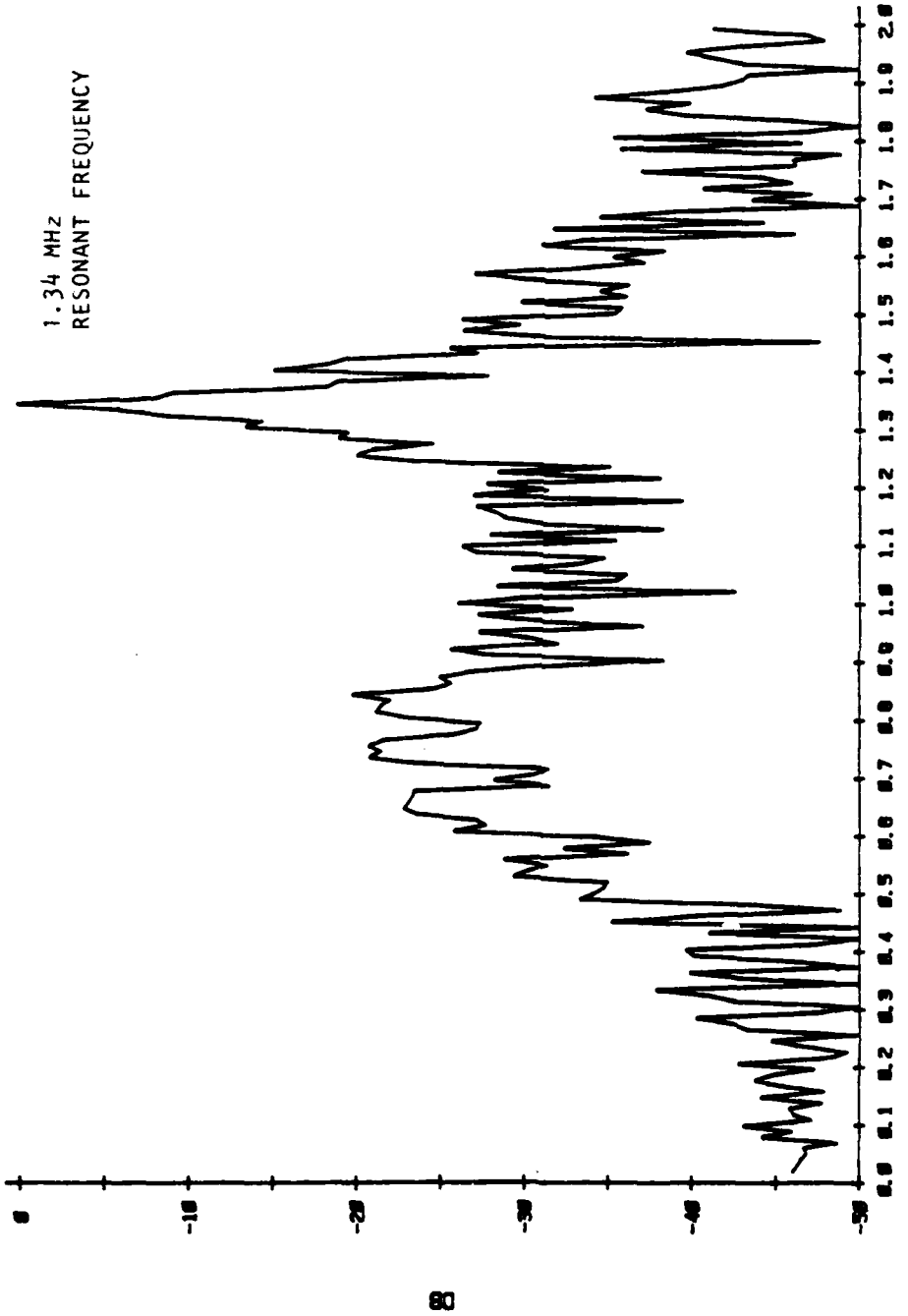

Figure 9. FFT of 7270 response to broken glass capillary.

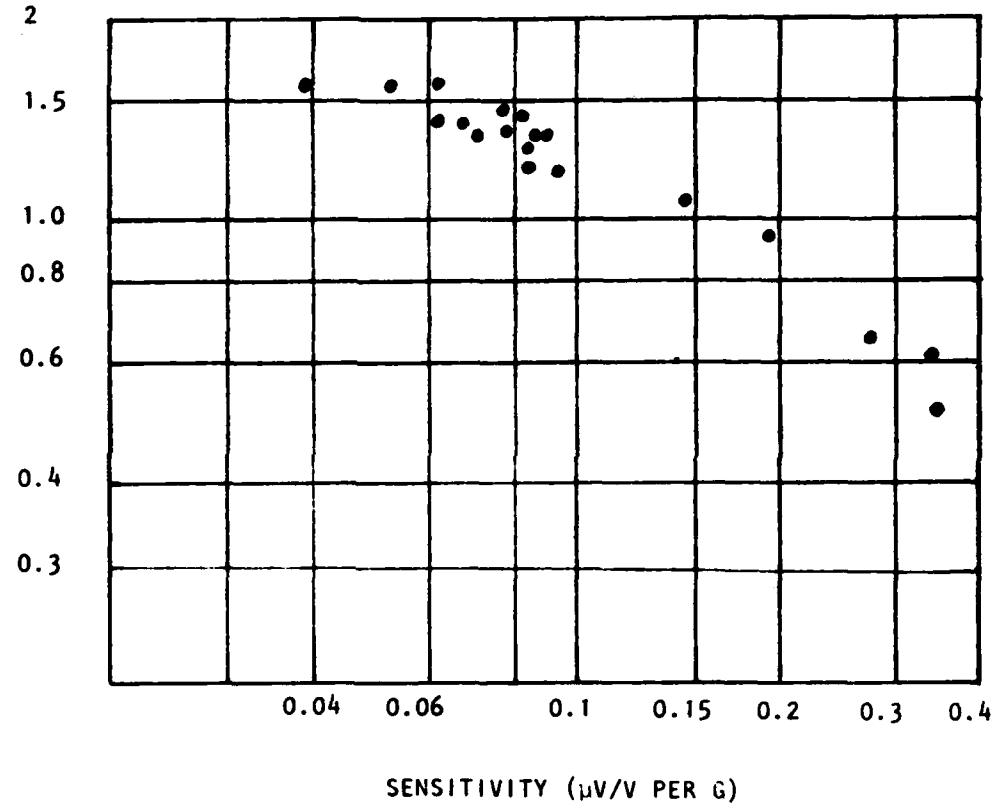

Figure 10. Resonant frequency vs sensitivity of the Endevco ® model 7270.

ADP002694

Aircraft Ground Vibration Test Instrumentation System

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ABSTRACT

The Structural Vibration Branch (FIBG) of the Air Force Wright Aeronautical Laboratories (AFWAL) is conducting an in-house Ground Vibration Test (GVT) on a full scale F-16 aircraft located inside FIBG's Vibration Aeroelastic (VIAER) facility at Wright-Patterson AFB OH. To measure 120 accelerometer signals simultaneously as required by the GVT, FIBG has designed and fabricated in-house a complete data acquisition system to measure and condition all the required transducer signals.

The GVT instrumentation system includes 120 piezoelectric accelerometers utilizing built in emitter followers, 120 6 pole low pass filters, 120 automatic gain changing (AGC) amplifiers, a digital multiplexer for multiplexing 360 gain code bits into two 12 bit wide digital words, a time code generator, a 14 channel wide-band magnetic tape recorder and a Programmable Data Acquisition System (pDAS). The pDAS encodes and multiplexes all 120 accelerometer signals, gain codes, and time code into a 600 Kilobit/sec Delay Modulation Mark serial bit stream for recording on magnetic tape. Combining AGC amplifiers and 11 bit digital resolution, allows measurement of very low acceleration levels. The GVT instrumentation system allows fast measurement of multiple accelerometer signals required for aircraft modal analysis and will be used on future FIBG in-house conducted tests requiring a large number of transducer signals to be processed. This paper describes the design, configuration, evaluation and calibration of the GVT instrumentation system.

BACKGROUND

The Flight Dynamics Laboratory (FDL) of the Air Force Wright Aeronautical Laboratories (AFWAL) at Wright-Patterson Air Force Base (WPAFB) OH, is responsible for conducting research and development required for the design of future Air Force Weapon Systems. In particular, the Structural Vibration Branch of the Structures and Dynamics Division of FDL (AFWAL/FIBG) is responsible for conducting experiments necessary to define the dynamics and loads environment of current and future Air Force Systems. A Ground Vibration Test (GVT) on Controlled Configured Vehicle (CCV) F-16 Tail Number 01567 was conducted from January-March 1983 in the former large acoustic test facility located in Bldg 461 in Area B at WPAFB. The GVT was conducted under an in-house work unit titled "Vibration Analysis and Testing Technology" (2ON 24010414). The project engineer for the work unit was Douglas Henderson and the project engineer for the F-16 GVT was First Lieutenant Richard Wright. The instrumentation system was designed, fabricated, checked-out and cali-

brated by instrumentation engineers David Banaszak and Richard Talmadge and instrumentation technicians John Self and Claude Orr.

A requirement for the F-16 GVT and future experiments (e.g. the AFTI/F-111 Mission Adaptive Wing (MAW) and Aircraft Ground Induced Advanced Loads Excitation (AGILE) programs), was the capability to simultaneously measure many dynamic signals (120 accelerations over a frequency range of 1.4Hz-100Hz for the F-16 GVT) without losing time correlation or frequency content. Also, the ability to measure very low levels of acceleration was necessary. This paper covers the overall test instrumentation setup, the Data Acquisition System in detail, and summary and conclusions. An appendix contains the referenced tables, photographs, and figures.

OVERALL TEST INSTRUMENTATION SETUP

The overall block diagram of the instrumentation required to conduct the F-16 GVT is shown in Figure 1. A list of equipment used during the test is included in Table I. The F-16 was supported at three aircraft jack points by a vibration isolation system which allowed the aircraft to float on a cushion of air at the three points. See Reference 8 for more details on the two 13,300 pound and one 5,500 pound air bearings used in the vibration isolation system. Using a shaker controller to control from one to four 75-pound force shakers, the aircraft was excited at single or multiple points as specified by the project engineer. Testing methods were sine dwell, sine sweep and random excitation. During aircraft excitation, signals from 120 Vibrameterics M-1000A accelerometers were filtered, amplified, mutliplexed and encoded into a 600-Kilobit/sec pulse code modulation (PCM) signal by the Data Acquisition System (DAS) designed by FIBG. The following sections of this paper describe in more detail, the design, configuration, evaluation, and calibration of this data acquisition system. Referring to Figures 1 and 2 there are a maximum of 120 accelerometer inputs to the DAS, a PCM output, and provisions for 32 channels of digital to analog (D/A) conversion outputs for monitoring or for use by an on-line modal analysis system. The recorded tape was analyzed using Structural Dynamics Research Corporation's "Modal Plus" software package on a DEC VAX 11/780 computer.

INSTRUMENTATION LOCATIONS

Test instrumentation area locations are shown in Figure 1. The F-16, shakers, 120 accelerometers and 3 air bearing suspension systems were located inside the former large acoustic test chamber in Building 461 at WPAFB (Photo 1). The shaker controller, data acquisition system, wideband tape recorder and modal analysis system were located in a control room adjacent to the large acoustic chamber (Photo 2). The VAX 11/780 computer is located in room 216 of building 24. Accelerometer wires (120 microdot cables about 100 feet long) were routed above the F-16, into the control room, and were connected directly into the anti-aliasing filter cards of the Data Acquisition System. The 600 Kilobit/sec PCM signal was routed from the DAS via coax cable and various patch panel connectors to the tape recorder. Standard coaxial cables were used to connect desired analog outputs from the DAS to the [illegible] modal analysis system for test monitoring.

GVT INSTRUMENTATION REQUIREMENTS

Modal analysis requires measurement of many acceleration points simultaneously to ensure time correlation between the various responses. Transfer functions between a reference point and each measured response must be computed in order to determine the modal properties of an entire aircraft. For the F-16 the frequencies of interest covered a range of 1.4Hz to 100Hz for each of a total of 120 accelerometers simultaneously. To meet these requirements, either many tape recorder channels or some form of multiplexing were necessary. Multiplexing onto a single tape track was determined to be the desired approach in order to more fully automate data acquisition and analysis. Since excitation levels in typical GVT's are very low to ensure linear response, the data acquisition system had to be capable of measuring a wide range of acceleration levels. For this reason automatic gain changing (AGC) amplifiers were used. To ensure noise immunity, a digital system was desired. Combining requirements for the F-16 GVT with requirements for future tests, resulted in the DAS described in this paper for measuring 120 low level signals simultaneously over a large dynamic range.

DATA ACQUISITION SYSTEM IN DETAIL

The decision to go digital required the interfacing of FIBG's accelerometers normally used for vibration testing with a digital, programmable Data Acquisition System (pDAS). The resultant block diagram of the DAS is shown in Figure 2. All components and equipment shown in Figure 2 were on hand or designed and fabricated in-house. Fabricated items included the 21 six-channel filter cards and the digital multiplexer. A detailed description of each component of the DAS from accelerometers to PCM output is given in the following sections. A picture of the DAS is shown in Photo 3, with the major system components labeled. Photo 4 shows the DAS with one set of doors open. These doors provided quick front access to the amplifier and filter cards. As shown in the photos, the total system fit into four standard 19 inch equipment racks. The data acquisition equipment is installed in the three left hand racks and a PCM decom system was installed in the right hand rack.

SENSORS

To measure F-16 vibration responses, Vibrametrics Inc., Model M1000A piezoelectric accelerometers which contain a FET follower inside the accelerometer case were used. The light weight accelerometers were glued in tri-axial configurations on a wooden block to provide electrical isolation from the aircraft. For each test condition of the GVT, the block was attached to the location desired on the aircraft by using double stick tape. To overcome the problem of accelerometers vibrating loose, hot melt glue was later used. This also allowed angling and positioning of the blocks for proper orientation. Each accelerometer has an integral two-foot long microdot cable with a microdot connector on the end. Microdot coax was used between the accelerometer and the filter input. The accelerometer output and the dc power input were on the same pair of wires. The constant current source (about 4 milliamps) was required to power the built-in FET follower. This power is provided by a reversed baised diode (IN5313) mounted on the filter card. A blocking capacitor on the filter input passes the dynamic

accelerometer output signal to the filter input, but blocks the dc bias voltage produced by the constant current source. These accelerometers are ideal for use on a GVT, since their small size and weight have a negligible effect on the structure being measured. They are usable at frequencies as low as .14Hz if the proper signal conditioning is used and the ambient temperature is relatively constant. A typical accelerometer attached to the F-16 wing is shown in Photo 5. Accelerometer signal flow through the DAS is shown in Figure 3.

FILTERS

FIBG's decision to digitize the 120 accelerometer signals required the use of anti-aliasing filters to avoid aliasing problems in the data. These had to be designed, fabricated, and tested since these items were not available in FIBG's current stock. Based on the final program used for the Base Ten Inc., programmable Data Acquisition System, which effectively sampled each of the accelerometer signals at a rate of 390.63 samples/seconds, the unity gain 6 pole filters were designed to have an upper cutoff frequency of 100 Hertz. A typical filter card consists of National AF-100s (2 chips per filter - 3 poles per chip) as shown in the schematic (Figure 4). Each card contained six complete 6-pole filters and included the IN5313 diode required to provide the constant 4 milliamps of current to power the accelerometer.

