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WRDC-TR-90-2064
MTI 89TR19

COMPUTER-ASSISTED STRAIN-GAGE MONITORING AND DATA REDUCTION SYSTEM

AD-A226 894

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Latham, New York 12110

August 1990

Final Report for Period July 1985 to May 1990

Approved for public release, distribution is unlimited.

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SEP 27 1990
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Prepared for

AERO PROPULSION AND POWER LABORATORY
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90 09 26 140

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION
Unclassified

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
Approved for public release;
distribution is unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S)
89TR19

5. MONITORING ORGANIZATION REPORT NUMBER(S)
WRDC-TR-90-2064

6a. NAME OF PERFORMING ORGANIZATION
Mechanical Technology Inc.

6b. OFFICE SYMBOL (If applicable)

7a. NAME OF MONITORING ORGANIZATION
Wright Research and Development Center
Aero Propulsion & Power Laboratory (WRDC/POTX)

6c. ADDRESS (City, State, and ZIP Code)
968 Albany-Shaker Road
Latham, New York 12110

7b. ADDRESS (City, State, and ZIP Code)
Wright-Patterson Air Force Base,
OH 45433-6563

8a. NAME OF FUNDING / SPONSORING ORGANIZATION

8b. OFFICE SYMBOL (If applicable)

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
F33615-85-C-2503

8c. ADDRESS (City, State, and ZIP Code)

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
62203F	3066	17	74

11. TITLE (Include Security Classification)
Computer-Assisted Strain Gage Monitoring and Data Reduction System

12. PERSONAL AUTHOR(S)
L. Lagace, P. Hayes

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 7/85 TO 5/90	August 1990	58

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Compressor Testing
Strain Gages
FFT Processing
Computer Monitoring
FFT Processing
Data Reduction
Alarm Limits
(KR

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The objective of this program was to design and build a computer-based strain gage monitoring system (SGMS) for the Wright-Patterson Air Force Base (WPAFB) using state-of-the-art electronics to assist in real-time monitoring and subsequent reduction and analysis of compressor analog data. During aerodynamic and aeromechanical testing at the WPAFB Compressor Research Facility (CRF), the SGMS monitors blade and vane stress level data provided by sensors attached to a turbine engine compressor. The system monitors vibratory responses, provides ample warning of compressor component failure, and assists test engineers in data analysis. On-line data are presented to the test engineers via a graphics display terminal and printed reports.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☒ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
Unclassified

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DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted.
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SECURITY CLASSIFICATION OF THIS PAGE
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PREFACE

The work reported herein was conducted by Mechanical Technology Incorporated (MTI) for the Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson Air Force Base, Dayton, Ohio, under Contract F33615-85-C-2503, "Computer-Assisted Strain Gage Monitoring and Data Reduction System." The technical monitor for the Air Force was Mr. John Datko. The MTI program manager was Mr. Lawrence Lagace.

The preliminary strain gage monitoring system (SGMS) architecture was developed by Mr. John Frarey. Mr. Frarey remained a technical advisor throughout the contract, providing additional guidance relating to data acquisition of the monitored signals and the subsequent process of converting data from the time domain into the frequency domain.

Mr. Donald Welch directed the SGMS electronics development and personally designed a major portion of the electronics. Mr. Peter Hayes directed SGMS software development and personally designed a major portion of the software. Additionally, once the SGMS passed the prototype evaluation phase, Mr. Hayes assumed the principal responsibility for successful completion of full system implementation and for system documentation.

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1.0 INTRODUCTION

This document, prepared by Mechanical Technology Incorporated, presents the final report for Wright-Patterson Air Force Base (WPAFB) under contract No. F33615-85-C-2503, "Computer-Assisted Strain Gage Monitoring and Data Reduction System." Section 2.0 presents an overview of the program, outlining events and comparing the projected program schedule to the actual schedule. Section 3.0 contains background information on the Compressor Research Facility (CRF), where the Strain Gage Monitoring System (SGMS) is installed, including information on related study contracts that influenced the design of the MTI system.

Section 4.0 of this report contains a detailed discussion of SGMS hardware, software, and system operation, with system design issues outlined in Section 5.0. Section 6.0 describes both implemented and proposed system enhancements. Section 7.0 presents the program results, including both the successful and the difficult aspects of the program. Finally, Section 8.0 contains program conclusions and recommendations.

2.0 PROGRAM OVERVIEW

MTI began work on this contract in July 1985 with a 4-phase, 36-month schedule, shown in Fig. 1. The SGMS was installed and tested at WPAFB in June 1989, for a total elapsed time of 48 months. Fig. 2 compares the projected program schedule to the actual schedule. The following paragraphs summarize program events, accomplishments, and causes for the schedule overrun.

In Phase I, MTI delineated the SGMS hardware and software design. All functional requirements were clearly defined, risk assessments were evaluated, and critical design trade-offs were selected.

Following Phase I design approval, MTI began work on Phase II by initiating the detail design, fabrication, and testing of a 36-channel prototype of the SGMS. Hardware design progressed from the block-diagram level to actual circuit design, printed circuit board design, and prototype fabrication. Software development proceeded from the system module design to actual software code generation. Phase II activity focused on

- Including a variable, full-scale frequency range for increasing frequency resolution in the alarm sensing module
- Modifying the system design to accommodate future addition of more extensive time domain monitoring hardware
- Providing high-speed performance of the four-channel spectrum analyzer function, since MTI's approach for implementing the function using the host computer was found to be unsatisfactory due to slow speed performance of the computer graphics processor
- Developing diagnostic programs to assist in debugging the hardware. These programs were refined and eventually used in the test plan to prove system performance. The programs were also suitable for testing and troubleshooting the hardware during final test and installation.

As shown in Fig. 2, Phase II required 9 months longer than originally projected. From April through August 1987, MTI developed a test plan and resolved several system-level problems. In September 1987, the 36-channel prototype was delivered to WPAFB and installed in the control room of the CRF. MTI and Air Force personnel spent one month evaluating the performance of the prototype.

In Phase III, SGMS hardware and software were updated and modified as a result of Phase II testing. Detailed technical reviews of design progress revealed the benefit of additional software features and a performance upgrade to the host computer. The overall schedule was extended with concurrence of the Air Force.

During Phase IV, MTI and the Air Force agreed to reduce the number of SGMS data channels from 144 to 108 due to financial constraints. The balance of the 108 channels was fabricated, tested, and installed in the CRF. MTI uncovered an unusually high failure rate with an FFT processor circuit board, one of the major purchased subassemblies. MTI worked with the vendor's engineering and quality assurance staff and resolved this problem.

SGMS testing took place from August 1988 to March 1989, which was longer than anticipated. However, several low-level problems were resolved using long-duration, unattended tests. Since the system was unattended during these tests, the level of effort remained close to the original budget. The test plan was refined during Phase IV testing

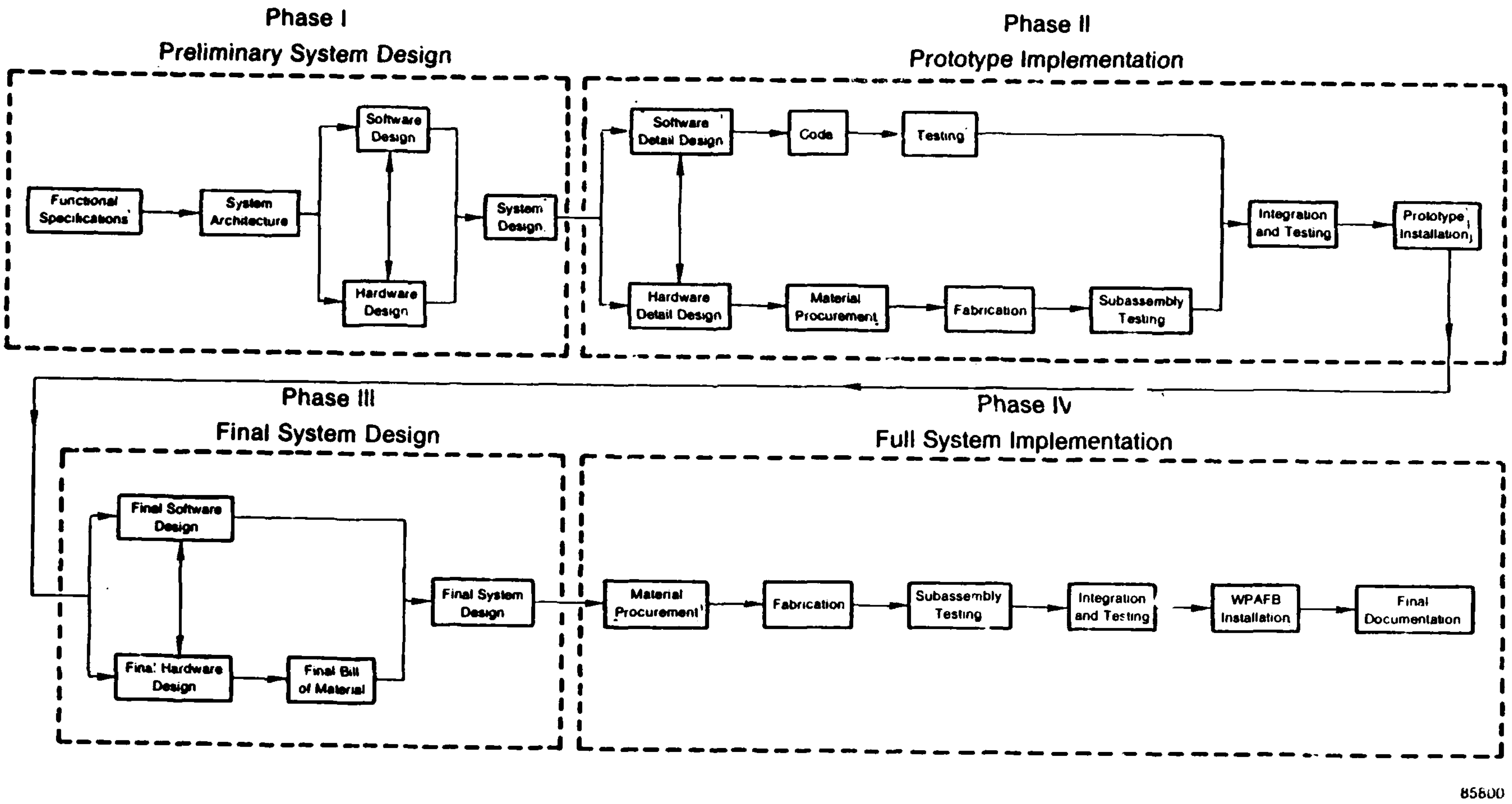

Figure 1. Program overview.