A picture of a typical filter card is shown in Photo 6. The low end 3dB cutoff frequency was about 4-5 Hz. Since transfer function measurements were the final objective, this made the data usable to less than 1.4Hz. A typical filter transfer function response is included as Figures 5a & 5b. The filter transfer functions were measured using a Hewlett-Packard Model 3582A Spectrum Analyzer and stored on disk with a Commodore 8032 System. The machine language IEEE handshake program used to transfer data from HP3582A RAM to Commodore 8032 RAM is contained in Reference 2. The routine was relocated to hexidecimal address 6800 to 68ef. In addition, a machine code Commodore 8032 screen to printer dump routine was utilized to produce the printouts shown in Figures 5 and 6. These plots are preliminary versions, since software is still being developed to format the final HP3582 analyzer display into a readable format. Thus, the figures are a hybrid of a dot matrix printer plot and manually typed labels inserted for reader clarification. The 126 filter transfer functions (including spares) were stored on three 5¼ inch minidisks for future analysis. Also, a typical function for filter and amplifier combination is shown in Figures 6a and 6b. The filter transfer functions will be compared to determine maximum, minimum, and variances between various filters. If variations between the filters are statistically small, then it can be assumed that all the filter transfer functions are identical.

AUTOMATIC GAIN CHANGING AMPLIFIERS

The output of each anti-aliasing filter is connected to an automatic gain changing (AGC) amplifier. These AGC amplifiers have been used heavily in most of FIBG's airborne and ground environmental measurements programs in the past ten years. The F-16 GVT required the dedication of 120 of FIBG's amplifiers for the DAS. A typical AGC amplifier card (Intech Model A-2583) is shown in Photo 7. A detailed description of the amplifier's operation can be found in reference 3.

Basically, when in automatic mode the AGC amplifier selects one of eight discrete gains (-10dB, 0dB, +10dB, +20dB, +30dB, +40dB, +50dB, or +6CdB) based on the voltage level of the input signal. Typically, these amplifiers are set up to give a voltage output in the range of 200 mv to 500 mv rms. For example, if the input is a sine wave with an amplitude of 10 mv rms, then the amplifier would automatically change its gain to 30dB to provide an amplifier output of 316 mv rms. The card provides both a dc voltage output and a 3-bit binary output proportional to gain setting. The 3-bit binary output (see Table II) were used by the DAS to keep track of the amplifiers gain setting for each accelerometer signal. For the F-16 GVT this meant a total of:

3 bits/accelerometer X 120 accelerometers = 360 bits

of gain information had to be recorded with the 120 analog outputs from the amplifiers. Thus, the digital multiplexer was designed and built in-house by FIBC to implement the DAS as shown in the block diagram in Figure 2. The analog outputs (data signals) from each of the AGC amps were connected directly to the input of the digital encoder shown in Figure 2. The binary outputs (gain setting) were connected directly into a digital multiplexer which will be discussed in the next section.

The normal procedure used for the F-16 GVT was to excite the aircraft with a shaker and allow the acceleration levels to stabilize while the amplifiers were in the automated gain mode. When the test condition was stabilized, all the amplifier gains were inhibited by three remote toggle switchs (on front of the DAS rack) which fixed the amplifier gain at their current gain setting. Then a recording of the response data was made by the project engineer. The amplifiers could also be set for fixed gain if desired for calibration and checkout, or known input signal levels.

DIGITAL MULTIPLEXER

The digital multiplexer was conceived and designed to allow merging all of the 360 binary gain code bits into two 12 bit digital words which could be input into the digital inputs of the programmable Data Acquisition System (pDAS) manufactured by Base Ten, Inc.. The digital interconnect diagram in Figure 7 shows the cabling required between the binary gain status outputs from the three amplifier racks and the digital multiplexer. Each of the three amplifier racks had 40 AGC amplifiers mounted in it, and thus 120 gain status bits were routed out of each rack and into the digital multiplexer. The output from the digital multiplexer consists of two 12 bit digital words for gain codes and a 12 bit digital word for frame count. A sychronization clock is supplied to the digital multiplexer by utilizing the frame clock output from J9 of the pDAS. This frame clock is input to an adjustable counter to allow up to 16 (0-15) levels of subcommutation. The counter was set for 15. This allows for 16 subframes for a major frame. Each subframe has two 12 bit words of gain codes which contains eight 3 bit gain codes. (See Table III). The frame counter is utilized as a frame ID for data playback and recovery.

PROGRAMMABLE DATA ACQUISITION SYSTEM

The programmable Data Acquisition System (pDAS) is the heart of the F-16 GVT DAS. The pDAS samples, digitizes and encodes into 11 bits plus parity.

all 120 analog outputs from the AGC amplifiers. Figure 8 shows the analog signal input interconnect cabling going into the pDAS. The gain code digital inputs were described earlier. In addition to the gain codes, the BCD outputs from an IRIG-B time code generator were input into three more 12-bit digital words. The format of the gain and time code bits are shown in Table III. After the start of the test, it was determined that more time resolution was required to recover the data efficiently, so tenths and hundreths of seconds were added in the upper eight bits of the subframe counter.

See reference 4 for detailed instructions for programming the pDAS. Basically, instructions stored on an EPROM described the number and types of inputs and the PCM output formats. The EPROM is then put in a socket which is on a card that fits inside the pDAS. For the F-16 GVT the EPROM was programmed to provide a 600 Kilobit per second (Kbps) serial bit stream which was recorded on one track of the tape recorder. Also the EPROM was programmed to sample and measure 120 analog inputs (±2.5V) which were converted into 120 11 bit digital words and a parity bit. The analog data was identified as words 1-120 corresponding to the accelerometers on the F-16. The EPROM was programmed to accept the six 12 bit digital words (identified as words 121-126) with no parity. No parity required changing a card jumper inside the pDAS. The 120 digitized analog inputs and six digital words were then converted by the pDAS into a serial bit stream which could then be recorded on one track of the tape recorder. The data format for a major frame of data is shown in Table III. Each accelerometer was sampled 390.63 times per second and the gain code for each amplifier was sampled 24.41 times per second.

The playback and monitor equipment was installed in empty rack space to allow quick decoding and check out of the DAS. Utilizing EMR PCM decom equipment, test personnel were able to easily determine the gain code of any given amplifier. The 120 BNC connectors (Photo 3) were installed on the front of the rack to allow easy access to monitor any of amplifier analog outputs directly. Also the PCM playback equipment had several digital to analog (DA) outputs which could be used to view recovered PCM data from the pDAS.

RECORDING DATA

The Delay Modulation Mark (DMM) serial PCM data from the pDAS was recorded on tape using direct recording on one of the wide-band recorders shown in Photo 2. The recorder was operated at 30 ips. Four passes were made for each tape. Recorder track assignments for each pass were as follows:

		Track Number			
Signal	Type Record	Pass 1	Pass 2	Pass 3	Pass 4
Analog Time Code	FM	1	5	9	13
PCM	Direct	2	6	10	14
Audio	Direct	3	7	11	15

Data for various test conditions, and the data tapes were taken to FIBG's Data Processing Area for analysis utilizing Modal Plus software on the VAX 11/780 computer.

CALIBRATION AND CHECKOUT

System checkout included filter evaluation as mentioned earlier (Figures 5 and 6), and digital multiplexer checkout to verify correct locations of gain codes in the PCM bit stream. In addition a per channel calibration for each accelerometer was performed. Initially, all the piezoelectric accelerometers were calibrated on a one g shaker in FIBG's calibration facility to check the sensitivity. This sensitivity value was then used as a insert voltage in place of the accelerometer to simulate a 1g signal. For a typical accelerometer with a sensitivity of 9.6 mvolts/g, a 9.6mv 80 Hertz signal was inserted and the AGC amplifier gain was set to the 40dB gain step. The amplifier gain pot was then adjusted until the amplifier had an output of 1 vrms. This normalized the sensitivity at the amplifier output to be 1g/volt in the 40dB gain step; 10g/volt in the 20dB gain step; 100g/volt in the 0dB gain step and .1g/volt in the 60dB gain step. Amplifier outputs were measured with the HP3582 spectrum analyzer.

Verifying location of gain code status in the PCM bit stream required substantial time due to having to troubleshoot several wiring problems. The PCM playback system was used to check gain code bits on a single word at a time basis. When it was available, a more capable EMR708 PCM playback system was used since all 360 gain code bits could be displayed at the same time on a CRT.

SUMMARY AND CONCLUSIONS

The described GVT instrumentation system allows for fast measurement of 120 accelerometer signals simultaneously as desired for ground vibration tests. Dedicated tape tracks are not required for each accelerometer and all data can be recorded for later analysis with just one tape recorder. The system is flexible and can be used for measurements of signals from transducers other than piezoelectric transducers. The system described will be used on an Air Force research test program called Aircraft Ground Induced Loads Excitation (AGILE) which will be conducted in the Flight Dynamics Laboratory's static test facility. After the AGILE test, the DAS rack is scheduled to be mounted into one of FIBGs mobile data acquisition vans for transportation to Edwards AFB where it will be used to acquire ground vibration data on the Mission Adaptive Wing (MAW). Thus this system provides the Air Force with a quick response data acquisition system.

In addition, the system has the capability to measure very low level signals. For example, in the F-16 GVT the 11 bit A/D converter for ±2.5 volts input gives a resolution of about 2.4 millivolts. If the AGC amplifier is in the 60dB gain step this is equivalent to 2.4 microvolts at the amplifier input, which for the accelerometers used on the F-16 GVT (about 10mv/g) is an acceleration level of approximately 240 micro g's. Since the pDAS can be programmed for an input range of ±10mv for digitization into 11 bits, even finer resolution than 240 micro g's can be obtained assuming the transducer and/or amplifier noise floor is not encountered. One problem with the pDAS is that the next range below ±2.5 volts input is ±50 mvolts. If the pDAS had a ±500mv range, better results could have been obtained.

As with any digital system, the F-16 GVT instrumentation system required anti-aliasing filters. The sampling rate can be changed quickly by reprogramming the pDAS EPROM, but each filter cutoff frequency change requires

changing component values. This means time to reconfigure 120 filter cards and time to get new components.

A future system to meet FIRG needs will have to be small in size and capable of handling up to 150 10KHz bandwidth transducer signals simultaneously in a digital format. This planned system is required for measurement of vibration and acoustic environments on current and future space limited aerospace vehicles. The described Data Acquisition System worked successfully on the F-16 CVT and will be used on the AGILE and MAW tests; however, future systems will need to be physically smaller and capable of wider bandwidths per channel.

REFERENCES

1. AFWAL-TR-80-3056, An Improved Ground Vibration Test Method, Volume I: Research Report, Boeing Military Aircraft Company, Seattle WA, September 1980.

2. Fisher, Eugene, and Jensen, C.W., PET and the IEEE 488 Bus [GPIB], Appendix F, OSBORNE/McGraw Hill, Berkley CA, 1980.

3. "Instruction Manual", Drawing No. 9025830-31 Rev. A, Intech, Inc., Santa Clara CA, 1974.

4. Instruction Manual Programmable Data Acquisition System Base Ten Systems, Inc., Model: 7-218. Base Ten Systems, Inc., Tenton NJ, 1976.

5. Osborne, Adam and Donahue, Carroll S., PET/CBM Personal Computer Guide, Second Edition, OSBORNE/McGraw-hill, Berkeley CA 1980.

6. Operating Manual Model 3582A Spectrum Analyzer, Hewlett-Packard Company, Loveland CO, 1978.

7. Operational Manual for TRIAD II System Using VK12-2 Transient Recorder, GHI Systems, Inc., San Pedro CA, January, 1982.

8. Serva-Levl (P) Isolation System Operation and Maintenance Manual "AL" or "X-15" Isolators, Document number DSW247 Rev. B, Barry Controls, Burbank CA, 1978.

9. Special Functions Data Book, pages 14-8 thru 14-26, National Semiconductor Corporation, Santa Clara CA, 1979.

10. Users Manual for CBM 5¼-inch Dual Floppy Disk Drives, Commodore Business Machines, Inc., Norriston PA, October 1980.

11. User's Reference Manual Commodore Base Version 4.0, Commodore Business Machines, Inc., July, 1980.

12. "VM-112 Integrated Accelerometer Short Form Brochure", Vibra-Metrics Inc., East Haven CT, October 1974.

APPENDIX

Figures - Photographs - Tables

Tables	Title
I	List of Components
II	Binary Gain Codes from AGC Amps
III	Format of PCM Serial Data

Figure No.	Title
1	Overall block diagram of F-16 GVT
2	Block diagram of F-16 GVT data acquisition
3	Data acquisition system accelerometer signal flow
4	Filter schematic
5a	Low frequency response of Filter 1
5b	High frequency response of Filter 1
6a	High frequency response of Filter 6 and Amp 6
6b	Low frequency response of Filter 6 and Amp 6
7	Digital interconnect cabling
8	Analog signal input interconnect cabling

Photograph No.	Title
1	F-16 GVT Aircraft Inside Large Acoustic Chamber
2	Overall View Building 461 Control Room
3	Data Acquisition System Components
4	Data Acquisition System With Open Amplifier And Filter Doors
5	Typical Accelerometer Mountings
6	Six Channel Filter Card
7	Automatic Gain Changing (AGC) Amplifier Card
8	Programmable Data Acquisition System (pDAS)

TABLE I LIST OF COMPONENTS

Manufacturer	Description	Quantity
Vibrametrics	M-1000A Accelerometers	120
FIBG In-house	Low pass filter cards, 6-pole, 6 per card	21
Intech, Inc	Model A-2583, Automatic Gain Changing Amps	120
Base 10 System, Inc	Model 7-128, Programmable Data Acquisition System	1
FIBG In-house	Digital Multiplexer	1
CGS/Datametrics	Time Code Generator - Model SF-400	1
FIBG In-house	AGC Amplifier & Display, ±15VDC, ±5, power supplies	3
Power-One, Inc	Power Supply 28VDC - 3 Amps	1
DEC	VAX 11/780	1
EMR	720 Bit Synchronizer, 708 PCM processor, Power Supply	1
Base Ten Systems, Inc	Model 500-520 Airborne Encoder Test Unit	1
Bruel & Kjaer	Type 4291-Accelerometer Calibrator	1
Honeywell	Model 96 Wide-Band Tape Recorders	1
Tektronix	465M Oscilloscope	1
Hewlett-Packard	3582A Spectrum Analyzer	1
EMR-Schlumbeger	720 Bit Synchronizer	1
EMR-Schlumbeger	2746 PCM Decommutator	1
EMR-Schlumbeger	2795 PCM Simulator	1
EMR-Schlumbeger	2748 Patch Board Demultiplexer	1
Unholtz-Dickie	Vibration Testing System No. TA100-4-6, including 2 ea Model 4 shakers	1
General Radio	Time Data System	1
Barry Wright Corp.	Serva-levl Vibration Isolation System	1
GHI, Inc	TRIAD IIA Transient Recorder System	1

TABLE II BINARY GAIN CODES FROM AGC AMPS

Binary Output MSB		LSB	Decimal Value	Gain
0	0	0	0	+60dB
0	0	1	1	+50dB
0	1	0	2	+40dB
0	1	1	3	+30dB
1	1	0	4	+20dB
1	0	1	5	+10dB
1	1	0	6	0dB
1	1	1	7	-10db

Binary Output: +5VDC = false = 0
Ground = true = 1

TABLE III FORMAT OF PCM SERIAL DATA

GAIN CODES AND FRAME COUNTER									TIME CODE IRIG - B 17 BIT BCD									
Word #121				Word #122				Word #123 FRAME COUNTER*	Word #124 HOURS				Word #125 MINUTES				Word #126 SECONDS				
									Tens			Unit	Tens			Unit	Tens			Unit	
5	6	7	5	6	7	5	0		1			9	3			9	5			8	Decimal
1	1	1	1	1	1	1	0	cntr	X	X	0	1	0	0	0	1	0	0	0	1	Binary
25	17	9	1	89	81	65	57	000000000000	XX	0	1	0	0	0	0	1	X	1	0	0	1
26	18	10	2	90	82	66	58	000000000001													2
27	19	11	3	91	83	67	59	000000000010													3
28	20	12	4	92	84	68	60	000000000011													4
29	21	13	5	93	85	69	61	000000000100													5
30	22	14	6	94	86	70	62	000000000101													6
31	23	15	7	95	87	71	63	000000000110													7
32	24	16	8	96	88	72	64	000000000111													8
49	41	73	33		113	105	97	000000001000													9
50	42	74	34		114	106	98	000000001001													10
51	43	75	35		115	107	99	000000001010													11
52	44	76	36		116	108	100	000000001011													12
53	45	77	37		117	109	101	000000001100													13
54	46	78	38		118	110	102	000000001101													14
55	47	79	39		119	111	103	000000001110													15
56	48	80	40		120	112	104	000000001111													16
25	17	9	1	89	81	65	57	000000000000	XX	0	1	0	0	0	0	1	X	1	0	0	0
AMP # GAINS																					

FRAME NUMBER

*Hundreths and tenths of seconds in 8msb of word #123 added later.

Sync Word 1	Sync Word 2	Word #1	Words 2-120	Words 121-126	Sync Word 1	Sync Word 2
111110101111	011100110100	010010101101 From Amp 1	101001100111 Amps 2-120	101010100110	111110101111	
Major Frame	390.63 times per second				Next Major Frame	

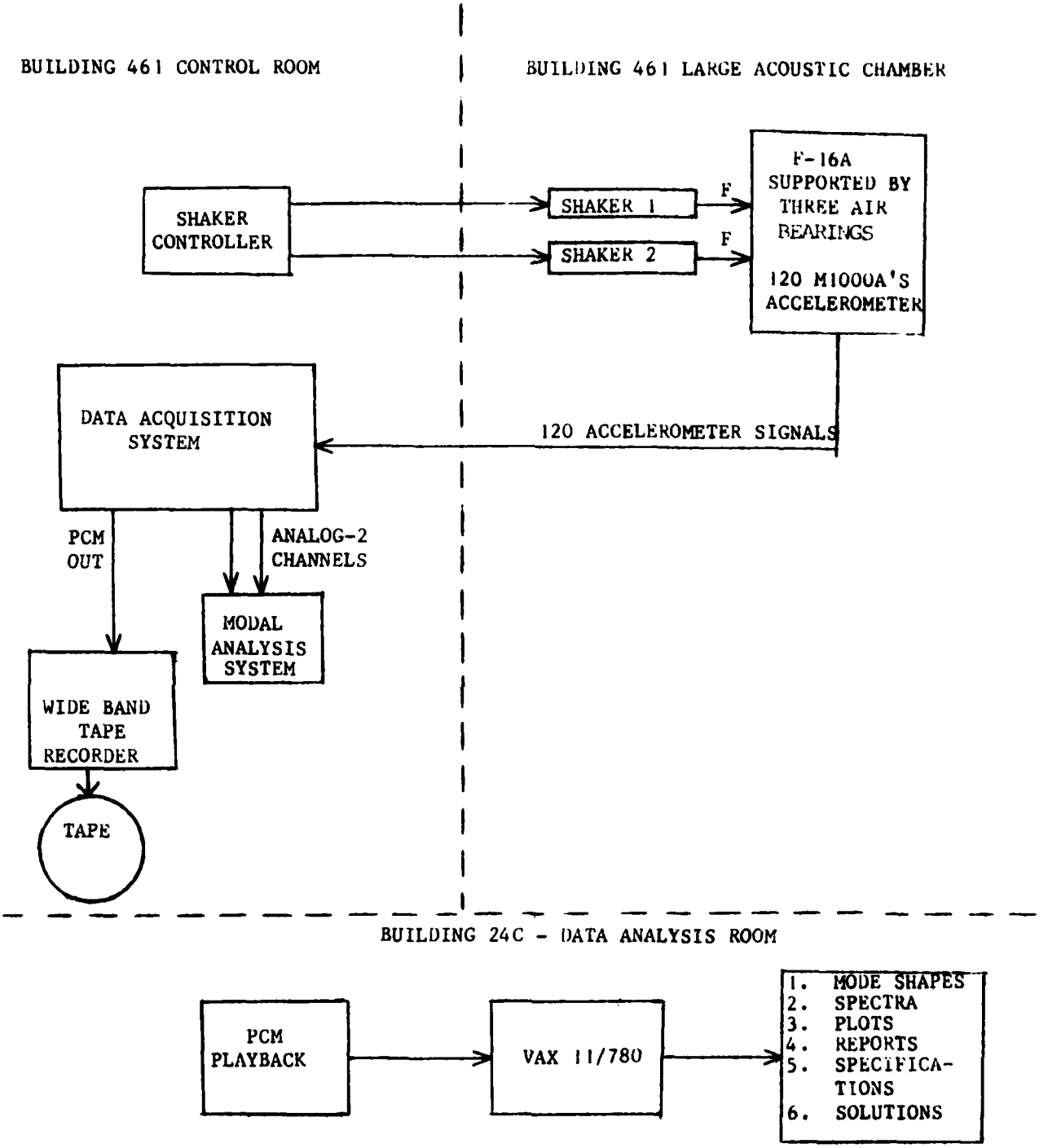


Figure 1. Overall Block Diagram F-16 GVT

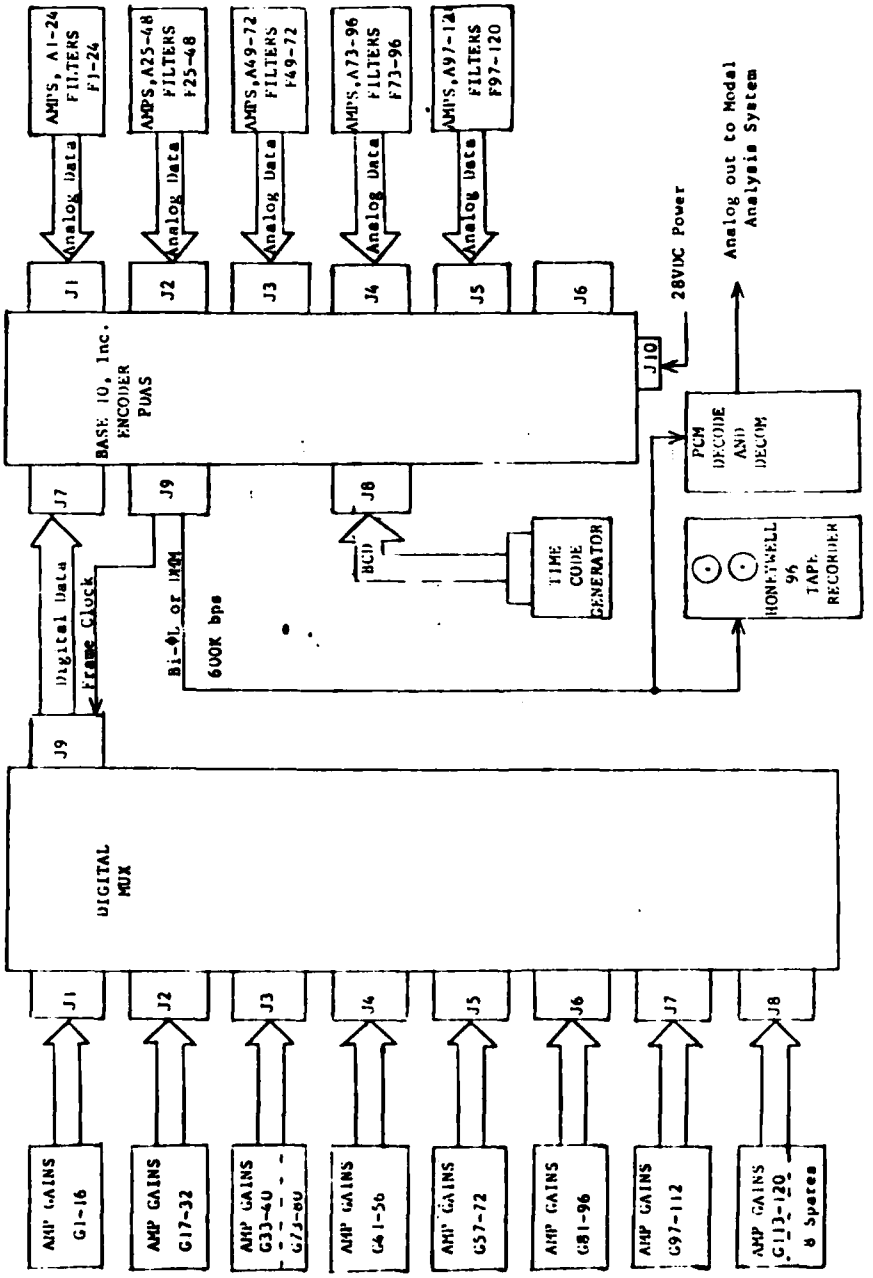


Figure 2. Block Diagram of F-16 GVT Data Acquisition

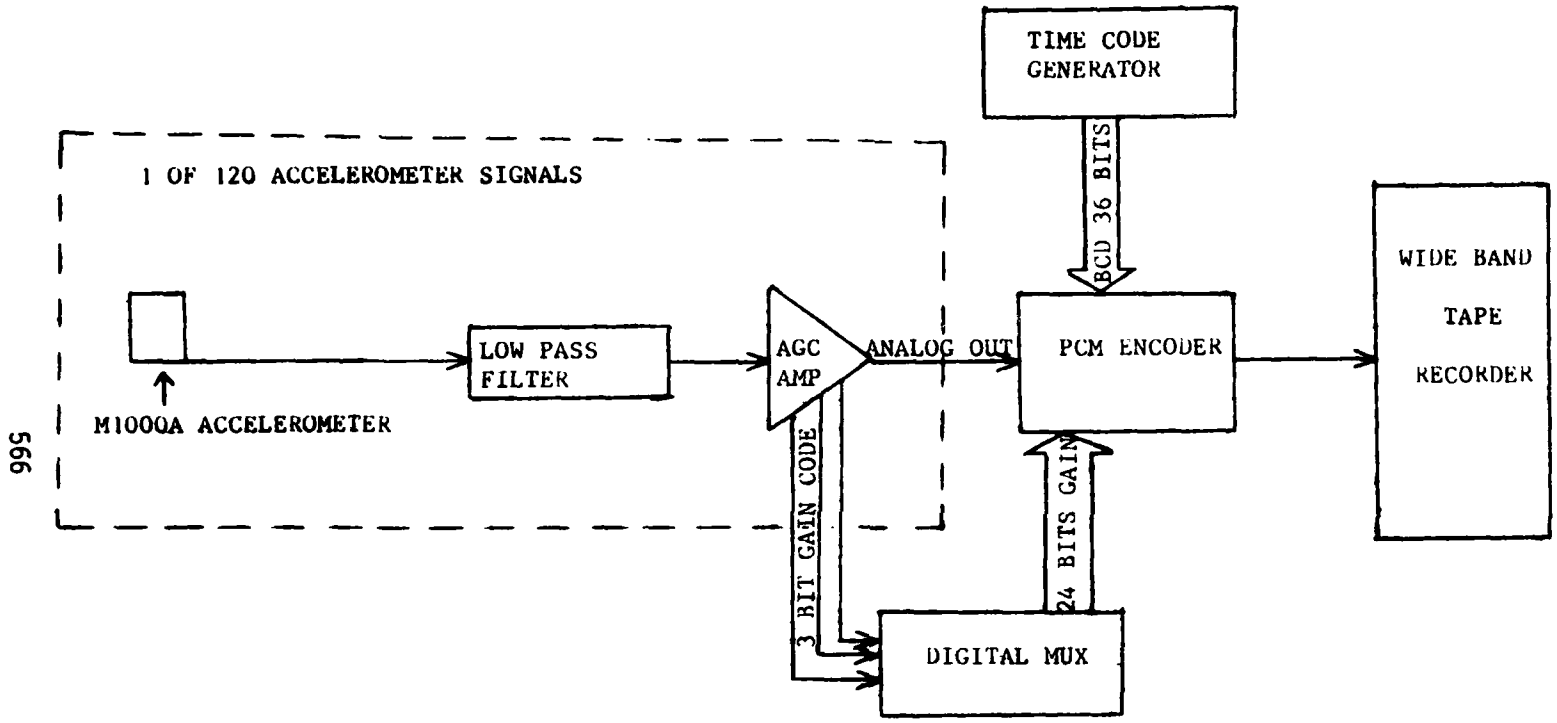
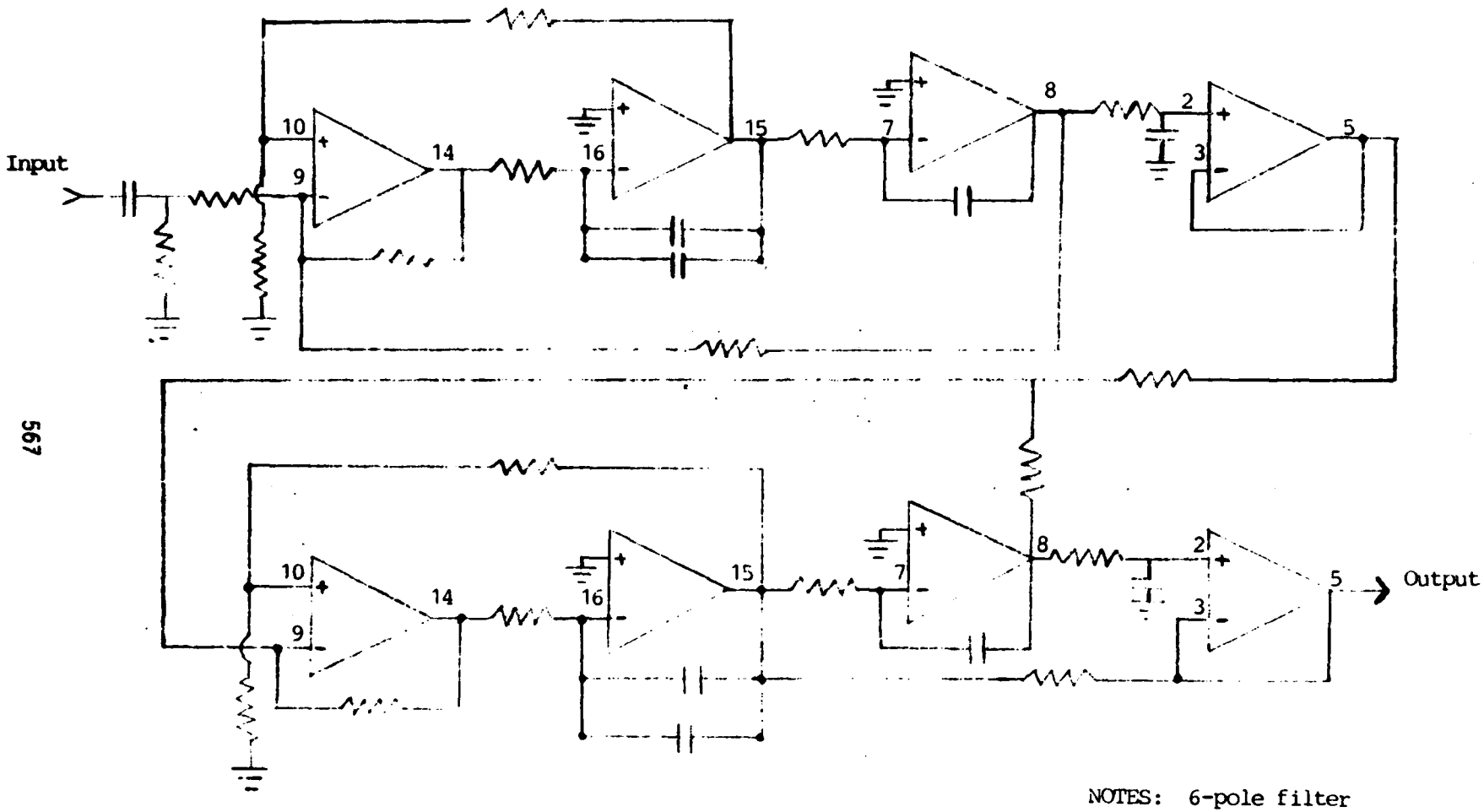