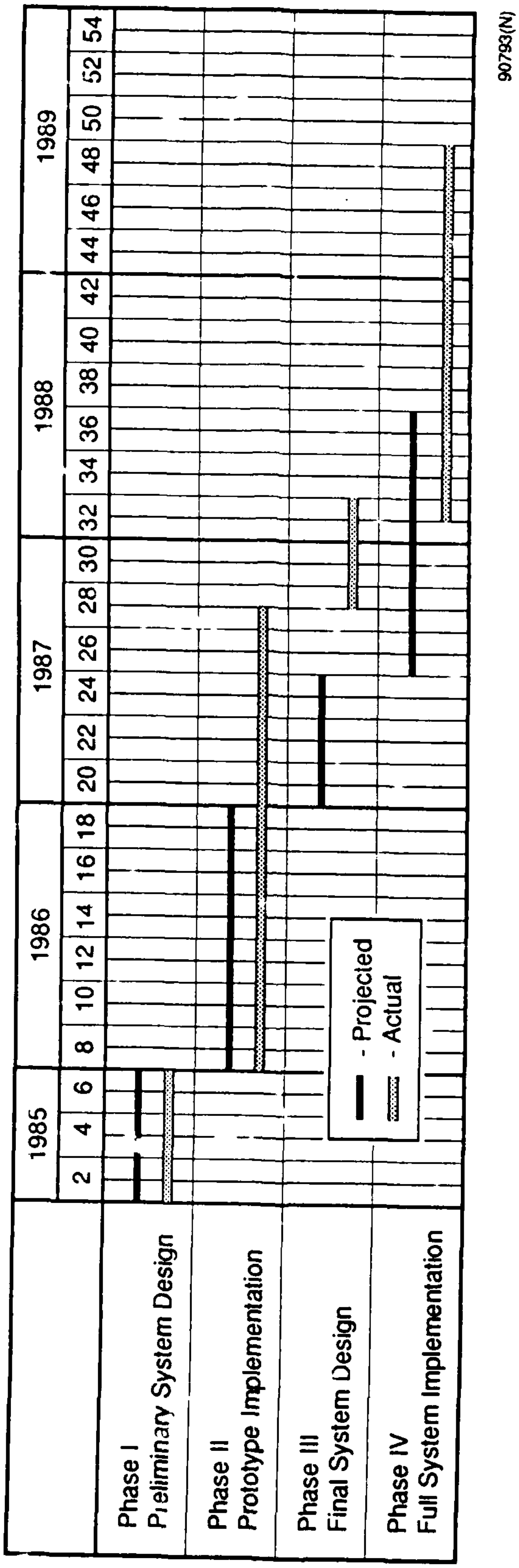

Figure 2. Comparison of projected vs. actual program schedule.

and the final version of the plan was issued in February 1989. An extensive check-off form was used to record the results of the test plan. A multichannel tape recording provided by CRF was also used to examine the system response to typical conditions at the facility.

Final installation of the SGMS in the CRF occurred in April 1989. The test plan was performed again to verify that the SGMS suffered no damage during shipment. This testing took place from April to early June 1989. Unfortunately, no live data were available from an active compressor, and testing was conducted with data simulated with test equipment. As of June 1989, SGMS installation was complete, with the extensive deliverable system documentation concluded in February 1990.

3.0 BACKGROUND

Aeronautical progress in the United States is paced by propulsion system technology. As propulsion systems become more sophisticated, test facilities for evaluating engines and engine components must do a better job of simulating actual flight conditions to provide realistic test environments.

In the 1950s, engines consisted of relatively simple turbojets with fixed inlets and exhaust. Engine throttle was simple and controlled only fuel flow to the engine. Engine and inlet testing were equally straightforward. The inlet could be tested separately from the engine in a conventional wind tunnel. The engine could be directly connected to the test cell's air supply for testing under more or less static conditions, i.e., setting a specified altitude and speed and taking engine performance data; setting different conditions and taking more data, etc.

Propulsion systems developed for operational aircraft in the 1960s and 1970s became more complex, with augmented turbofans, multidimensional power control systems, variable inlets and exits, and other features. Some systems (e.g., the F-111, with a TF-30 engine) experienced operability problems that could have been identified sooner with a better simulation of true mission environment.

Emerging engine technologies, such as thrust vector control and inflight reverse thrusts for highly maneuverable tactical aircraft, are further increasing the complexity of propulsion systems. Today's propulsion systems are more highly integrated with the aircraft and interact to a greater degree with other aircraft systems. For example, aircraft flight altitude may be trimmed for minimum drag by varying the direction of the thrust vectors. Similarly, by varying engine thrusts while holding airflow constant, the excess drag produced by inlet airflow spillage can be minimized. Because the aircraft aerodynamics and propulsion system performance are so intimately related, and because the systems are so independent, the entire propulsion system must be tested together in a true mission environment.

As engine design complexity increases, so does the complexity of individual components within the engine itself, e.g., the compressor stage. Major system components must be tested individually in a simulated mission environment prior to full engine testing. However, as component complexity has been increasing, increasing demands have been placed on the capability of the test facility. As shown in TABLE 1, the number of channels used during a specific test continues to increase. Therefore, the transition from manual data review and interpretation to a more automated approach is necessary.

3.1 Compressor Research Facility

To accommodate the increasing complexity of engine testing, the Air Force developed an advanced CRF at WPAFB. The CRF was commissioned as fully operational in 1984.

The CRF provides a national capability for performing full-scale jet engine compressor research under realistic steady-state and transient conditions. This facility supports the conduct of compressor research in the areas of:

- Blade change effects
- Increased pressure ratio
- Efficiency improvement
- Stator optimization
- Transient effects.

TABLE 1. Illustration of Increasing Requirements for Monitoring Data Channels on Increasingly Complex Compressors.

8-STAGE J-85 COMPRESSOR

Number of Channels	Required Measurements
30	Strain Gages (Dynamic)
1	High-Response Pressure Transducer (Surge Detection)
5	Miscellaneous Signals (Speed, Acoustic, etc.)
Total of 36 Channels	

2-STAGE GENERAL ELECTRIC HIGH TIP SPEED COMPRESSOR

Number of Channels	Required Measurements
35	Strain Gages (Dynamic)
21	High-Response Pressure Transducers (Define Tip Shock)
1	Surge Detection
5	Light Probes (Tip Deflection-Monitor for Flutter)
10	Miscellaneous Channels
Total of 72 Channels	

2-STAGE GENERAL ELECTRIC FAN

Number of Channels	Required Measurements
40	Strain Gages (Dynamic)
65	High-Response Pressure Transducers (Define Unsteady Aerodynamic Environment
3	Surge Detection Probes
4	Hot-Film Sensors
10	Light Probes
10	Miscellaneous Channels
4	Static Strain Gages
Total of 136 Channels	

10-STAGE PRATT & WHITNEY F-100 CORE COMPRESSOR

Number of Channels	Required Measurements
64	Strain Gages (Dynamic)
52	High-Response Pressure Transducers
20	Miscellaneous Signals
Total of 136 Channels	

In addition to the research described above, development work has been performed at the CRF to obtain performance maps, to remedy operational problems, and to determine aerodynamic/mechanical interactions. Such capabilities allow the CRF to fully define compressor performance and thus accommodate:

- Improvements in the state of the art of gas turbine compressors
- Advances in compressor design techniques
- Assessment of system performance and operability
- Assessment of engine development cost, durability, and reliability.

TABLE 2 contains a listing of the CRF's characteristics. TABLE 3 contains both current and planned capabilities of the CRF data acquisition system.

3.1.1 Compressor Testing at the CRF

One key element of compressor research involves detailed analysis of the vibration characteristics of various components within the compressor. These vibrations may originate from interactive forces or may be self-excited:

Forced Vibration

- Nonresonant vibration
- Resonant vibration
- Rotor blade tip rub
- Unlatched or misrigged vane
- Separated flow vibration
- Rotating stall
- Pulse-type stall and surge

Self-excited Vibration

- Stall flutter
- Supersonic shock flutter
- Choke flutter.

At the CRF, vibration studies of gas turbine compressors are facilitated by installing strain gages on the compressor blades, vanes, and instrumentation probes. Prior to testing, the strain gage maximum allowable dynamic stress limits are determined. These limits are based on knowledge of the blade and vane resonant frequencies, strain gage location with respect to critical locations (the point where a high-cycle fatigue crack would initiate when the component is dynamically overstressed), gage orientation, and maximum allowable stress limits for the particular blade and vane materials.

During on-line monitoring of all signals, amplitude limits should be established for each mode of blade vibration and an alarm should trigger when the amplitude limit is exceeded. This is only possible in the time domain if a single mode is present. The most straightforward approach to monitoring several modes is to transform time domain data to the frequency domain using a fast Fourier transform (FFT). In the frequency domain, amplitude limits can be established that may also vary with frequency, such as shown in Fig. 3. Since different vibration modes occur at different frequencies, it is possible in the frequency domain to set different limits for many modes.

In addition to providing on-line vibration monitoring, safety precautions must exist to avoid catastrophic failure during compressor performance tests. During testing it is feasible to create a condition where a blade suddenly begins to vibrate excessively. If the vibration amplitude is sufficiently high, the blade will break and potentially travel

TABLE 2. Facility Characteristics.

Feature	Capability
Speed/Power	3,000 to 16,000 rpm at 30,000 hp 16,000 to 30,000 rpm at 15,000 hp
Airflow Rate	8 to 500 lb/sec
Inlet Pressure	2 psia
Discharge Temperature Range	Up to 1490°F
Test Chamber Length/Diameter	65 ft/20 ft
Flow Conditioning Barrel Length/Diameter	20 ft/10 ft
Acceleration Rate	10%/sec

TABLE 3. Current and Future Capabilities of the CRF Data Acquisition System.

Feature	Current	Future
Digital Signals	558 Channels	2000 Channels
Sample and Hold	100 Channels	256 Channels
Sampling Rate	100 kHz	416 kHz
Analog Signals	300 Channels	400 Channels
Frequency Response	20 kHz	20 to 100 kHz

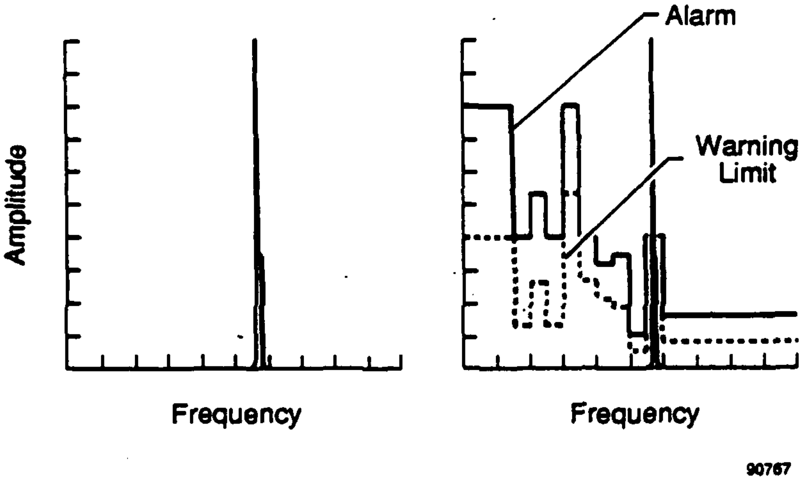

Figure 3. Limit monitoring in the frequency domain.

downstream. The broken blade could break additional blades in the same row and/or blades on subsequent stages. In a worst-case scenario, one broken blade could strip an entire compressor. The resultant debris would not only damage the compressor, but also the strain gage instrumentation, the anemometers, the pressure transducers, and other associated instrumentation. The cost of such a failure in terms of the compressor, the instrumentation, and lost test time would be substantial.

3.1.2 CRF Monitoring Capabilities Prior to SGMS

Prior to performance of this contract, monitoring of the strain gages was performed at the CRF by visually monitoring 144 oscilloscopes and manually switching each input channel to one of several spectrum analyzers for frequency analysis. The ability to monitor in the frequency domain was limited by the number of available spectrum analyzers. Initially, four single-channel spectrum analyzers were available. When a significant event with an out-of-limit condition occurred, there was no assurance that such an occurrence could be visually detected. Subsequent logging of out-of-limit conditions was performed manually. In order to ensure that a test was conducted safely, facility and test compressor conditions were changed slowly so that each channel could be adequately monitored.

During the actual conduct of a test, all 144 channels of analog data were also recorded on a multichannel tape recorder. Post-processing and reduction of this data was time consuming, manpower intensive, and cumbersome, since all were performed manually. Also, to ensure that out-of-limit conditions were not missed and were correctly identified, recorded data were repeatedly played back so that each channel could be thoroughly checked.

3.2 Related Prior Research

At the outset of this contract, MTI reviewed two study contracts performed by the United Technologies Research Center (UTRC) and General Electric Company (GE) for the Aeropropulsion Laboratory dealing with the interpretation of strain gage signals originating from jet engine testing.* MTI was particularly attracted to the suggested front-end processing approach posed by UTRC. As shown in Fig. 4, this implementation suggests a series of parallel processors. The front-end preprocessing would be performed by an array of processors, a computer, or special hardware. The preprocessing involved acquiring both strain-gage and speed-buffered data, scaling these data for conversion to engineering units, and calculating global features, i.e., stress, histogram, and FFT. The classifier computer would then combine the calculated features along with spacial and temporal information (i.e., compressor-specific information and certain run-time parameters) to predict the active aerodynamic phenomena.

This approach had a striking similarity to the hardware implementation proposed by MTI. Items in Fig. 4 surrounded by short-dash lines are similar to functions already designed into the MTI equipment. Surrounded by heavy-dash lines in the figure, the classifier central processing unit (CPU), required to perform the histogram and summation of the histogram and stress and FFT computation, was the only major missing

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*"Conceptual Development of Strain Gage Signal Interpretation System for Jet Engine Applications," UTRC, October 1985; "Strain Gage Signal Interpretation," (GE), February 1986.

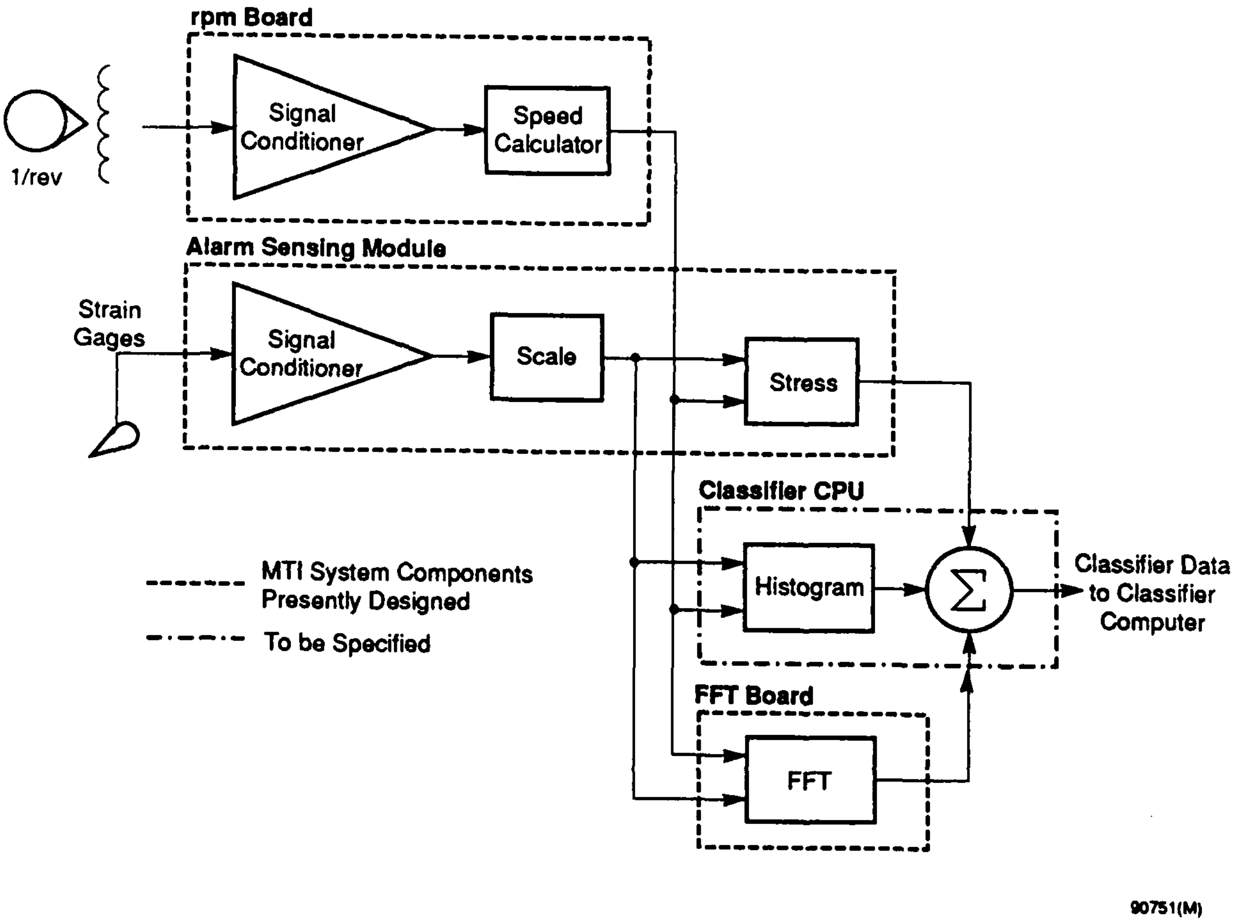


Figure 4. UTRC front-end processing block diagram for one strain gage channel.

element. In the UTRC design, the classifier CPU computes pseudo-probability calculations. These calculations combine time and frequency global parameters to characterize and recognize aeromechanical phenomena.

In addition to reviewing the study contracts, MTI visited the Aeropropulsion Systems Test Facility (ASTF) at Arnold Engineering Development Center (AEDC), Tennessee. The ASTF is designed to test aircraft propulsion systems in true mission environments without leaving the ground. Although the specific needs of the CRF and the ASTF are quite different, AEDC was interested in potential future applications of the CRF-developed system. With this interest in mind, AEDC participated as a technical monitor in the execution of this contract.