Figure 3. Data Acquisition System Accelerometer Signal Flow



NOTES: 6-pole filter
2 AF-100-CNs per filter
6 filters per card
1-V, 4 GND, 6 +V, 11-13 NC

Figure 4. Filter Schematic

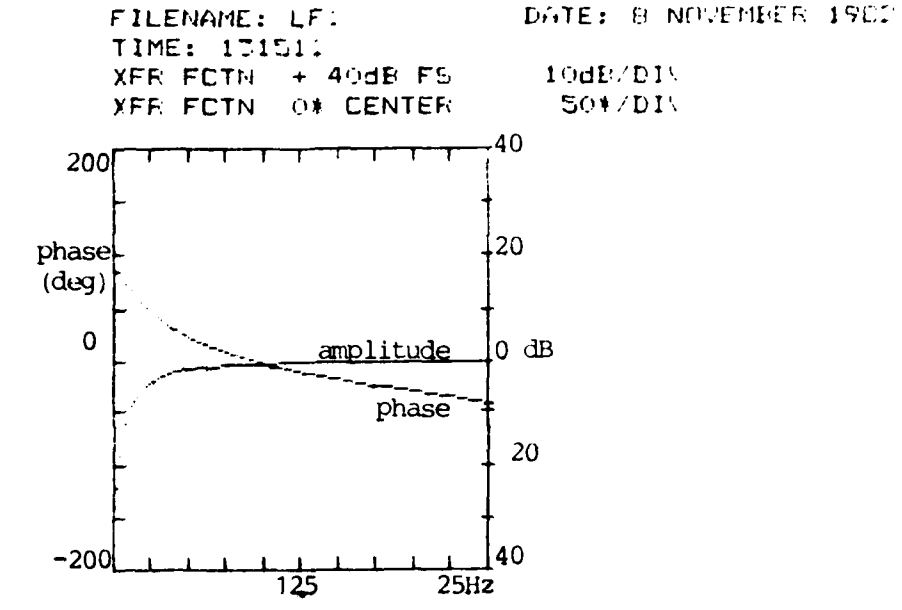


Figure 5a. Low Frequency Response of Filter 1

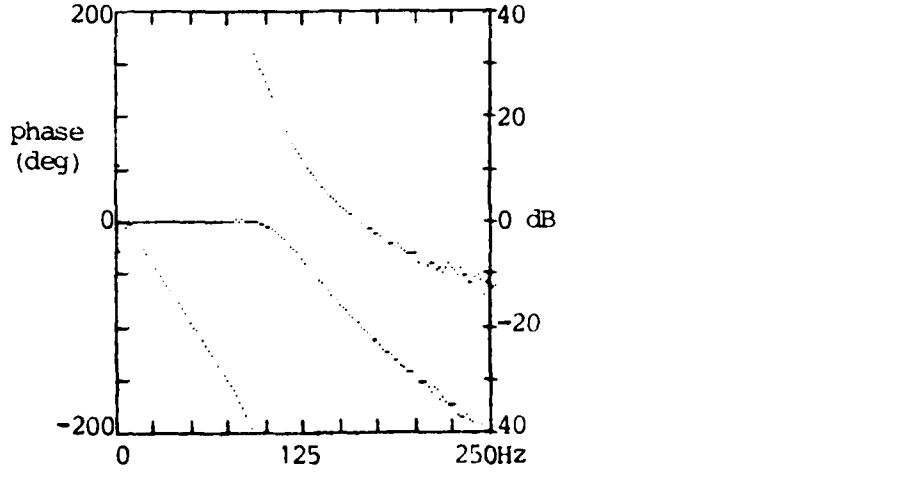
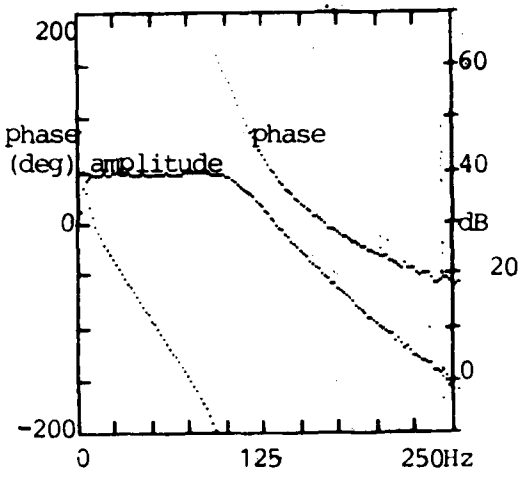


Figure 5b. High Frequency Response of Filter 1

FILENAME: HFA6 DATE: 12 NOVEMBER 1982
TIME: 135959
XFR FCTN + 70dB FS 10dB/DIV
XFR FCTN 0* CENTER 50*/DIV

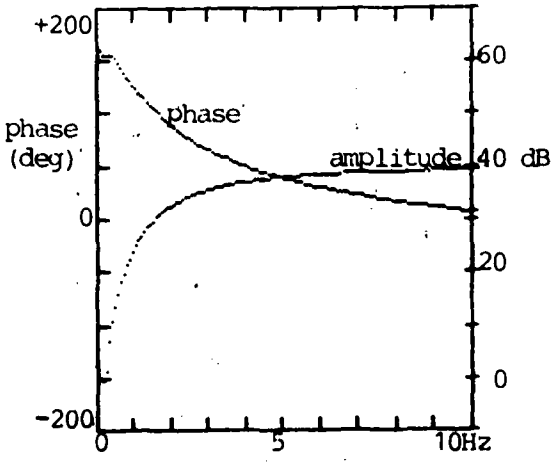


\ 0 Hz 250 Hz /

AVERAGE 4 BW 2.00 Hz

Figure 6a. High Frequency Response of Filter 6 and Amp 6.

FILENAME: LFA6 DATE: 12 NOVEMBER 1982
TIME: 144402
XFR FCTN + 70dB FS 10dB/DIV
XFR FCTN 0* CENTER 50*/DIV



\ 0 Hz 10 Hz /

AVERAGE 4 BW 80.0 mHz

Figure 6b. Low Frequency Response to Filter 6 and Amp 6.