The review of the funded study contracts and input from AEDC prompted MTI and the Air Force to consider future expansion capability of the SGMS to incorporate monitoring techniques not addressed by the current contract requirements. Design changes included allowing system space in the hardware configuration to accommodate an additional classifier CPU for each pair of data channels. Additionally, the system architecture would need to accommodate a classifier computer. The Air Force recognized the value of the potential system expansion and granted a minor change to the contract to allow MTI to provide space accommodation in the system hardware for the necessary classifiers and to ensure that the system power supplies were capable of accommodating these additional CPUs. MTI's overall system, incorporating these design changes, is outlined in Section 4.0, with details of system expansion provided in Section 6.0.

4.0 SYSTEM CONFIGURATION AND OPERATION

The objective of this program was to design and build a computer-based SGMS using state-of-the-art electronics to assist in real-time monitoring and subsequent reduction and analysis of compressor analog data. During aerodynamic and aeromechanical testing at the CRF, the SGMS monitors blade and vane stress level data provided by sensors attached to a turbine engine compressor. The system monitors vibratory responses, provides ample warning of compressor component failure, and assists test engineers in data analysis. On-line data are presented to test engineers via a graphics display terminal and printed reports.

Fig. 5 illustrates the overall system configuration, which consists of a graphics display terminal and keyboard, a Versatec video plotter and a dot matrix printer, an alarm display, and four electronics cabinets. One cabinet houses the host computer and data reduction unit, and the remaining cabinets house the alarm sensing modules. Fig. 6 presents a functional diagram of the key system components and illustrates the interfaces between the CRF equipment, the host computer, the data reduction unit, and the alarm sensing modules. Details on these components and their operation are presented in the following subsections.

4.1 CRF Equipment

The CRF equipment that interfaces with the SGMS includes 144 sensors and a multichannel tape recorder. The sensors are a combination of dynamic strain gages, static strain gages, accelerometers, high-response pressure transducers, high-response thermocouples, and other miscellaneous sensor types. Signals from these sensors are routed through the CRF analog signal conditioners, patch panel, and oscilloscopes. Of the 144 channels, any one of 108 can be routed to the SGMS, since the system does not restrict the mix of sensor types. T connections at the oscilloscope input jacks serve as signal input points for the system. The CRF equipment also includes a tachometer and a time code generator that provide input to the SGMS.

In addition to direct sensor input from the oscilloscopes, some or all sensor signals may be obtained from the CRF multichannel tape recorder. When the SGMS is actively monitoring a compressor under test, the tape recorder records the data, which can then be input to the system for data analysis during postprocessing. In this case, CRF cabling is adjusted so that the SGMS takes the played-back data as input. The SGMS does not distinguish whether information is coming from the sensors themselves or the tape recorder.

4.2 Host Computer

The SGMS architecture uses distributed processing to meet the requirement for real-time monitoring. A high-performance MASSCOMP Model MC-5500 serves as the host computer and provides a sophisticated user interface that reduces the time and manpower required to perform data reduction and analysis. As the host computer, the MASSCOMP performs several functions:

- Supports all system configuration and control via a menu-driven interface
- Interfaces with and monitors the alarm sensing modules
- Provides for and controls the display of warnings and alarms. Archives overlimit data on disk.

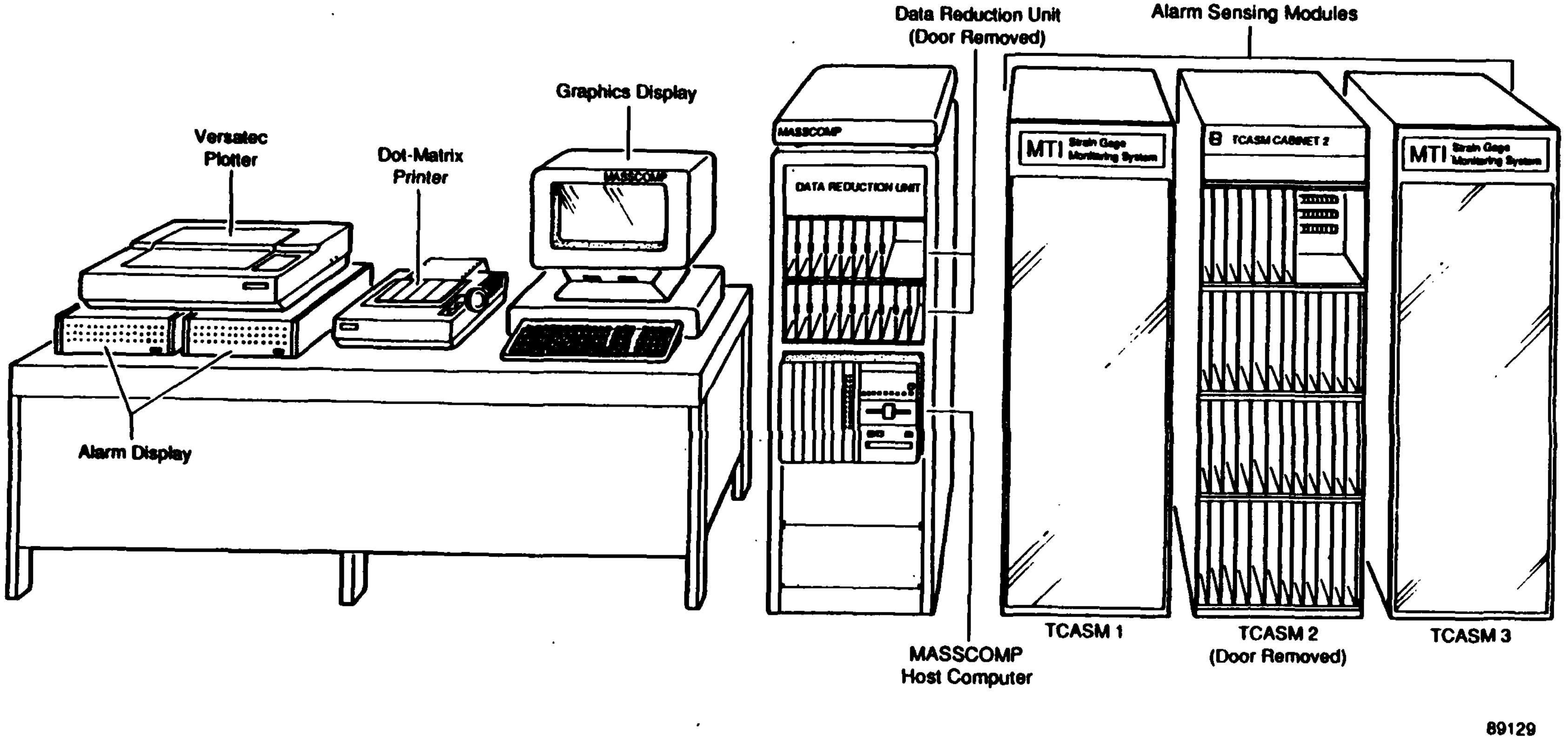


Figure 5. System configuration.

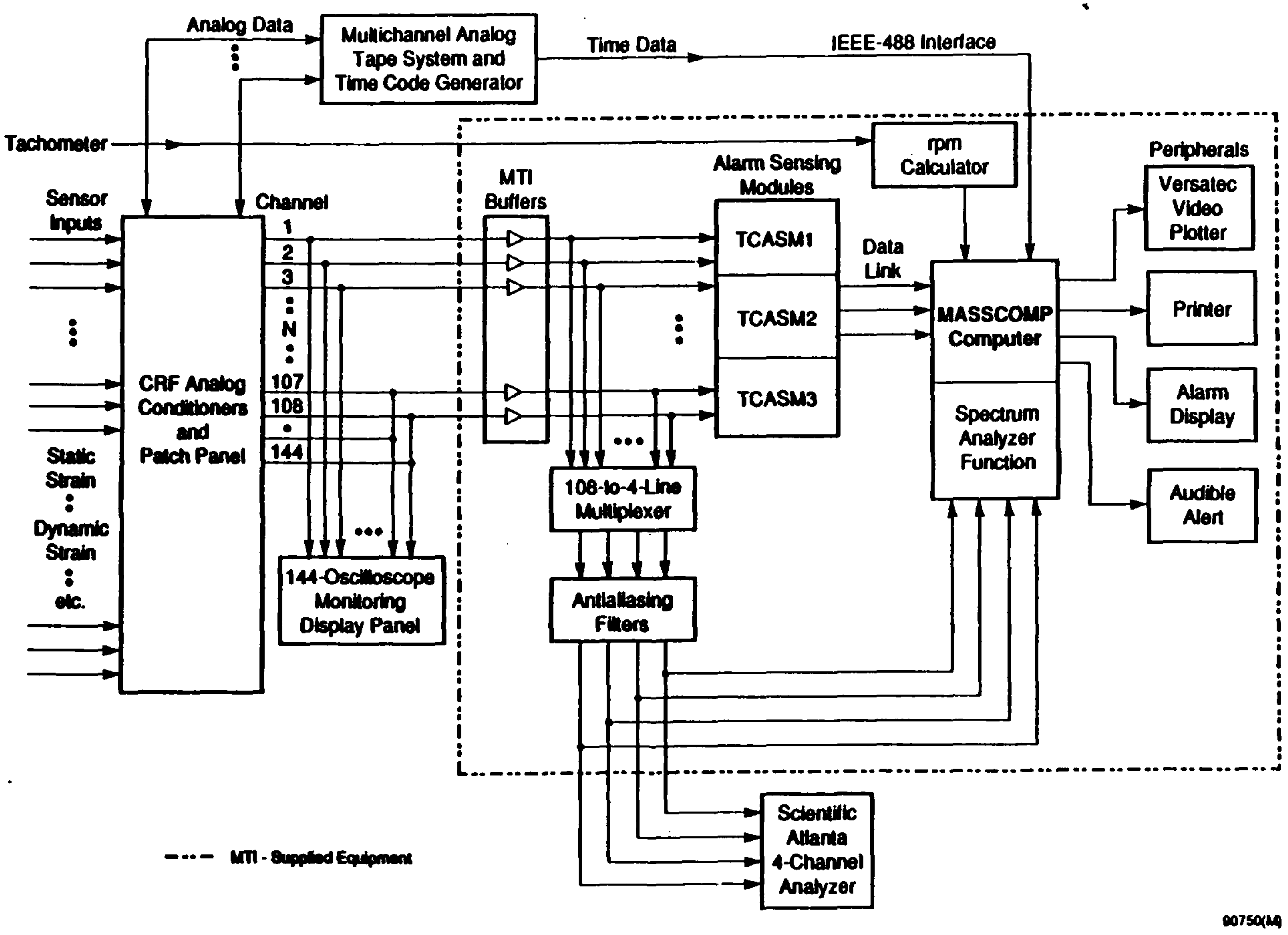


Figure 6. Key components and functions of the SGMS.

- Controls data acquisition of the spectrum analyzer function and computes and displays the frequency spectrum of four selected channels. Integral to the MASSCOMP, a data acquisition processor gathers data for this function.
- Controls all system peripherals.

The MASSCOMP consists of a Motorola processor with a 4-megabyte memory and a UNIX™-based operating system. A MULTIBUS™ architecture allows for parallel real-time data acquisition, computation, and graphics display. Given this powerful architecture, the MASSCOMP can perform four-channel spectrum analysis and monitor the alarm sensing modules simultaneously. A separate graphics processor, software libraries, and a 19-in. display terminal allow for superior graphics presentation without burdening the main processor. TABLE 4 lists the items included with the MASSCOMP.

The MASSCOMP supports all system configuration and control via a menu-driven interface that provides the user with an interactive list of options for system operation. Fig. 7 summarizes the system menus that allow the user to control all aspects of the SGMS. In order to correctly interpret CRF data, the user inputs sensor characteristics and connection information to the system configuration files, which include the following:

- Sensor Description File — amplitude units, gain, sensitivity, offset and description for each sensor
- Sensor-to-Channel Assignment — sensor number and corresponding channel number
- Engine Speed Range Configuration — engine speed ranges for each of five possible sets of overlimit levels
- Cluster Controller (Cluster CPUs) Description — maximum frequency for analysis and 16 frequency ranges for each alarm sensing module
- Warning and Alarm Levels — warning and alarm levels for each channel and each specified engine speed range and associated time domain filter type.

To accommodate the interface to and monitoring of the alarm sensing modules, the MASSCOMP includes the cluster CPUs that consist of three Intel microcomputers. Each of these microcomputers communicates with one of the alarm sensing modules over a high-speed data link. The cluster CPUs send system configuration data to the alarm sensing modules and gather overlimit data as they accumulate. They also send overlimit data to the SGMS software running on the MASSCOMP, which then lights the alarm display and archives the overlimit data on disk. In this way, the MASSCOMP controls the display of and archives all warnings and alarms. Each data point logged includes the channel number, amplitude, and frequency of the overlimit conditions. Specifications for the cluster CPUs are presented on TABLE 5.

Also integral to the MASSCOMP, a data acquisition processor allows the host computer to perform many of its interface requirements. The data acquisition processor contains parallel I/O cards that control the alarm display and the circuit boards in the data reduction unit that support the spectrum analyzer function. It includes the sample-and-hold and A/D converter boards that digitize data for spectrum analysis and subsequent display on the graphics terminal. The data acquisition processor also contains the General Purpose Interface Bus (GPIB) IEEE-488 that interfaces the MASSCOMP to the time code translator. The time code translator provides the time to the host computer and is set by taking the time from a channel of the CRF tape recorder or by taking the current time of day from the CRF time code generator. In either case, the SGMS

TABLE 4. Deliverable Items Included with MASSCOMP Host Computer.

DESCRIPTION
70-in. Cabinet
15-Slot CPU Enclosure with 5 Empty Slots
Motorola 68020 CPU with 3 Serial Ports
4-Megabyte Memory
RTU UNIX-Based Real-Time Operating System
Set of Floppies Containing Stand-Alone Utilities
ANSI-Validated C and FORTRAN 77 languages
Lighting Floating Point Coprocessor
5-1/4-in. Floppy Disk
71-Megabyte Formatted 5-1/4-in. Hard Drive
19-in. Color Graphics Display Terminal with 6 Planes, 832 by 600 Pixels
9-Slot Data Acquisition Processor with Programmable Sampling Clock
12-Bit, 16-Channel, 1-MHz A/D Converter
16-Channel Sample-and-Hold Function
Two 16-Line, 200-kHz Parallel I/O Boards
IEEE-488 Interface
Cluster CPUs (Three Intel 8086 Microcomputers)
Versatec MULTIBUS 115 Interface Board
A Complete Set of MASSCOMP and Other Vendor Manuals
MTI Documentation • User's Manual • Operation and Maintenance Manual • Programmer's Reference Manual • Test Plan • MTI Engineering Drawings

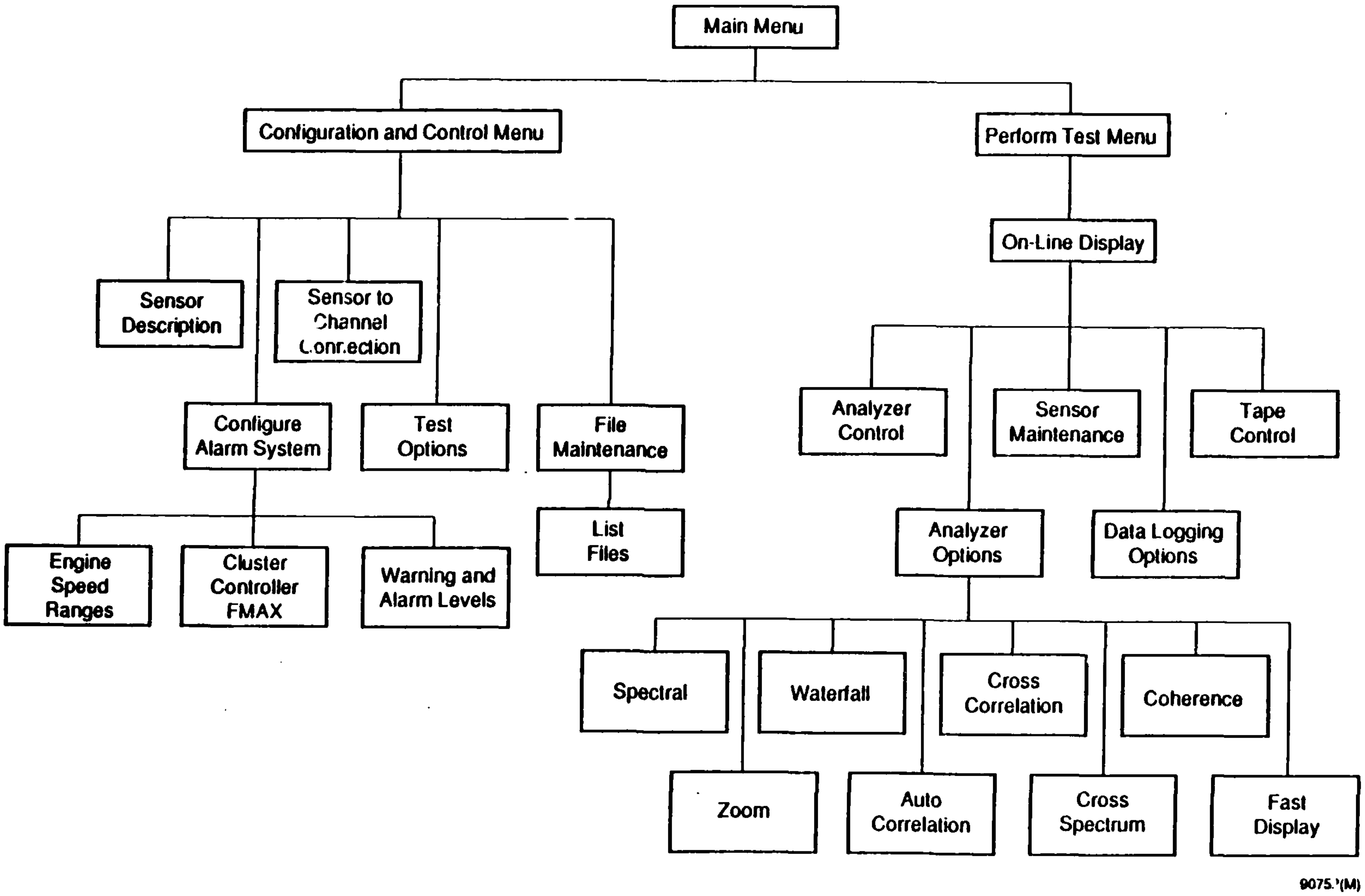


Figure 7. Overview of system menus.

TABLE 5. Specifications for Cluster CPUs.

Item	Specification Requirement
Board Type	Intel SBC 86/30
System Clock	8 MHz
CPU	Intel 8086
RAM	128 kilobytes
EPROM	Two 2764 PROMs; 16 kilobytes each
Serial I/O Port	8251A
PIO Lines	24 Lines Using 8255
On-Board Timer and Interrupt Controller	8259A

accepts this time and displays it on the graphics terminal. If the time code translator is not present, the SGMS uses its own local time. The clocks used by the alarm sensing modules for sampling also originate from a clock card in the data acquisition processor.