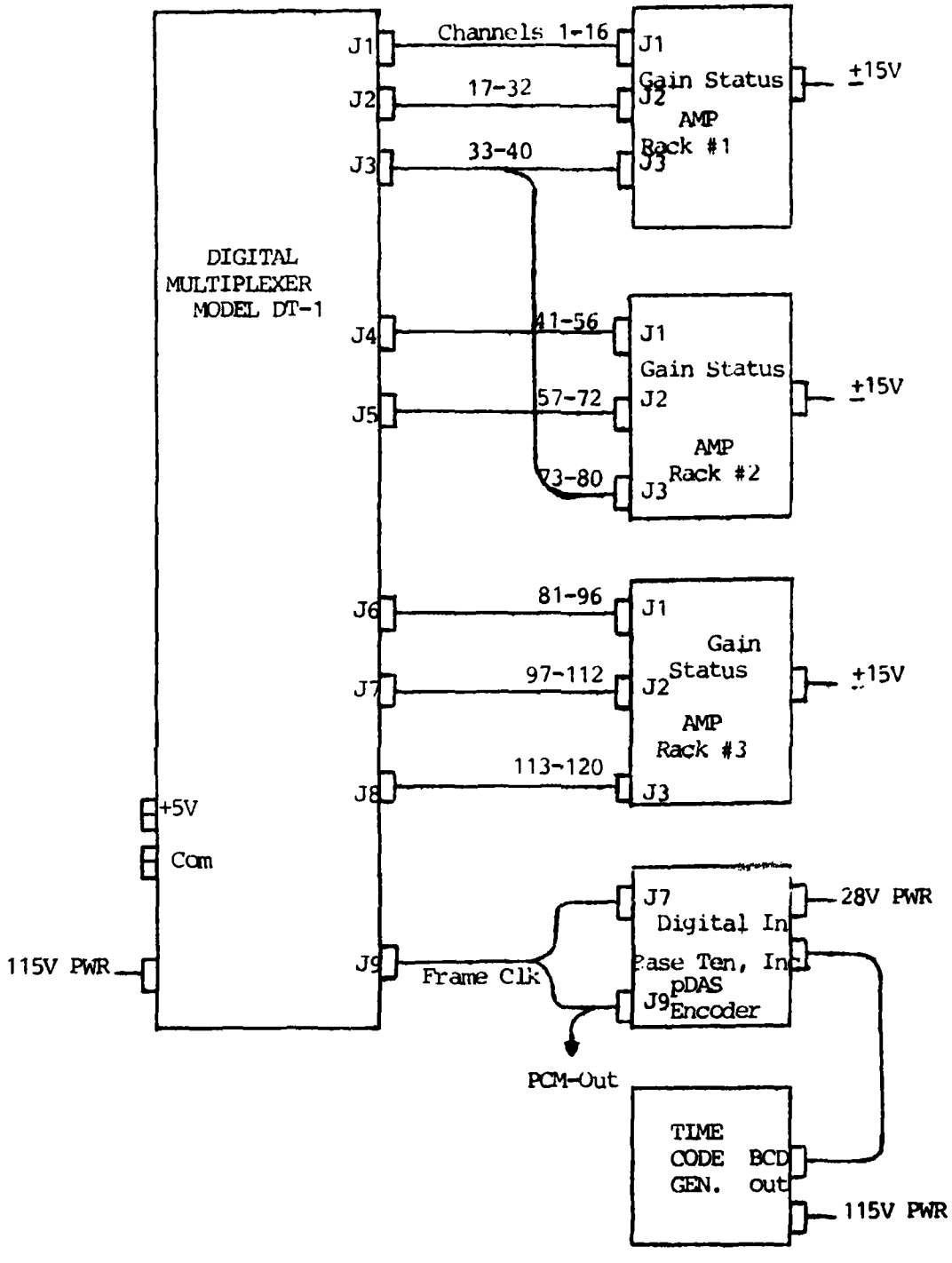


Figure 7. Digital Interconnect Cabling

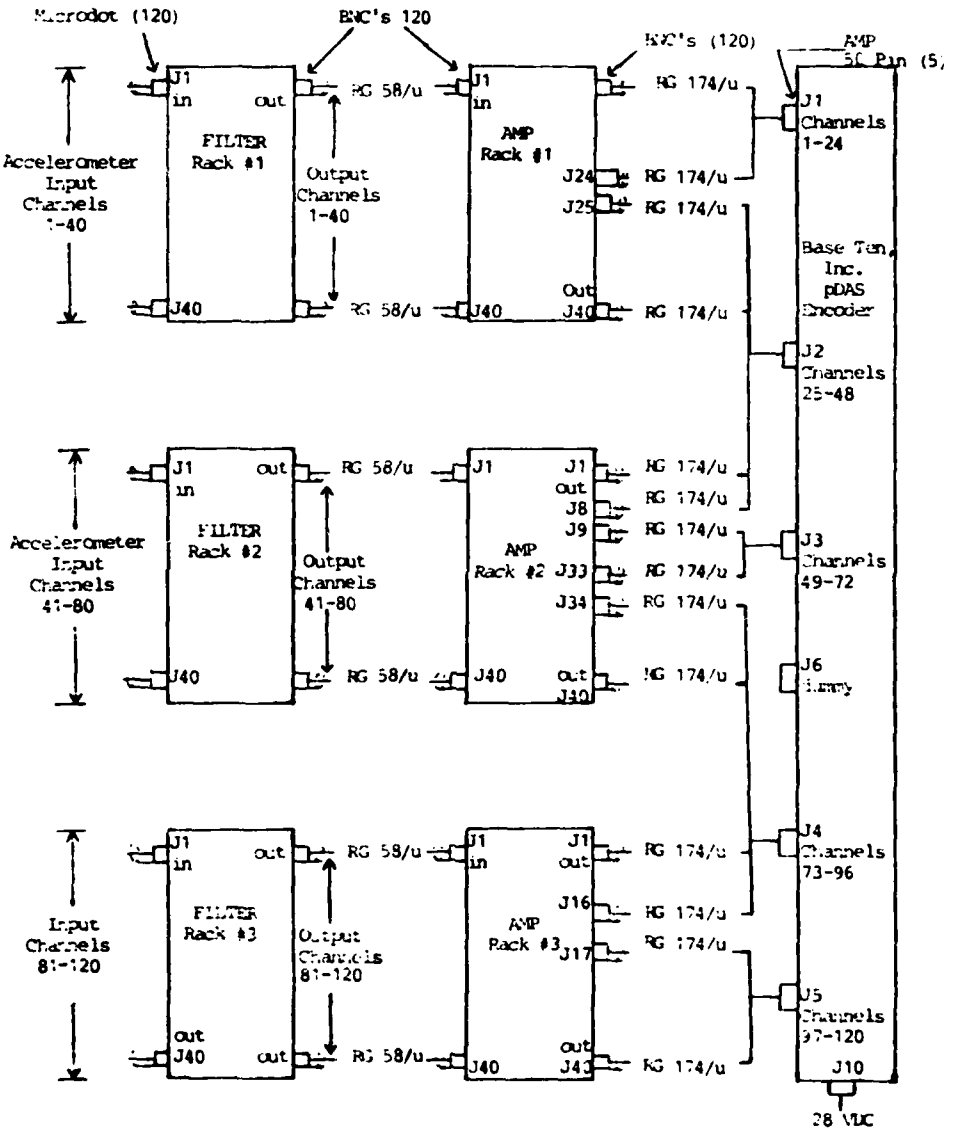
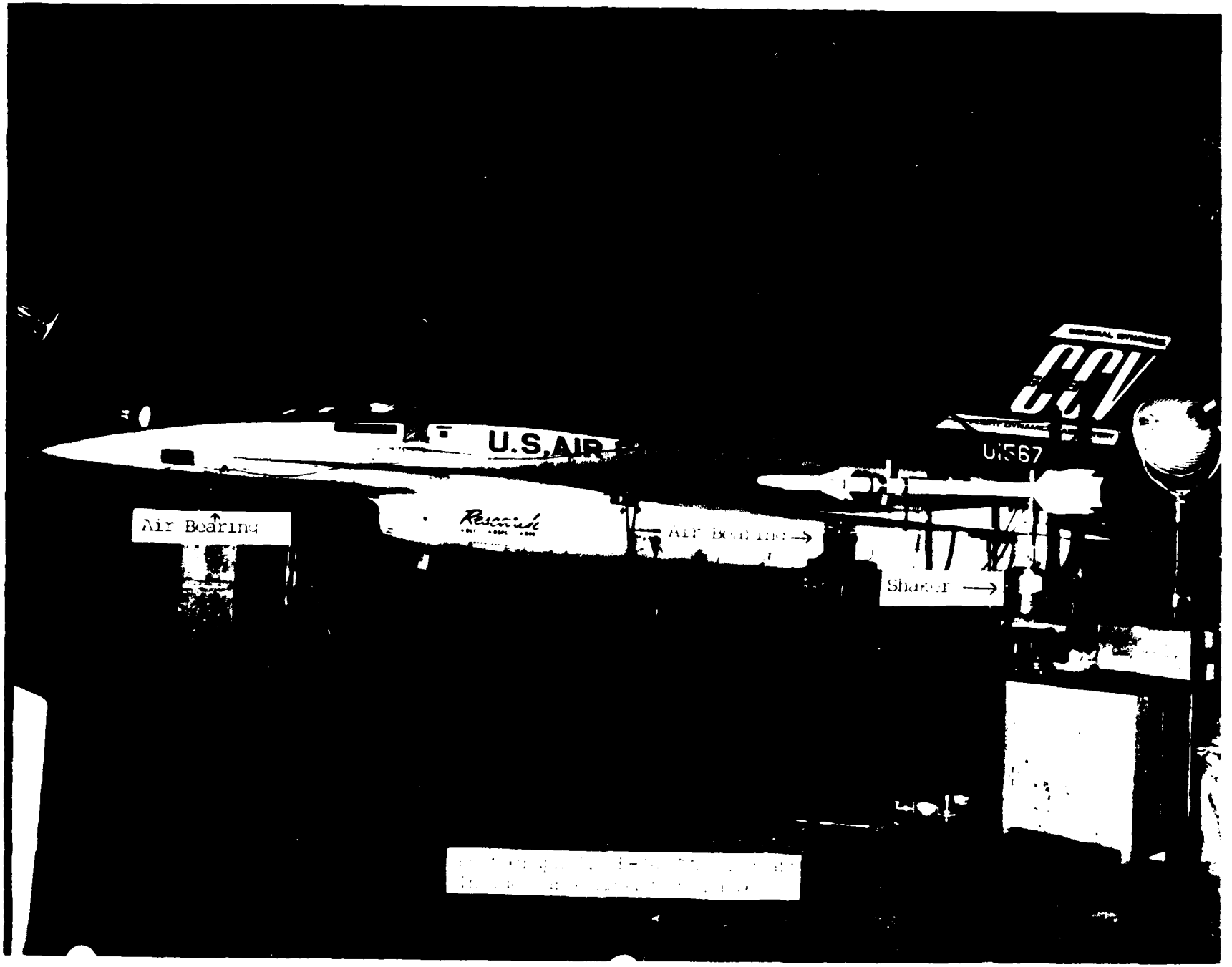
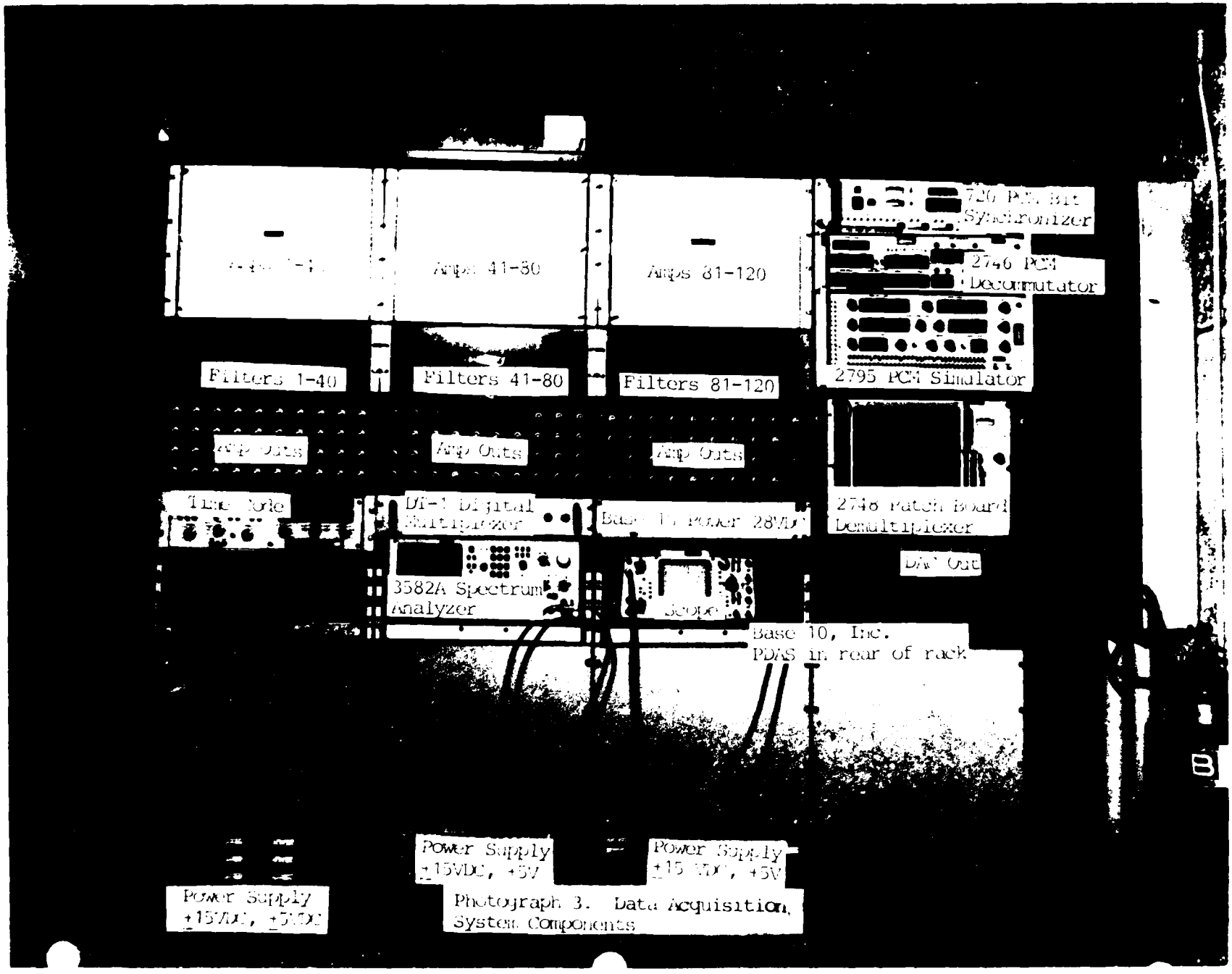


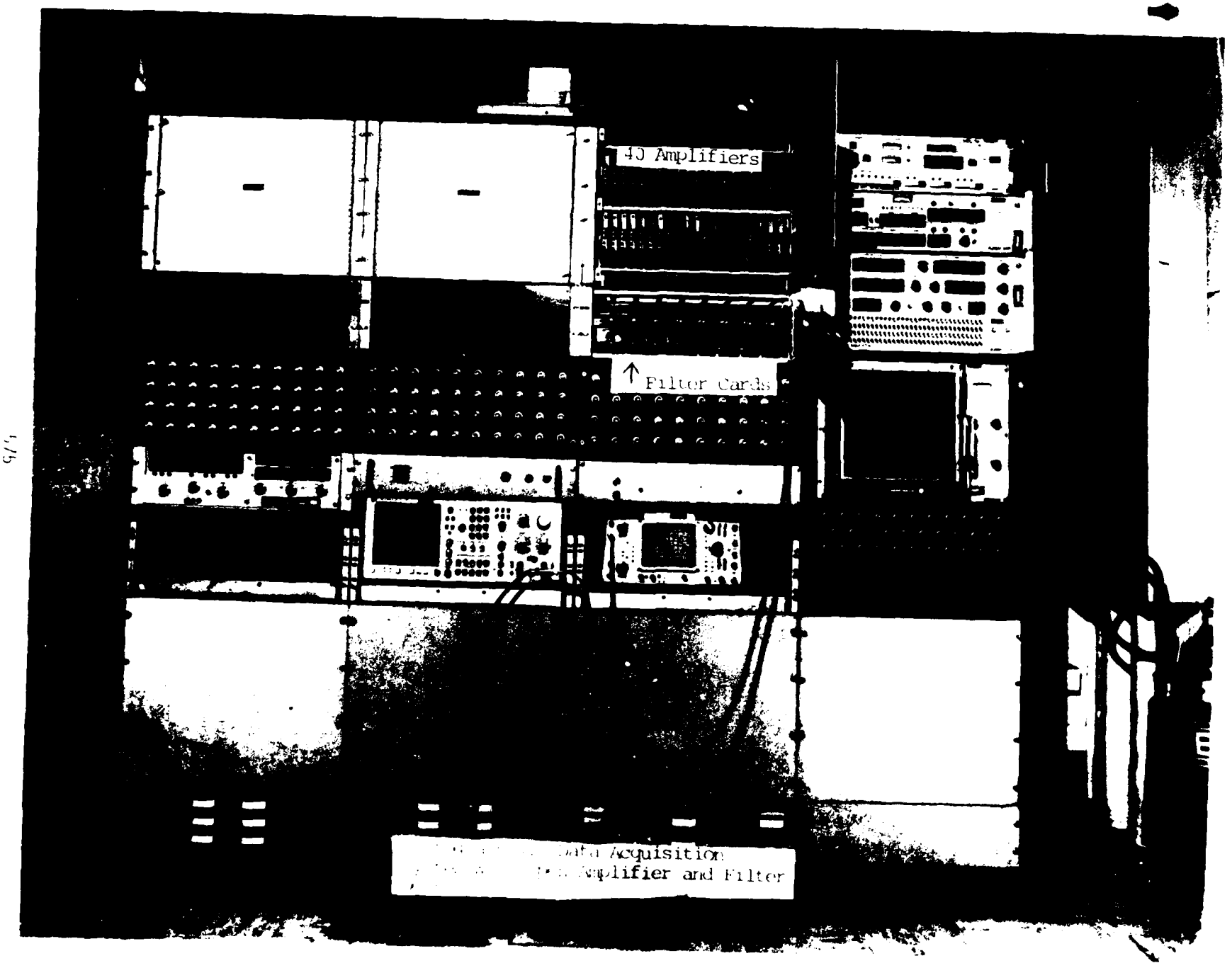
Figure 8. Analog Signal Input Interconnect Cabling

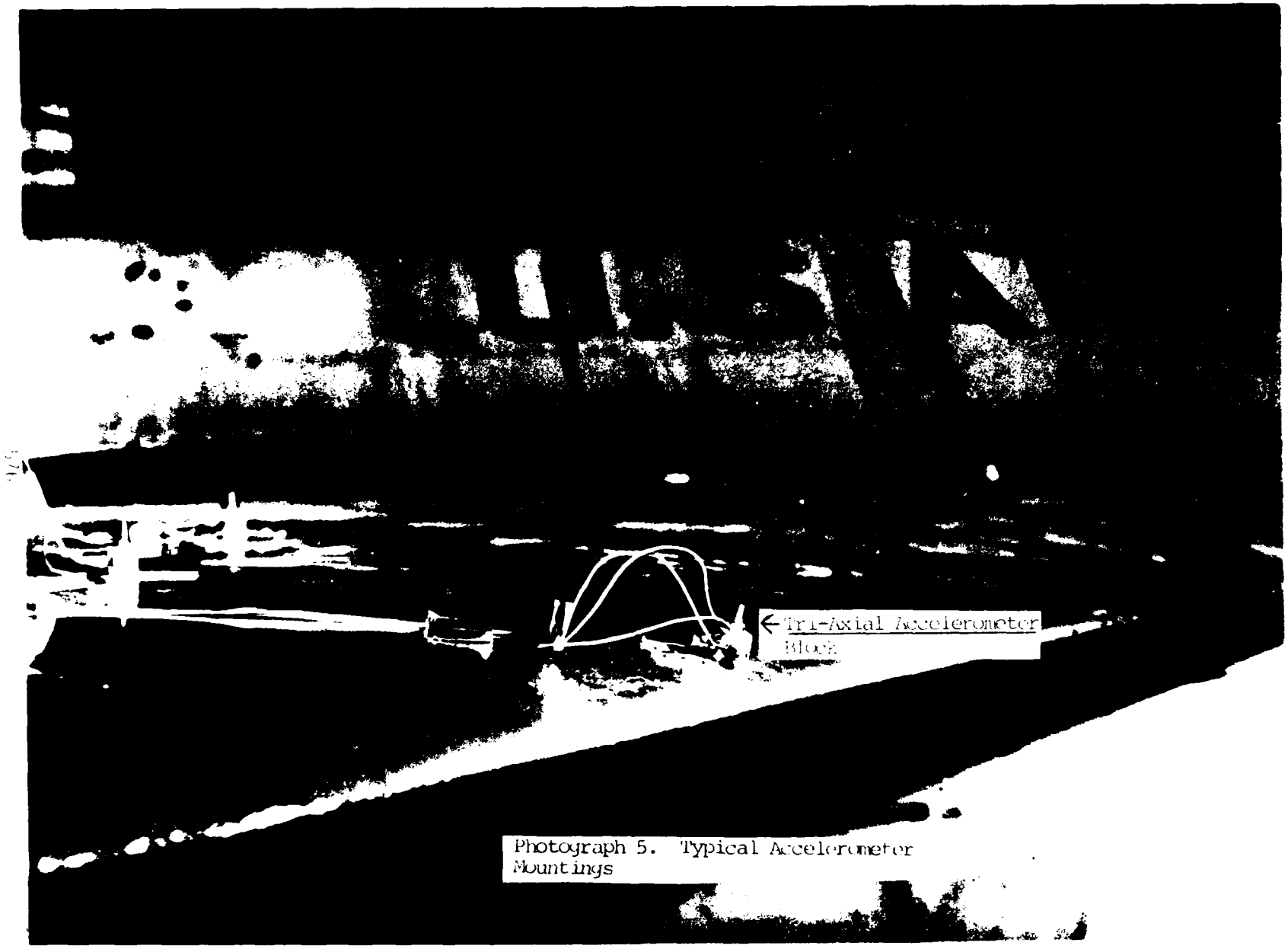

U.S.AIR
CCV
Air Bearing
Research
Shaker

Photograph 2. Overall View of the
461 Control Room

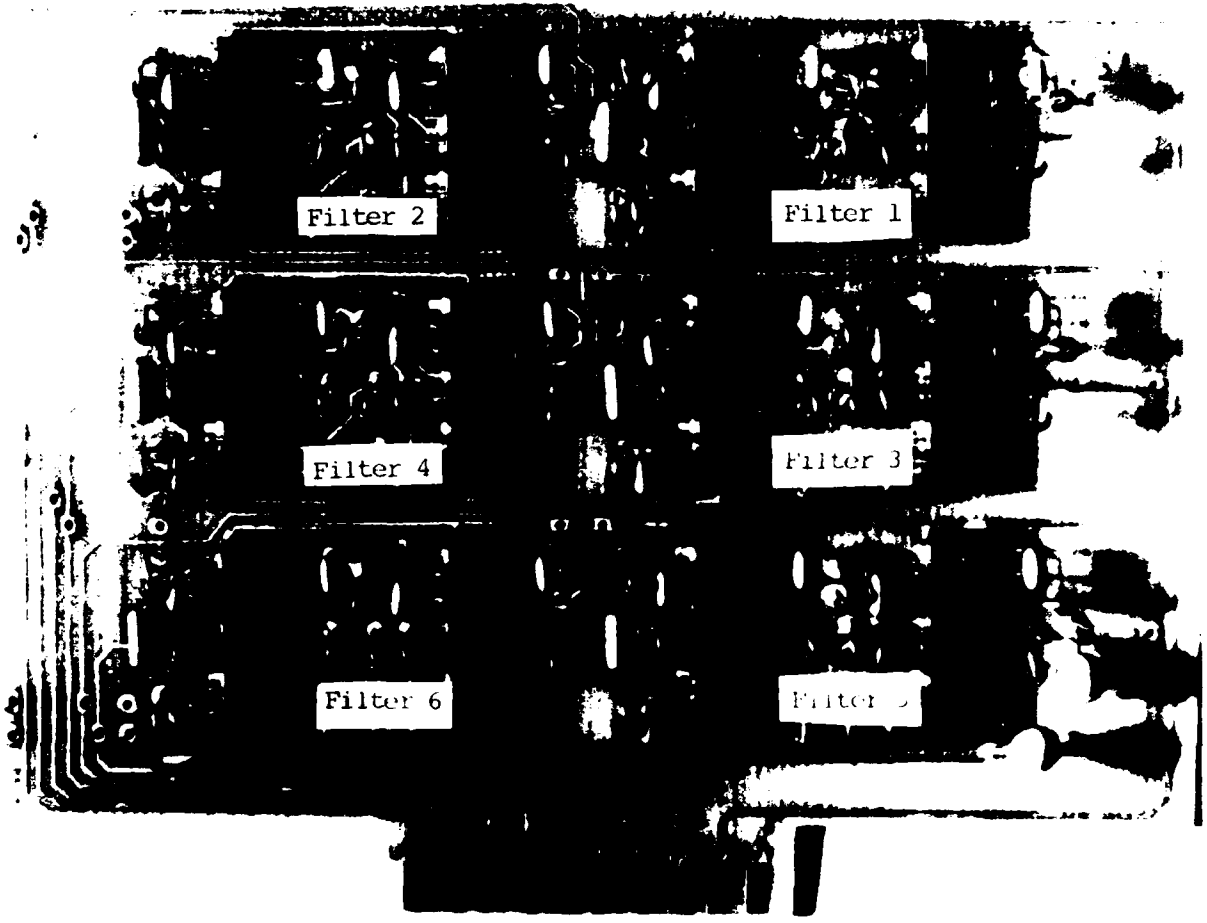


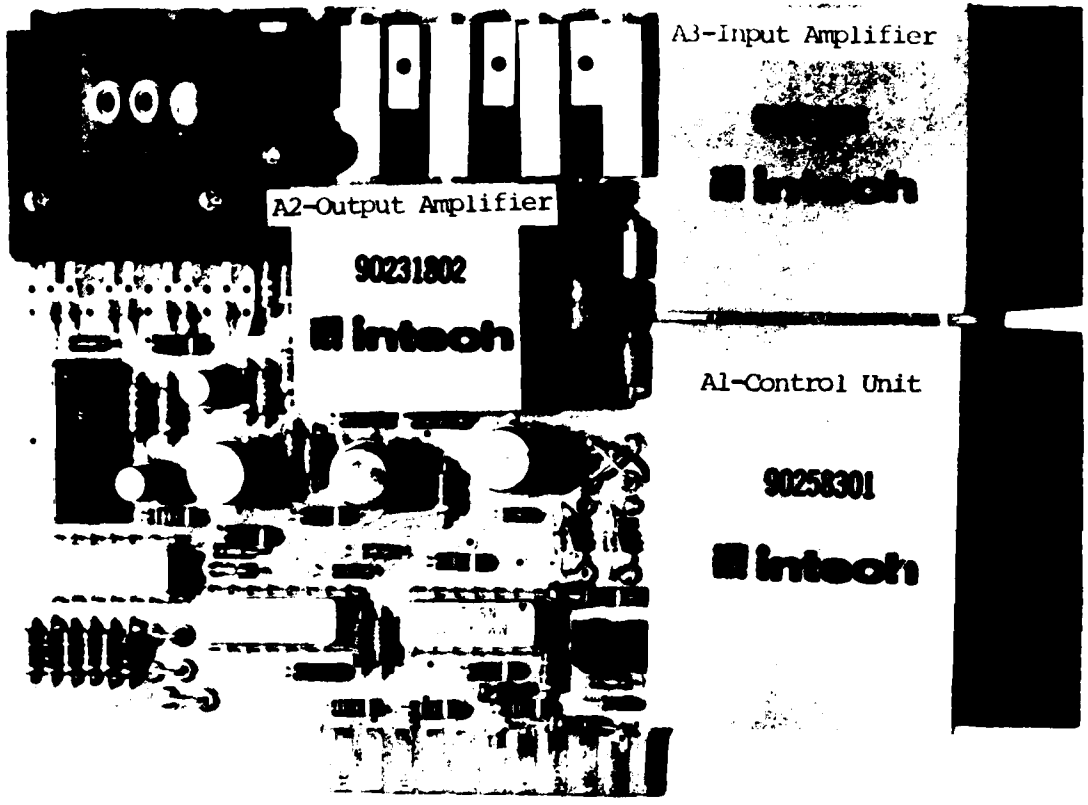
Photograph 3. Data Acquisition System Components


40 Amplifiers
↑ Filter Cards
Amplifier and Filter



Photograph 5. Typical Accelerometer Mountings


Filter 2
Filter 1
Filter 4
Filter 3
Filter 6



Photograph 7. Automatic Gain Changing (AGC) Amplifier Card

Photograph 8. Programmable Data Acquisition System (pDAS)

THURSDAY MORNING Q&A SESSION

Q: BOB GEORGE, AMES RESEARCH CENTER, TO BOB SILL, ENDEVCO

Your little accelerometer looks so keen I was wondering if you might anticipate using it for lower g values? Seems like your hingeless accelerometer sounds like a good idea.

A: BOB SILL

The accelerometer comes right now in a fairly wide range of sensitivities. Indeed we are trying to extend the line, and at this point we do have prototypes that have 10 times the sensitivity that you see here; 10 microvolts per g, 400 kHz resident frequency. It tends to lie on that same graph.

Q: PAUL LEDERER, WILCOXON, TO BEV PAYNE, NBS

On one of the graphs where you showed the calibration sensitivity, I think it was millivolts per g versus frequency, and it looked to me like the lower portion up to maybe 5 kHz was essentially flat with frequency and then it decreased. Do you have any explanation for that?

A: BEV PAYNE

Yes, I intended to point that out when we made the presentation. That particular accelerometer has a built-in signal conditioner which has a filter which reduces the high frequency output. That's the reason for the drop off.

Q: RICHARD PEPPIN, B&K, TO MARK GROETHE, S-CUBED

I have a couple of questions about the device that you have. It seems very unique. One question had to do with the torque that you measured to impose a normal force on the cylinder. And the question I had was, when you put a torque on one bolt the chances are good that it is going to change the torque on the other bolt. Do you check for that? Is it an average torque you use? The second question has to do with the thermal expansion of the inner and outer bearing or inner or outer cylinders The question is: if there is some expansion during the measurement, the normal force that you've calculated using the torque may change, and have you looked into that too?

A: MARK GROETHE

To answer your first question, what we do when we adjust the clamping screws is what you typically do when you are adjusting the bolts on the head of a car. You alternate with increasing torque between the two screws until you reach the torque you want to apply to the screws. To answer your second question, what I need to state here is that we are simply looking for a device that would clip at an approximate acceleration level and if it were to clip at something like 20,000 gs plus or minus 5,000, I'm perfectly happy with that. So if there is some variation due to heating of the piston as it slides through the bar, it doesn't really affect what we are saying. We are more interested in just clipping acceleration transients that could damage the transducer or upset our measurements. We are really interested in what happened after that.

Q: JOE QUINTANA, AF WEAPONS LAB, TO BOB SILL

I was curious to know if you've looked at any of the transverse characteristics of your transducer? Number two, would you like to comment on what you did, or if you had the problem of cable shear at the interface with the envelope of the transducer itself? I know in the past you've had some sort of problems of that nature. You want to comment on those?

A: BOB SILL

Sure. The transverse sensitivity of the accelerometer has been tested in a very difficult manner. We ended up mounting it on a resident beam on a dynamic shaker. We mounted it transverse and, indeed, with the low output device, had difficulty measuring output. Those who did the test claimed 1 percent transverse sensitivity in any orientation. I have not repeated that measurement. It appears to have been done correctly. In regard to your second question, as to the shearing of the cable you saw as the cable leaves the case of the accelerometer, that has not been a problem for us for this accelerometer in that the cable is quite small and quite light. Being very close to the mounting surface we tend not to have much displacement of the cable during shocks. The shearing problems that we've had in our prototype accelerometers were on the inside and we've now taken steps to correct that, but not on the external surface.

Q: LARRY SIRES, NAVAL WEAPONS CENTER, TO DAVE BANASZAK, AFWAL

I may have missed it somewhere but other than the Ayden-Vector airborne version of this AGC amplifier, the ones you are using were obviously card mounted. Is

that something you built in-house, or is that commercially available, or did somebody build that for you?

A: DAVE BANASZAK

Intech amplifiers are ones we've been using for about 10 years in an airborne environment that Intech built for us and we're trying to get a more state-of-the-art version than the Ayden-Vector ones.

Q: LARRY SIRES

Are they still building that or can they still build that?

A: DAVE BANASZAK

Special applications I believe.

Q: RAY REED, SANDIA NATIONAL LABS, TO BOB SILL

With regard to your calibration on the 7270 accelerometer. What are your plans when customers come to you and ask for traceability to the NBS on the calibration of that unit?

A: BOB SILL

At this point I have done static measurements of the gage factor of the strain gages mounted on the bar. It's not a very convenient test, but it does entail

rewiring the bridge with the two gages on the bar such that they respond to bending as opposed to compression loads and I verified, using my own techniques, one and a half percent agreement between the manufacturers stated gage factor of those gages and my results. We have done, dynamically, tests at approximately 10,000 gs of many accelerometers on both the Hopkinson bar and the standard ball drop technique using the 7270 and its traceability to NBS. At this point, we haven't yet tried to convince NBS of the traceability of the Hopkinson bar technique.

C. BEV PAYNE

We have had problems maintaining shock calibration facilities due to budgetary restrictions. We have had a few requests over the years, but it is something that we get a request for maybe every other year; that sort of thing. The way it works is: if the service is not requested, very often it is assumed not to be important. So the problem for us is to justify the expense of setting up such a system. If there was sufficient demand from the outside, I'm sure that the Bureau would respond to such a need.

Q: RAY REED, SANDIA NATIONAL LABS, TO FRED SCHELBY, SANDIA NATIONAL LABS

In one of the figures, you overlaid the frequency response of the two accelerometers and the filtered version seemed to have a resonance at a higher frequency than the unfiltered version. Presuming the two accelerometers really aren't built the same internally, apart from the filter, have you had any word from the manufacturer on that point?

A: FRED SCHELBY

I don't have any word from the manufacturer. But I would assume that if you put an extra filter in there and you change the connector to a bulkhead, that you are changing the loading on the crystal stacks and you do have a shift in that secondary resonance which we see there. Maybe Bob Lally has more to add there?

C: BOB LALLY, PCB PIEZOTRONICS, INC.

The explanation on that to accommodate the extra components of the filter and keep the height within reason, there were likely some adjustmenns made in the dimensions of the seismic mass. I have one other comment to make or one other observation on that. In a measuring system test object the resonance of the accelerometer is only one of the structural resonances that you have to contend with. Usually there are many others in the test object structure, and they can cause the same type of problems that the transducer resonances cause. So that filtering is of importance for reasons other than accelerometer resonances. There are situations where there are IQ resonances in the vicinity, or near the bounds of the frequency that you are interested in which makes shock measurements extremely difficult, perhaps even impossible.

Q: BOB SILL TO MARK GROETHE

You showed on one of your slides an averaged output of one of your protected accelerometers using your device. The average tended to ramp up to about 80 kgs. I was wondering if you had thought about what caused that increase in the frictional force?

A: MARK GROETHE

What is causing that increase in frictional force is that - I really didn't go into any details but there is a high-pressure lubricant applied on the surfaces between the bore and the piston. And what's happening here is that with the normal force applied across that contact surface it is breaking through the lubricant and getting metal-to-metal contact - increasing metal-to-metal contact between the two surfaces which increases the coefficient of friction.

Q: PETER STEIN, STEIN ENGINEERING, TO BOB SILL

I think the Schelby and Sill papers are among the significant ones at the conference. But I want to ask some nasty questions in a very friendly way. I just hope to make things more interesting. Mr. Sill, one of the factors in your calibration experiment is that the strain rate is proportional to the acceleration. The strain rate therefore requires very good reproduction of the rise time of the strain signal. And the strain gage itself has an unknown rise time not yet experimentally determined by anyone. Theoretically it can't be much less than a half a microsecond for a one-eighth-inch gage. I don't know how long a gage you were using. How would that influence your calibration? That's question one.

A: BOB SILL

I don't find that as being a difficulty in that quite of bit of effort has gone into the shaping of the pulse in making it very slow. So if, indeed, it had a microsecond rise time, I would be very pleased.

Q: PETE STEIN

So that automatically falls out by the way you could control the pulse?

A: SOB SILL

I feel it does.

Q: PETE STEIN

Second question: strain gages under impact conditions have been known to put out strain induced voltages on non-negligible amplitudes which can be determined by running the impact test without powering the strain gage to see what comes out. Has that kind of thinking gone into to some of the tests that you've run?

A: BOB SILL

I have accidently run the test without plugging in the strain gage excitation voltage. It didn't trigger the scope, so I don't know how much it gave out. It must have not been much.

C. PETE STEIN

That's the proof of the pudding, and the fact that it was accidental is a by-product.

Q" PETE STEIN TO FRED SCHELBY

The reason you designed that accelerometer with the filter before the amplifier built right into the accelerometer is presumably to get rid of the resonance excitations that occur in the very early part of structural impact testing where the various reflections can build up and excite resonances to very high levels. If you cannot excite the resonance of an accelerometer, as with the new one that Mr. Sill presented, is the necessity for such a design still there?

A: FRED SCHELBY

Well, I'd like to think so. We do have all the electronics internally. You might need a constant current diode externally; you wouldn't need an amplifier. You have five volts out full scale instead of maybe 10 millivolts or whatever. I think there is some justification for it.

Q: LYNN MEYER, ENDEVCO, TO FRED SCHELBY

Considering the high schock accelerometers very often required to measure a low level vibration after exposure to pyro shock, I was wondering if you have done any testing on the transient characteristics such as base strain, thermal transient sensitivity? And if you had, do you have any data with respect to equivalent "g's" per microstrain or equivalent "g's" per degree?

A: FRED SCHELBY

I did do some base strain measurements, and they are in the back of the paper - base strain .2 equivalent g per microstrain. I checked the thermal sensitivity shift .02 percent per degree Fahrenheit. Transverse sensitivity was a little over 5 percent, a little high.

Q: LYNN MEYER

On that thermal sensitivity, is that temperature response or is that the ISA thermal transient test?

A: FRED SCHELBY

No, that is not the transient test, that is the thermal response. I didn't do a transient test on that.

Q: JOE QUINTANA TO MARK GROETHE

I was curious if you had measured the residual pole relative displacement of your piston, with respect to the bore pre- and post-test, to see if that aspect of your device was as per prediction? In other words, you measure the location of the piston and see if it is slipped as much as it should have.