In addition to the above components, the MASSCOMP supports the following peripherals:

- Dot-matrix printer — used for text reports of data logged during warning and alarm conditions and for printing system configuration files. Figs. 8 and 9 present examples of typical hard-copy output.
- 1200-baud modem — installed to facilitate telephone line access to the MASSCOMP for maintenance by the vendor during the host computer's warranty period, which occurred while the SGMS was being configured at MTI. Although the installed SGMS is not currently connected to a telephone line, this connection can be added easily if the host computer requires vendor maintenance.
- Versatec video plotter — prints any screen display of the graphics terminal. This feature is particularly useful for quick reproduction of spectral plots (see Fig. 10).
- Alarm display — enables the user to see at a glance which channels are in alarm or warning. An arrangement of green, yellow, and red lights corresponds to the layout of the CRF oscilloscopes, thus providing visual cues for the user.
- Audible alert — signals the user of a warning or alarm occurrence.

TABLE 6 outlines the specifications for the host computer peripherals.

4.3 Data Reduction Unit

The data reduction unit contains those circuit boards that support the MASSCOMP in performing the spectrum analyzer function (see TABLE 7). Located in two racks above the MASSCOMP in the host computer cabinet, these boards contain MTI-built input buffers, antialiasing filters, a multiplexer, an rpm calculator board, a cluster CPU interface, and a PIO interface board that buffers electrical signals between the MASSCOMP and the rpm board and multiplexer. TABLE 8 presents the specifications for these boards.

The input signal buffers provide electrical isolation between the SGMS and the CRF equipment. From these buffers, analog data are routed to both the alarm sensing modules and the multiplexer. An electrical switch in the data reduction unit, the multiplexer is controlled by the user from the MASSCOMP keyboard and any of the 108-channel inputs can be selected as one of the multiplexer's 4 outputs. Each of the 4 outputs of the multiplexer is routed to an antialiasing board in the data reduction unit, with the filter breakpoint controlled by the system software. The filtered data are then input to the MASSCOMP's data acquisition processor for display on the graphics terminal (see Fig. 11). The user can display the spectrum of the 4 outputs simultaneously on the graphics terminal, including an overlaid warning and alarm profile as shown earlier in Fig. 3, or obtain a hard copy of the screen display from the video plotter. These outputs can also be examined by an external spectrum analyzer using the 4 BNC jacks located at the 108-channel interface. During postprocessing, the spectrum analyzer function also supports several signal analysis tools, including spectral plots, spectra waterfall displays, and other correlation functions. Collectively, this interaction between the data reduction unit to filter the analog signal data and the MASSCOMP data acquisition processor to acquire and display these filtered data comprises the spectrum analyzer function of the SGMS (see TABLE 9).

Warning (W) and Alarm (A)	Channel	Frequency (Hz)	Amplitude (V)	Engine Order (EO)
W	1	120.00	0.85	0.20
A	4	360.00	1.62	0.60
W	10	180.00	0.50	0.30
W	51	420.00	0.95	0.70
A	55	200.00	2.05	0.33
W	66	60.00	0.50	0.10
W	67	120.00	0.90	0.20
A	80	480.00	0.92	0.80

901000(N)

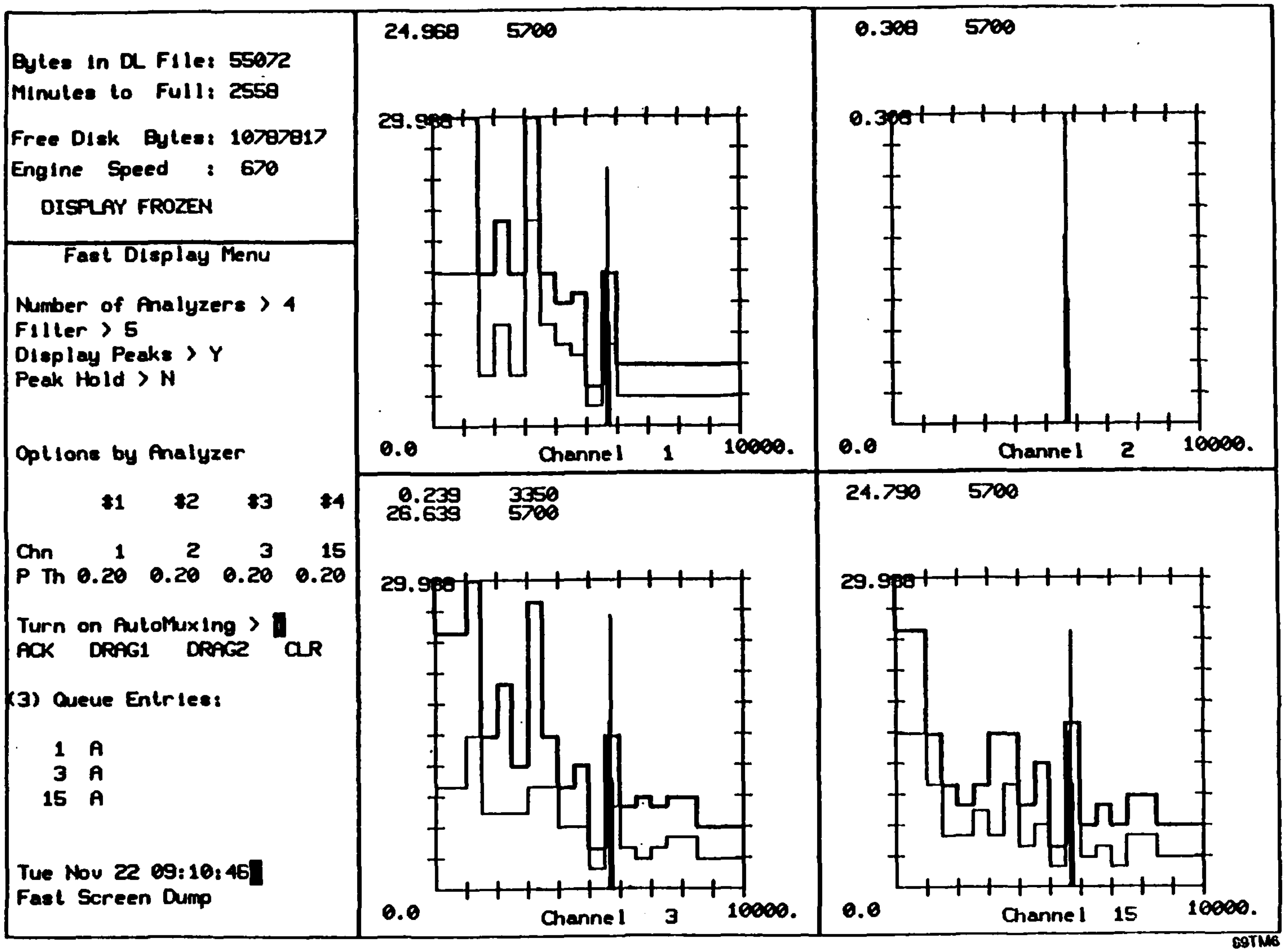
Figure 8. Typical hard-copy output of current overlimit values.

Type of Overlimit[1]	Channel Number	Frequency Range	Time Overlimit Started	Amplitude	Frequency	Speed	Engine Order
W ST	CH 1	R 3	9:24:49				
W ST	CH 4	R 3	9:24:49				
W ST	CH 4	R 4	9:24:49				
W ST	CH 19	R 3	9:24:49				
W ST	CH 19	R 4	9:24:49				
W ST	CH 62	R 4	9:24:49				
MAX	CH 1	R 3	9:24:49	0.85 volts	120.00 Hz	296 RPM	EO .49
W EN	CH 1	R 3	9:24:52				
MAX	CH 4	R 3	9:24:49	0.85 volts	120.00 Hz	296 RPM	EO .49
W EN	CH 4	R 3	9:24:52				
MAX	CH 4	R 4	9:24:49	0.86 volts	160.00 Hz	296 RPM	EO .65
W EN	CH 4	R 4	9:24:52				
MAX	CH 19	R 3	9:24:49	0.85 volts	120.00 Hz	296 RPM	EO .49
W EN	CH 19	R 3	9:24:52				
MAX	CH 19	R 4	9:24:49	0.91 volts	160.00 Hz	296 RPM	EO .65
W EN	CH 19	R 4	9:24:52				
MAX	CH 62	R 3	9:24:49	0.87 volts	120.00 Hz	296 RPM	EO .49
W EN	CH 62	R 3	9:24:52				
MAX	CH 62	R 4	9:24:49	0.93 volts	160.00 Hz	296 RPM	EO .65
W EN	CH 62	R 4	9:24:52				

[1] "W" or "A" lists type of overlimit for warning and alarm, respectively. "ST" identifies the start of an overlimit; "MAX" identifies the maximum overlimit; and "EN" identifies the end of an overlimit.

90797(N)

Figure 9. Typical hard-copy output of overlimit values in last minute of monitoring.



```
Bytes in DL File: 55072
Minutes to  Full: 2558

Free Disk  Bytes: 10787817
Engine  Speed   :  670
   DISPLAY FROZEN
```

```
     Fast Display Menu

Number of Analyzers > 4
Filter > 5
Display Peaks > Y
Peak Hold > N


Options by Analyzer

        $1     $2     $3     $4

Chn      1      2      3     15
P Th 0.20   0.20   0.20   0.20

Turn on AutoMuxing > █
ACK    DRAG1    DRAG2    CLR

(3) Queue Entries:

    1  A
    3  A
   15  A


Tue Nov 22 09:10:46█
Fast Screen Dump
```

Figure 10. Screen dump output of video plotter: automuxing mode screen display.