A: MARK GROETHE

Yes, we did that on every test and it pretty much agreed with what we would calculate from doubley integrated acceleration. The difference between the bore-mounted accelerometer and the piston-mounted accelerometer, and for the test that we were performing is around the drop bar or the Howitzer, those difficult displacements, was on the order of a millimeter or two.

Q: JOE QUINTANA

That was by actual measurement or just by looking at the records?

A: MARK GROETHE

No, that is by actual measurement.

Q: LARRY SIRES TO BOB SILL

Have you measured the base strain sensitivity on the new accelerometer?

A: BOB SILL

Yes, and the way I would spec it is 50 equivalent gs per the standard base strain, which was 250 microstrain. If you take his .2 x 250, it turns out to be 50 microstrain. So they seem to be equivalent.

Q: JOE QUINTANA BOB SILL

When you showed your slide of the seismic system, with your strain gages mounted, that seismic system was apparently mounted on some other base and the base had a couple of grooves in it. Could you explain those?

A: BOB SILL

Yes, those grooves allowed the leads to the pads for the strain gages underneath. I didn't point out that this sensor has two sides to it that are symetric, and those grooves in the pedestal to which the silicon sensor is glass-fused allow those leads in and out.

Q: STEVE KUEHN, SANDIA NATIONAL LABS, TO BEV PAYNE

In our lab we do temperature sensitivity tests of higher reliability components on a 5-g shaker. The particular reference in this shaker has a published spec of less than one percent change in sensitivity over the temperature range we are interested in. The problem is that it would be nice if the reference sensitivity were characterized as a function of temperature so that our test and its temperature sensitivity could be measured more precisely. Certainly we could try to do more temperature isolation, and we've endeavored to do that. But I was wondering if NBS has done any published work or any sort of comprehensive test comparing the sensitivity of different piezoelectric accelerometers?

A: BEV PAYNE

Yes, we have done in the past some special tests, but we don't offer that as a routine calibration. We don't have the facilities available at the present time. In other words, if you sent in an accelerometer tomorrow we would not be able to do a temperature response calibration. I have done a limited amount of testing for temperature. We do not have any recent tests on transducers that I think would be of interest to you. Again, if this is something that you see as a recurring need, it is certainly something that the Bureau of Standards could look at with the possibility of setting up such a service.

Q: JOHN WILSON, ENDEVCO, TO FRED SCHELBY

I wondered if the shift in resonant frequency might be due to some kind of phase characteristics of the filter? Did you look at the phase characteristics at all?

A: FRED SCHELBY

I looked at the phase characteristics from 50 Hz to 21,000 Hz; it was linear. It was a Butterworth filter with .7 damping, so it came out the way it was supposed to. I didn't go any higher than that.

Q: MEL HATCH, EG&G, TO MARK GROETHE

Regarding the friction factors between the piston and the cylinder and also in the fastner which actually did the clamping actions: I had problems in getting

repeatability between torque and clamping in some past experiments that I have done. I was just wondering if you had any experience in that regard because I noticed you mentioned a lubricant between the cylinder and the piston? I wonder what you did in regard to heat treating between those two stainless steel surfaces? Because it was stainless steel that I had problems with in fastners to get repeatability between torque and force.

A: MARK GROETHE

I might mention that there wasn't any heat treatment done on the surfaces between the piston and the bore. They were machined to a micro finish of 8 microinches, and the type of lubricant that we used was a simple anti-seize compound. I can't remember the name but it was a copper-loaded seize compound and a high pressure lubricant. Now as far as the repeatability in setting the torque versus clipping acceleration level, again, I might mention that we are using it as a protection mechanism, as insurance, and I was making measurements much much lower than what I was setting the clipping acceleration level at. The range of interest to me was on the order of 5,000 gs or so. So whether or not it was repeatable to ±5,000 gs, it really didn't matter. From the test that I have done over a number of these fixtures and over a number of different tests, repeating it over and over again with the same fixture, I found a fair repeatability in setting the torque and obtaining a clipping acceleration that I desired. Does that answer your question?

A: MEL HATCH

I think so. I just had some problems more or less in the screw threads with about a quarter-inch bolt at one time and with using stainless steel. I started getting nonrepeatability in that particular area, and I was wondering if that carried over in your particular case either in the threading or in the cylinder surfaces?

C: MARK GROETHE

We were typically torquing the screws to the 100-inch pounds or so, and the screw threads themselves were also coated with the anti-seize compound. So we weren't getting any galling between the screws and the threads in the clamping block.

Q: PAT WALTER, SANDIA NATIONAL LABS, TO BOB SILL

In the test where you keep the accelerometer on the bar, I might first comment, if it was possible I'm sure you would like to give your accelerometer to Mr. Payne and have him run a frequency response for you, but obviously his stimuli would be fairly low and I think it would be extremely difficult to do. But I was just wondering out of curiosity, in theory when you keep the accelerometer on the bar you have an input/output relationship. In fact they are in different frequency domains because the inputs are velocity and the outputs are acceleration. And maybe noise characteristics, when you try and get in the same domain, can preclude you from doing that. I wondered have you considered trying to get a transfer function relationship and look at amplitude frequency response?

A: BOB SILL

Yes, and in fact you are absolutely right, the noise characteristics of trying to differentiate that strain gage output really did preclude us from getting any well believable numbers. We might in the future with higher resolution transient recorders, or some improvements in that matter, be able to get enough data points per sample that we could then, by means of digital filtering or what not, have a better feel for the frequency content. I do want to point out though that we do have high sensitivity versions of this with 10 times the sensitivity, which was just enough to put it in on our system 50 kHz shaker. We're very pleased it was flat, as we could measure up to 50 kHz. We had 1 dB glitch in that region that appeared to be related to the rocking resonance of the shaker and we could determine the glitch by mounting the accelerometer in various locations on the shaker.

Q: PAT WALTER TO BEV PAYNE

Bev, I had a couple comments for you. First, you are asking about work that the Bureau should be doing and I think that one thing I am particularly pleased about was all this model analysis equipment that has come out in the last few years - 12- and 14-bit resolution that has really put emphasis on the 2 or 3 percent front end of the system. The one thing I see in particular is cross axis sensitivity for accelerometers. The problem has been around forever and we know that the accelerometers are not unijunctional measuring devices and we suspect that the transfer sensitivity ought to be a function of frequency and perhaps even amplitude. Now there are a lot of things that

evolve. We've got different transform techniques around that we can look at. We can look at properties and materials in our calibrations and things like that. You find when this model test is being done, the computer people aren't well trained to think in terms of the front end sensor. So a lot of times when they have the accelerometers mounted they are getting distinct components. If you look at their response from the accelerometer that's due to transfer sensitivity and so they are getting an axial mode in the structure that's coupling in and a transverse method through the accelerometer and they are getting glitches in their frequency data. It is sitting there and they are fitting mode shapes to this. You can see that it's being done erroneously, and so I think that certainly is an area of endeavor that the Bureau ought to be working in.

Q: BEV PAYNE

Do you have any feeling for the frequency response? Is there a need for a higher frequency response measurement in the area we were talking about?

C: PAT WALTER

On transfer sensitivity, I think most of the model testing that is being done is generally the dynamics of the structural precluding you from going up too much above 2 to 5 kHz. And I think certainly 10 kHz in today's technology is probably as high, at least if you relate it to structural testing as people are interested in transfer sensitivity. The thing that you are talking about is just the vibrating systems above 10 kHz, and you ask if people are interested in that. I think the answer is clearly yes, because one of the things is that you can have minor

resonances in your accelerometer. The manufacturer typically hits them with a hammer to get the major resonance but you can find minor resonances that preclude you from successfully getting data and so the identifications of deviation and the response of an accelerometer from an ideal second order system, or whatever, I think is very important to do. Then you have the advent of this filtering type of thing that Fred talked about. Also, there are other companies making these filters, and being able to characterize the roll of these filters is important. So I think the answer is definitely yes.

The other comment I would like to make to the NBS is - I think that after sitting through two or three days of these discussions where people have talked about blast measurements, impact tests, and hundred thousand gs - to suggest that you only get one or two phone calls a year on shock. I might suggest if I wanted to buy steak. I wouldn't go to McDonalds. I think we've abandoned the Bureau. That problem has been around for 15 to 20 years within the Department of Energy. That I'm sure you are well aware of. We have a primary laboratory and we've established our own shock calibration capability at 30,000 gs, and it lacks in someways. We're putting nuclear weapons into stockpile right now with standards requiring shock calibration of levels up to 30,000 gs. We look at the Bureau and we get 10 gs so we don't bother with you any more. The last thing I would think to do would be to call, because for the last 20 years I know there hasn't been any response to that. One time we did give money to the Department of Energy. There was a group that was funding something - I think the Navy, the Army or whatever - and a fellow by the name of Fetterman came up and just about the time he was trying to get some shock calibration done, which was less than adequate because of that machine you had with the bad surface

motion - the Bureau had to cut back and he disappeared. So I think for all the money we threw in, I think we have one calibrated accelerometer back that works and that's why you are not hearing about many problems.

Q: RICHARD PEPPIN TO MARK GROETHE

One question about your transducer: when you add a lubricant do you change the mechanism of the friction from kinetic to viscous, and if so, what happened to your analysis?

A: MARK GEOETHE

I'm not sure I really understand what you're asking.

Q: RICHARD PEPPIN

Well, you're adding a lubricant to the interface?

A: MARK GROETHE

Yes, we're adding a lubricant to the interface, and what we are were really after there was trying to reduce the difference between the static coefficient of friction and the dynamic coefficient of friction.

Q: RICHARD PEPPIN

Is that all it does, or does it perhaps change it into a viscous type friction rather than a step? Is it a constant friction force or, I'm saying, could it be a functional velocity, and if so, what happens?

A: MARK GROETHE

Well, again I want to point out that we're just using it as a protection mechanism and it really doesn't matter what type of friction we're talking about at that interface as long as the friction force remains fairly constant.

Q: RICHARD PEPPIN

Is this on the high dynamic?

A: MARK GROETHE

Well, what I demonstrated - the slides I showed today - was rather low; a small dynamic test with a drop bar facility which got approximately one to two thousand g input. Then I went on to test it at a level I was more interested in, on the level of 100,000 g level, and obtained a final gage velocity on the order of between 50 to 100 meters a second. Now on that particular test that I showed today, done with a Howitzer, I'd set that piston to slip at approximately 20,000 gs based on the dynamic coefficient of friction, and that's the average that I saw initially. Again, I saw it climb somewhere over 50,000 gs

to 100,000 gs by the time it stopped slipping. So I think that demonstrates that under the dynamic conditions that simulate what I was interested in, it performed adequately.

Q: RICHARD PEPPIN

What does the addition of lubricant do?

A: MARK GROETHE

What we are mainly after by adding a lubricant to the surface was to prevent, since they are both made out of the same material, galling between the two or cold welding as it begins to slide. In addition to that we wanted to try to reduce the difference between the static coefficient of friction and the dynamic coefficient of friction.

Q: PAUL LEDERER TO BEV PAYNE

I can't let the attack on Bev Payne go totally unchallenged. Bev, would you translate the equivalent of 123 nanameters at 30 kHz into gs.

A: BEV PAYNE

That would be about 439 gs.

C: PAUL LEDERER TO PAT WALTER

See Pat, it's not just 10 gs.

C: PAT WALTER

I have to be careful what I say here because I realize it's being printed. It's hard sometimes for a scientist to set the policy when the decisions are made at a higher level. So even though we had strong feelings about the shock calibration facilities, it's not always easy to convince the administrative people that it is necessary and that's why it is important that people and laboratories who have needs make them known. That gives us ammunition and it is very important to push for new areas, even though there have been efforts in the past. The people who make the decisions constantly change the structure. So it is important to make your needs known.

C: PETE STEIN, STEIN ENGINEERING

To underscore the comment that Pat Walter just made, there is the case study from the late 50s of a Rolls Royce Avon engine that blew up under zero indicated gs on the accelerometer. What had happened is a relatively nominal axial response to axial excitation was coupled with the resonance in the transverse mode whose resonance had a g large enough to give a signal just about the same as the one axially. The phasing was such that they cancelled each other. So the accelerometer output indicated 0 gs and the Avon engine blew up. I know of only one

paper in the literature that deals with the effects of frequency on transfer sensitivity, the Whittney Paper presented at the 5th Transducer Workshop, and we do need that kind of information very badly.

Q: PETE STEIN TO MARK GROETHE

When you impact the bottom of your fixture at time near zero there are traveling waves that go back and forth through that frictional joint. The frictional joint at time near zero is like a distributed, geometric discontinuity. You have reflections that are almost impossible to calculate from that distributed joint. There have been doctrinal dissertations done on this quite some time ago. But at time near zero where this traveling wave phenomena does occur, how does that influence your accelerometer output? It will see quite a few reflection cycles of relatively high acceleration pulses, is this not correct?

A: MARK GROETHE

Yes, I would agree with you, that is one of the reasons why we want to make the fixture as small as we possibly can in order to push the frequency we are talking about as high as we possibly can. In addition to that, as I briefly mentioned, we did see some of those problems and we attempted to reduce them by going to a composite piston which would help damp out the reflections back and forth through the piston. In-ground motion studies - the initial high, short-duration transient accelerations, the rise times - generally aren't high enough to excite what you're talking about. But making the fixture as small as possible would reduce the time for the piston to start sliding within the bar as those waves reflect back and forth.

Q: PETE STEIN

Have you considered grooving that rod and putting some strain gages in and actually measuring what goes on in the rod just to see what is going on?

A: MARK GROETHE

No, since we are more interested in developing some sort of protection device; an insurance policy for protecting the transducer from being damaged and the recording instrumentation from being overranged. We are more interested in obtaining the overall acceleration versus time and then, if need be, enacting some sort of protection mechanism for the transducer.

SESSION VI

INFORMAL WRAP-UP

LeRoy Bates, Chairman

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APPENDIX

"MURPHYISMS"

for the

12th TRANSDUCER WORKSHOP

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"MURPHYISMS"

1. While doing early morning (4 a.m.) pre-flight and equipment checkout, we met Mr. Murphy. One of the early-morning chores is to turn on instruments for warmup and calibration, clean recorder heads, install magnetic tape on analog recorders, etc..... Normal method to cleaning heads is to spray and swab with freon. This morning a can of yellow runway marking paint became mixed with the freon..... Result...YELLOW HEADS!!! Moral: Don't "color" your data with misinformation.

2. The moving table of a vibrator used for accelerometer calibration was modified to use a steel insert instead of an alumina insert to mount the items being tested. Realizing that this would affect the high-frequency transmissibility, this modification was fully evaluated.

Calibrations with many types of accelerometers proved to be correct. All of a sudden a few accelerometers of one design appeared to have a lower resonant frequency than they should have had.

The problem was finally traced to an electrical grounding difference. These particular accelerometers used an anodized aluminum case. Now and then the electrical isolation from the anodize would be broken. This had not made any difference when using the alumina vibrator insert, but with steel, it now changed the grounding.

3. When a failure mode makes itself common in early testing, it is natural to jump to pessimistic conclusions when a similar looking failure pops up again, and so a very incomplete analysis seems sufficient. A week of work could have been avoided by rechecking a few switch positions, something which could have been detected with a very minimal exploration of the problem.

4. We were asked by a very secretive-type test engineer to provide pressure measurements at various points in a system for cooling various on-board components. He said they must be capable of measuring fluids up to 100 psia with ¼ percent accuracy. All we could have access to or knowledge of were various ports. Not having transducers of this range and accuracy, we were forced to order a number of them at some expense and delay to the test. When testing finally got underway, they'd run the system for 15 minutes. We'd give the data to the test engineer who'd give it to the analyst, who'd go away for 15 minutes to run calculations, then make changes and run again for 15 minutes, then calculate for 15 minutes, etc., etc.

After about 2 days, I asked the analyst, who was quite open, why it took so long to run the calculations each time? He replied, "It's a real pain to have to subtract all the outlet pressures from the inlet pressures before calculating."

If only we had asked what the measurements were really for, we could have used half as many 0-5 psid transducers of 5 percent accuracy (of which

we had a full stock), giving him his required "differential" pressure directly at no purchase cost and with no test delay.

5. Variable reluctance-type pressure transducers intended to operate at only a few or fractional psi have very compliant sensing diaphragms to provide adequate deflection to be transduced by their inductive coils. A 0.2 psid transducer provided a false pressure indication on a recent test. The transducer's electronics had been zeroed with the transducer positioned so that its diaphragm was in a vertical position. In operation, the transducer was situated with its diaphragm in a horizontal position. Deflection of the diaphragm due to gravity provided a false pressure indication.

6. Several years ago we manufactured a very low-range differential pressure transducer which employed dual isolation diaphragms and oil fill. The unit's overload was 2 times range. We had experienced some difficulty in shipping units by air, since the plastic dust plugs were not vented and any change in pressure would be seen by one side before the other; destroying the units with pressure overload.

Therefore, an instruction was issued to vent the dust caps. About twenty finished units were sitting on a shipping bench with caps installed. And then, you guessed it, the technician took an ice pick and vented each cap and also each and every diaphragm.

7. The noise on any particular data channel is directly proportional to the importance of the customer observer.

8. To keep this story anonymous, let us not be concerned with the location of this test, nor what was being tested. It is important to know, however, that it was a one-time event. After the desired explosion, damage to the test item was anticipated to be so extensive that no further testing would be practical.

High-speed cameras were positioned at several locations. Measurement and recording of 36 channels of strain, acceleration, and pressure was to be accomplished in an instrumentation trailer located near the firing bunker.

A 10-second countdown would be used to coordinate data acquisition. The tape recorder would be started at "6", the film cameras would start at "3" and the explosion would occur at "0".

To accommodate any possible problems, a two-way intercom between the firing bunker and the instrumentation trailer was installed. Hence, the countdown could be stopped at any point prior to firing if problems occurred.

Needless to say, a problem occurred. For some unknown reason, the main circuit breaker in the instrumentation trailer tripped when the countdown reached "4". Unfortunately, the power for the intercom came from this circuit breaker. The loud cries of "STOP THE COUNT" were not heard in the firing bunker, and the explosion occurred at "0".

Fortunately, all the high-speed camera data were OK. The 36 channels were never recorded. This event is the reason that TWO intercoms are now used between the firing bunker and the instrumentation trailers, one using trailer power, and another using power in the firing bunker.

9. During evaluation of filter cards used in an instrumentation system, a 1 db hump was noticed in the transfer function at an undesired frequency. After several perplexing days, it was discovered that the holes near the printed circuit board's contacts were plated through, which shorted the contacts on opposite sides of the board. This resulted in connection of filter inputs to filter outputs. Drilling the holes to remove undesired plating cleared up this murphyism.

10. Objective: Measure the side on and reflected pressure levels in a large explosive-driven shock tube. Tube diameter is approximately 10 feet.

Technique: Use piezoresistive pressure gauges covered with a silastic material ablative to protect against temperatures associated with blast wave.

Result: Instead of the sharp rise in pressure expected, and which is the normal result of shock tubes, the time history profiles showed a distinct rise in the output of the gauge a few milliseconds before arrival of the shock front. This rise was promptly dubbed "The Pucker Factor" in that the gauge seemed to know it was about to get hit with a very severe blast and appeared to "pucker" in anticipation.

Analysis: Despite much speculation about how pressure waves in solids could outrun the blast wave and affect the gauges, it was discovered that the silastic was transparent to certain infrared wavelengths and as the shock wave approached its luminescence was stimulating a photoelectric response in the gauge.

11. Air Specifications on a particular telemetry antenna specify a VSWR not to exceed 2:1. However, after a couple of thousand missile launches with this antenna, it was decided to conduct tests to verify its conformance with the environmental specifications. These tests, which were more severe than actual conditions, convinced people that these antennas should not be used, thereby ignoring the thousands of flight tests which proved the antennas were adequate for all the environments under which the missiles were flown. As the old saying goes, "Penny Wise & Pound Foolish". In the testing of air-to-air missiles, strain gages and temperature transducers were installed on the missile wings. Most all precautions were taken except one. At approximately 350°F data gathering terminated. It was premature termination caused by molten 60/40 solder and separation of the connection wires from the gages. Temperatures in the region of the installed gages were programmed to reach approximately 700°F. Laboratory tests conducted with 60/40 solder confirmed that separation would occur at 350°F with minor strain on the connecting wires. Again we closed the barn door after the cow was gone.

12. In a continuing effort to collect flight data, including angular vibration, a new angular sensor was added to a helicopter flight test program on a "piggy back" basis. The angular sensor operated on the basis of a spinning torus of liquid metal setting up an oscillating magnetic field. Two axes of angular motion could be measured, and it appeared that this sensor could represent an

improvement over rate gyros. An AC voltage was required to spin the torus of liquid metal, so a special power supply was constructed yielding satisfactory, though noisy, performance in the laboratory.

All sensors were installed in the aircraft, calibrated, and tested successfully on the ground. On the first flight, a clear AC signal matching the frequency of the power supply dominated all channels of data. On the ground, the system tested out satisfactorily. A second flight revealed the same problem. The instrumentation package was tested with the helicopter hovering a few feet above the runway. Everything tested out OKAY. Still a third flight was scheduled, and the same problem persisted. By now all who were working on the project were unaware that all the effort was being put into the "piggy back" instrumentation, neglecting the original purpose of the flight test. The flight test engineer was on board for the fourth flight test, and when the same elusive "poltergeist" showed up in the data in flight, the troublesome angular sensor was unplugged from the rest of the instrumentation. All the data for the original purpose of the flight test was collected on this last flight,and the angular sensor was quickly discarded. The moral to this experience is that a simple piggy back using an untried new sensor is never simple---Murphy's law prevails!

13. Manometer Nonlinearity--The measurement of a pressure in a high-temperature vapor had been very elusive. A year of bad experience left the project managers with a low confidence in electronic transducers. They allowed the installation of a new high accuracy electronic system with the stipulation that an in-place calibration would be based on a basic physical standard.

The standard was chosen a well-type manometer, designed for vacuum application, having a full scale vernier. A vacuum system was designed and built to provide the manometer reference and the transducer pressure. The manometer was filled with a carefully selected fluid advertised for vacuum use. The system was sealed, leak checked and evacuated for a week to reduce out gassing. Finally, all was in order - calibrations began.

The first transducer was connected for calibration and three sets of data were taken from zero to one psia. The engineer hurried away to study the data. Impossible! The transducer was nonlinear, drooping as it approached full scale. No, wait! The data was bad. Each progressive calibration had less droop than the previous one. Must be a leak, or outgassing or Murphy. More pumping, more calibrating. The data repeated. First a large droop, then less and less. Unbelieving, he ran another calibration without additional pumping. The data followed the last curve which had almost no droop.

A suspect was identified. Knowing that the manometer fluid absorbs gases and that data showed the nonlinearity to be greatest after overnight evacuation with the vacuum pumps, a hypothesis was formed. What if the fluid changed its density, when absorbing gas, enough to show up in the calibrations? The fluid was changed to another more carefully selected fluid; one designed for diffusion pump use. It was chosen particularly for its low vapor pressure and low absorption of gases. A new fluid, more pumping, more calibrations resulted in linear data.

Moral: A manometer is only as good as its fluid, or seeing is not necessarily believing.

14. A field experiment involved 300 1/8-in diameter metal-sheathed thermocouples, each about 50 ft long and all of type K (chromel-alumel) material. In metal-sheathed elements the material type is not visually evident. The elements were not color coded and were not identified other than by an instrument tag. All were checked before the experiment. One extra thermocouple measurement was added at the last minute to monitor a combuster temperature.

Several days into the experiment the primary recording system began to indicate the monitor thermocouple temperature was out of range. The loop resistance of the circuit showed the thermocouple to be intact. Alternate measurement of the thermocouple with a hand-held type-K indicator showed the temperature to be stable at about 3100°F. The primary recording channel was judged to be malfunctioning so the temperature indicated by the hand-held meter was recorded as data.

Later, it was noted that type K thermocouples melt at about 2606°F (494°F lower than the indicated temperature). It was suggested that the thermocouple be rechecked in-place to assure that it was actually type K. The experienced field crew had previously identified the material as type K and now reconfirmed it as type K by using a conventional check that depends on the magnetic nature of the negative Alumel leg; it attracted a small magnet. The thermocouple was judged to be substantially out of calibration. It was replaced. The "defective" thermocouple was returned to the laboratory for examination. There, it was immediately identified as a normal type E (chromel-constantan) thermocouple with a non-magnetic negative and positive leg. If read in the field with a type-E indicator it should have properly indicated a temperature of 1593°F in place. The extra thermocouple was a calibrated, but unlabeled, spare left-over from a previous experiment where only type E material was used.

Several of "Murphy's assistants" had erred in a chain of "goofs".

1. SUPPLIERS. The "faulty" assembly had been ordered without specifically requesting permanent labeling. The manufacturer had supplied without permanent tagging. The crew from the previous experiment had not labeled the left-over.

2. FIELD INSTALLERS. The identification of the material type had been by a conventional test improperly conducted.

3. INDICATOR MANUFACTURER. The designer of the hand held thermocouple meter had unwisely allowed the indicator to report values beyond the valid range of the sensor.

4. RECORDING CREW. The magnetic check made by the field crew was a definite test that failed because it was not correctly performed. The bare thermocouple wires had been left connected to apparently nonmagnetic brass terminal posts of the junction cannister. Unfortunately, the screw on the positive terminal was non-magnetic plated brass but the screw on the negative was magnetic plated steel. The magnet had responded to the screw, not to the negative wire element!

Note that in this instance the measurement error was noticed only because the temperature indication went off-scale. If the hand held meter had been the primary recorder or if a less sensitive type K thermocouple had been substituted for a more sensitive type E the error might have gone unrecognized.

"Murphy" had struck in several ways to thwart the measurement but serendipity had eventually triumphed. "Murphy" does not always win, but don't rely on good luck in measurement.

15. The nature of my work requires that I calibrate a variety of high pressure transducers and gages at pressures up to 100,000 psi. This is accomplished by using a hydraulic pump to generate the pressure, which is then measured by means of a manganin wire pressure transducer and resistance measuring bridge. As anyone who is familiar with this type of system knows it is not void of pressure leaks and anything that can leak, will.

However, once these were overcome another problem surfaced. The system seemed to behave with a noticeable amount of sluggishness. The measurement equipment was slow to respond at pressures above 70-75,000 psi. This sluggishness was an indication that the hydraulic fluid in the system was breaking down and solidifying at these high pressures. The fluid we were using was recommended by the manufacturer of the pump and was supposed to be capable of operating at these pressures. We contacted the manufacturer and they admitted this to be a problem, but said it could be remedied by diluting the fluid with kerosene. We tried this and the problem was immediately corrected.

We continued operating with the mixture of oil and kerosene for approximately two (2) months when we began having problems with our manganin wire transducer. It appeared to have shifted calibration and was no longer producing the expected results. After several hours of testing on our part, we decided that the transducer was defective and returned it to the manufacturer for repair.

We were later informed by the manufacturer that the pressure fluid we used during testing is in direct contact with the manganin wire and that acid present in the kerosene corroded the manganin wire causing severe resistive changes. This rendered the transducer useless and a new one had to be purchased and calibrated causing a temporary suspension (approximately six (6) months) of our high pressure calibrations. This is an example of how fixing one problem can result in a more serious and costly problem which was totally unforseen.

16. Low pressure variable reluctance transducers are constructed so that there is close spacing between the diaphragm and its support. This is necessary in order to make the measurement accurate and to protect the diaphragm against overpressure. In a particular group of VR transducers tested in our lab, calibrations were not repeatable. The full scale measurements were consistently low. The calibrations were repeated many times with no significant improvement in the results. Finally, out of desperation, low heat and dry nitrogen were applied to the transducer. The calibration became repeatable and the full scale readings could be obtained. Apparently, surface tension due to moisture between the diaphragm and the support caused the diaphragm to deflect and effect the measurement.

17. The Grumman Calibration Laboratory calibrates all bi-directional differential pressure transducers from full positive, through zero, to full negative differential pressure. This we thought was a standard procedure throughout the industry. Unfortunately we have discovered, the hard way, that some manufacturers calibrate their transducers over the positive half of the range only.

Least square linear curve fits of the data over the full range often yield rejection; whereas, the same data applied to the positive half might meet the required non-linearity specification.

We have since clarified our specification requirements but, unfortunately, still receive many units with manufacturers' data inadequately verifying them.

18. Establishing required performance for a new type of blast pressure transducer, the user specified a sensitivity figure. The manufacturer accepted the figure as producible, and a new generation of blast pressure transducers was developed.

Several years later, and after 2 years of struggling to use the transducer in applications where higher sensitivity would surely have enabled successful data acquisition, the user remarked about the situation to the manufacturer. The casual reply consisted of words to the effect that additional sensitivity was no problem. In fact, the original transducer could have been produced with three times the specified figure!

Not really a "boo-boo," I guess, and possibly not covered by any of Murphy's Laws (if that's possible)---but certainly a classic "you didn't tell me--you didn't ask me" situation.

Moral: Users and manufacturers must thoroughly communicate needs, desires, and capabilities to optimize hardware for the intended purpose.

19. A pressure transducer in the skin of a missile container was intended to measure the change in pressure between the inside of the submarine and the sea outside when the container was ejected. Data from the experiments showed unexpectedly large values, several times higher than calculated. Much head scratching followed by step function pressure testing with gaseous media seemed to eliminate most plausible explanation for the observed discrepancies.

Finally, a thermal transient test was performed by rapidly dipping the sensing end of the transducer (normally at room temperature) into a large bowl of water at about 40°F. This produced about the same magnitude and direction of pressure transducer output as the submarine test. Thus what had been taken as a measured change in pressure was really the product of a thermal transient.

20. The measurement of the pressure-time history between blades in a gas turbine compressor required a flush-mounted quartz pressure transducer mounted on the shroud of the compressor. The strange outputs from the transducer prompted us to mount a second one in a blind hole (not going all the way through to the inside of the shroud, but vented to atmosphere to prevent pressure build-up in the cavity). That check channel showed us that the measuring channel was acting more like an accelerometer than pressure transducer at several points on the compressor map being generated by the tests. Subsequent tests had such a check channel installed to begin with.

21. In the design of liquid level sensor probes, the suggestion was made to put a cage (a shield made of mesh) around the probe tip to protect the probe from physical damage. It seemed like a very good idea and was subsequently implemented. Problems began to occur in the operation of the probe in the nature of false liquid

detection and slow response time. Further investigation showed that liquid was bridging the air gap between the cage and the probe which was producing the false indications. The probe was redesigned by removing the cage and strengthening the tip design.

LESSON: An idea to improve the design of a product must be carefully considered to ensure all implications have been taken into account.

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