TABLE 6. Specifications for Host Computer Peripherals.

PRINTER

Specification	Requirement
Model	ProWriter 8510/1500 S/SC + NLQ
Speed	180 cps
Character	7 x 8 Dot Matrix
Paper	Fan Fold Sprocket Paper; Width 4.25 to 10 in.

MODEM

Specification	Requirement
Model	EC1200-31
Baud Rate	1200 and 300
Interface	RJ11 Telephone, DB-25 to DTE (Computer)

VIDEO PLOTTER

Specification	Requirement
Media	Electrographic Paper
Writing Method	Electrostatic
Resolultion	200 Points/in.
Interface	Model 115 MULTIBUS Controller

ALARM DISPLAY

Specification	Requirement
Maximum Possible Channels	144
Number of Installed Channels	108
Number of Indicators	3 Per Channel
Type of Indicators	Red - Alarm; Yellow - Warning; Green - Normal
LED Persistence	1 sec ±20%
Viewing Angle	90°
Maximum Distance of Cable to Display	50 ft
Indicator Lighting Time	250 to 500 msec, when FMAX = 16,000 Hz

AUDIBLE ALERT

Specification	Requirement
Tones	Warble for Warning, Steady for Alarm
Controls	Volume, 3-Way Switch for: 1. Silence 2. Alarms Only 3. Warning and Alarms
Cable Distance	Wired for 50 ft; Maximum of 100 ft

TABLE 7. Data Reduction Unit Components.

Quantity	Description
14	Input Buffer Boards, Plus 1 Spare
3	48-to-4-Line Multiplexer Used to Provide 108-to-4-Line Multiplexing
1	rpm Board
1	4-Channel Antialiasing Filter Board
1	PIO Interface
1	Alarm Interface
3	Cluster CPU Interface
4	Output BNC Connectors (Allow External Monitor of Spectrum Analyzer)
3	BNC Channel Input Panels, 36 Channels Each
108	50-ft Cable, 36 Spares
108	T BNC Connectors, 36 Spares
1	Tachometer Input BNC
1	Digital Control Rack
1	Analog Input Buffer Rack
1	Power Supply ±5 V; ±15 V

TABLE 8. Specifications for Data Reduction Unit.

INPUT BUFFER BOARDS

Specification	Requirement
Channels Per Board	8
Power Requirements	±15 Vdc
Bandwidth	100 kHz
Input Impedance	100 kΩ
Output Impedance	1 Ω at 50 kHz
Gain	1 or 0 dB
Output Offset Voltage	<0.5 mV After Initial Adjustment
Drift	50 µV/°C
Common Mode Rejection Ratio (CMRR)	100 dB at 60 Hz; 75 dB at 10 kHz
Bandwidth Gain Flatness	0.1 dB to 50 kHz

MULTIPLEXER BOARDS

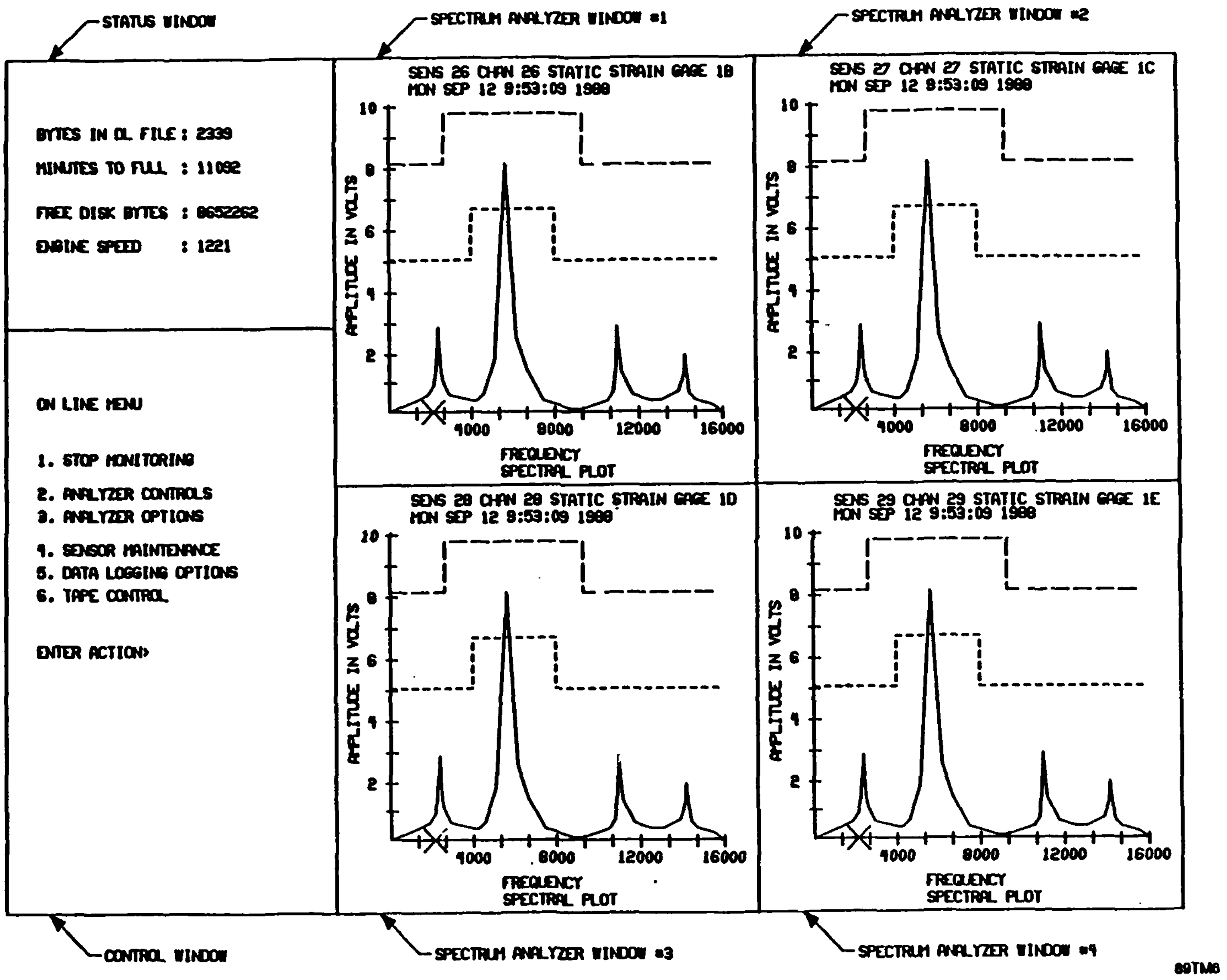
Specification	Requirement
Off-Channel Isolation	-70 dB
Gain Linearity	0.5%
On-Channel Distortion	0.2%
Adjacent Channel Crosstalk	-67 dB
Channel on Impedance	160 Ω Nominal
Channel Loss	-0.5 dB

rpm BOARD

Specification	Requirement
Resolution	10 µsec
Range	20 rpm to 6,000,000 rpm
1% Accuracy	0.00000166% at 1 rpm; 0.0100% at 3,600 rpm; 0.0400% at 10,000 rpm; 0.1000% at 30,000 rpm
Input Duty Cycle Range	1% to 99% Either Positive or Negative
Clock Trigger	Rising Edge
Signal Characteristic	TTL Logic Level

ANTIALIASING FILTER BOARD

Specification	Requirement
Filter Type	8-Pole Lowpass Butterworth, Critically Dampened
Frequency Range	100 Hz to 25.6 kHz
Frequency Steps	100 Hz Steps
Frequency Stability	±0.01%/°C
Operating Temperature Range	10°C to 45°C
Ripple in Pass Band	0.5 dB
Noise	50 µV rms
Maximum dc Offset, 40°C	5 mV



BYTES IN DL FILE : 2339

MINUTES TO FULL : 11092

FREE DISK BYTES : 8652262

ENGINE SPEED : 1221

Figure 11. Typical on-line graphics terminal display of the spectrum analyzer function.

TABLE 9. Capabilities of Spectrum Analyzer Function.

<table>
<tr><th>Feature</th><th colspan="4">Capability</th></tr>
<tr><td>FFT Display</td><td colspan="4">Any of the 108 Channels</td></tr>
<tr><td>Display</td><td colspan="4">1 or 4 Channels Simultaneously</td></tr>
<tr><td>FFT Spectrum</td><td colspan="4">400 Lines</td></tr>
<tr><td>Selectable Gains</td><td colspan="4">1x, 2x, 4x, 8x</td></tr>
<tr><td>Set Up Configurations</td><td colspan="4">Save of 10 Possible</td></tr>
<tr><td>Amplitude Scales</td><td colspan="4">Linear, log</td></tr>
<tr><td>Number of Averages</td><td colspan="4">1 to 100</td></tr>
<tr><td>Types of Averages</td><td colspan="4">Linear, Peak, Exponential</td></tr>
<tr><td>Optional Peak Display</td><td colspan="4">Up to 8 Peaks</td></tr>
<tr><td>Windows</td><td colspan="4">Hanning, Maximally Flat, Uniform</td></tr>
<tr><td>Time Labeled on Plot</td><td colspan="4">Taken Optimally From Time Code Translator</td></tr>
<tr><td>Zoom Factors</td><td colspan="4">2x, 4x, 8x, 16x, 25x, 50x, 100x</td></tr>
<tr><td>Waterfall Plot</td><td colspan="4">2 to 15 Spectra</td></tr>
<tr><td>Autocorrelation</td><td colspan="4">Any Channel, Selectable Maximum Lag</td></tr>
<tr><td>Cross Correlation</td><td colspan="4">Between Any Two Channels, Selectable Maximum Lag</td></tr>
<tr><td>Cross-Spectral Display</td><td colspan="4">Between Any Two Channels</td></tr>
<tr><td>Squared Coherence Plot</td><td colspan="4">Between Any Two Channels</td></tr>
<tr><td>Automuxing</td><td colspan="4">Up to 10 Most Recent Channels in Warning or Alarm</td></tr>
<tr><td rowspan="8">Selectable Frequency Ranges</td><th>Range</th><th>Maximum Frequency Displayed (Hz)</th><th>Filter Cutoff (Hz)</th><th>Sample Rate (Hz)</th></tr>
<tr><td>1</td><td>500</td><td>800</td><td>1,280</td></tr>
<tr><td>2</td><td>1,000</td><td>1,400</td><td>2,560</td></tr>
<tr><td>3</td><td>2,000</td><td>2,600</td><td>5,120</td></tr>
<tr><td>4</td><td>5,000</td><td>6,400</td><td>12,800</td></tr>
<tr><td>5</td><td>10,000</td><td>12,800</td><td>25,600</td></tr>
<tr><td>6</td><td>16,000</td><td>20,400</td><td>40,960</td></tr>
<tr><td>7</td><td>20,000</td><td>25,600</td><td>51,200</td></tr>
</table>

As another circuit board in the data reduction unit, the rpm board reads and converts the tachometer signal input from the CRF into an rpm value that can be read by the MASSCOMP. The tachometer input is a once-per-rev signal proportional to the test compressor's rotational speed. This value is used by both the spectrum analyzer function and by the alarm sensing modules. It appears on screen displays of spectrum, is stored on disk with overlimit data, and helps determine which speed-dependent warning and alarm overlimit profiles will be used by the alarm sensing modules.

4.4 Alarm Sensing Modules

The alarm sensing modules monitor all 108 channels of analog sensor data routed to the SGMS from the CRF equipment. Each one of three cabinets contains 18 alarm sensing modules. Since each module can service 2 channels, the two-channel alarm sensing modules (TCASMs) can service 36 channels of data (see TABLES 10 and 11 for related specifications). Each TCASM consists of four circuit boards:

- Node CPU — controls the flow of data between the DSP, dual port memory, and analog input boards. Communicates with the MASSCOMP's cluster CPUs over a high-speed data link.
- Analog Input Board — accepts analog data and contains antialiasing filters. Also provides the time domain peak detectors that check overlimits and are programmed by digital-to-analog converters.
- Dual-Port Memory Board — interfaces between the node CPU and analog input board. Accepts digitized data from the analog input board and holds these data until a block of data is complete. Contains two distinct buffers that enable the four boards of the TCASM to service two channels of data.
- DSP Board — provides high-speed, 400-line FFTs. The DSP board is given a complete block of data from the dual port memory board and calculates the resulting spectrum.

A high-speed parallel data link connects the node CPU to the cluster CPUs in the MASSCOMP. The data link has a master/slave protocol, with the cluster CPUs as the master. At the beginning of monitoring, the cluster CPUs send system configuration information to the node CPU and then continually poll each of the modules. If an overlimit condition exists, the node CPU sends the overlimit information to the cluster CPUs. The alarm display then indicates which channel and which oscilloscope should be examined for further analysis.

Each TCASM performs both time domain and frequency domain warning and alarm checks on the spectral magnitude of 36 analog data channels. Buffers in the data reduction unit send signals to the analog input board, where the signals are sent to time domain and frequency domain checking circuitry. Each channel has a configurable single value time domain warning and alarm level checked by the system.

To check frequency domain limits, a profile of warnings and alarms over a range of frequencies is necessary (see TABLE 12). The analog data are passed through an antialiasing

TABLE 10. Alarm Sensing Module Components.

Quantity	Description
3	70-in. Cabinets
18	Analog Input Boards
18	DSP Boards
18	Node CPUs
18	Dual-Port Memory Boards

TABLE 11. Specifications for Alarm Sensing Module.

NODE CPU

Specification	Requirement
Board Type	Intel SBC 86/30
System Clock	8 MHz
CPU	Intel 8086
Random Access Memory	128 kilobytes
EPROM	Two 2764 PROMs; 16 kilobytes Total
Serial I/O Port	8251A
PIO Lines	24 Lines Using 8255
On-Board Timer and Interrupt Controller	8259A

ANALOG INPUT BOARD

Specification	Requirement
Input Impedance	100 kΩ
Input Capacitance	10 pF
Input Voltage Range	±5 V Peak
Time Domain Alarm Function	
• Filter Selections	10 Hz (5 Pole) or 16 kHz (2 Pole)
• Minimum Resolution	2.44 mV (12 bit/A/D)
• Maximum Offset Error	30 mV
• Gain Error	6.75% or 0.61 dB
• Drift	30 µV/°C
• Noise	25 mV rms

DUAL-PORT MEMORY BOARD

Specification	Requirement
Interface	Multibus™ Compatible
Storage	Temporary Storage for 2 Channels of 12-Bit Data
Address Decoding	2-Stage Scheme
Data Buffers	2 Octal Bus Transceivers

DSP BOARD

Specification	Requirement
Board Type	DSP Systems Corporation FFT-1B
Self-Test	17 sec
Crystal	24 MHz
FFT Time (Read/Write Data, Window, FFT, and Magnitude)	12 msec
Number of Lines	400
Window	Hanning
Number of Data Points	1024
Total Time	12 msec/Channel

TABLE 12. Specifications for Freqency Domain Alarm Function.

<table>
<tr><th colspan="5">FREQUENCY DOMAIN ALARM</th></tr>
<tr><th>Specification</th><th colspan="4">Requirement</th></tr>
<tr><td>Antialiasing Filter</td><td colspan="4">7-Pole Elliptical</td></tr>
<tr><td>Warning and Alarm Profiles</td><td colspan="4">In 16 Steps</td></tr>
<tr><td>Programmable Clock</td><td colspan="4">1 Per TCASM Cabinet</td></tr>
<tr><td>Status Report</td><td colspan="4">Channel, Amplitude, Frequency</td></tr>
<tr><td>Resolution</td><td colspan="4">4.8828 mV (12 bit A/D)</td></tr>
<tr><td>Full Scale Range</td><td colspan="4">±5 V Peak</td></tr>
<tr><td>Gain Error</td><td colspan="4">3%</td></tr>
<tr><td>Drift</td><td colspan="4">60 µV/°C</td></tr>
<tr><td rowspan="5">Available Frequency Ranges</td><th>Range</th><th>Maximum Frequency Displayed (Hz)</th><th>Filter Cutoff (Hz)</th><th>Sample Rate (Hz)</th></tr>
<tr><td>1</td><td>1,000</td><td>1,297</td><td>2,560</td></tr>
<tr><td>2</td><td>5,000</td><td>6,392</td><td>12,800</td></tr>
<tr><td>3</td><td>10,000</td><td>11,470</td><td>25,600</td></tr>
<tr><td>4</td><td>16,000</td><td>17,897</td><td>40,960</td></tr>
</table>

filter, converted to digital values by an A/D converter, and then placed in the dual port memory. When 1024 samples have been collected, the data are transmitted to the DSP board for a high-speed FFT that converts the data into the frequency domain. After the FFT is complete, the node CPU checks the resulting spectrum against the warning and alarm levels configured by the user. When the node CPU determines that an overlimit condition exists, whether in the time or frequency domain, the event is transmitted along with details of the condition to the MASSCOMP. The SGMS can analyze frequency components up to 16 kHz without missing any data.

4.5 External Spectrum Analyzer

The SGMS is equipped for interface with an optional spectrum analyzer that is external to the MTI-supplied equipment. This four-channel Scientific Atlanta spectrum analyzer connects to the four BNC jacks of the 108-to-4 line multiplexer in the data reduction unit, thus taking advantage of the SGMS multiplexer and antialiasing filters. Equipped with certain features not available in the SGMS, this external spectrum analyzer is most useful during the automuxing mode of operation when the host computer automatically queues channels that go into warning or alarm.

5.0 SYSTEM DESIGN APPROACH

Of the many specific performance requirements for the SGMS, a few dominated and, in turn, dictated the design approach. These key requirements include the ability to:

- Monitor 144 channels of analog time domain data to prescribed limits in the frequency domain
- Investigate frequency components to 16 kHz
- Provide continuous monitoring with no gaps in time domain data gathering
- Provide maximum accuracy in determining warning and alarm conditions
- Provide simultaneous time domain and frequency domain limit checking on some channels
- Convey a message to the system operator within approximately 0.25 sec when a limit has been reached
- Provide a robust host computer for the operator interface
- Provide an integrated four-channel spectrum analyzer.

The following subsections address the impact of these requirements on MTI's approach to the SGMS design.

5.1 Monitoring of 144 Channels in the Frequency Domain

When considering the requirement to monitor 144 channels of data, the efficient method of converting time domain data to frequency domain data is to apply an FFT to the digitized analog data. This process involves filtering the analog time domain data, digitizing the resultant signal, and computing the FFT. To implement these functions, three devices are required: an antialiasing filter, an A/D converter, and a computational machine. Although there are many possible approaches to implementing these three functions, technical requirements and cost considerations constrain the selection.

For the SGMS, MTI's approach was to:

- Design the antialiasing filter using a switched capacitor
- Utilize one integrated circuit 12-bit A/D converter, one per analog channel
- Purchase a specialized microprocessor optimized for calculation of FFTs, one per pair of analog data channels.

The use of the switched capacitor antialiasing filter provided a considerable advantage due to the small circuit board space required to implement the function and its relatively low power consumption versus the more traditional implementation of a total analog approach using multiple operational amplifiers. Both space and power savings resulted in lower total system cost. The relatively low cost of high performance 12-bit A/D converters allowed for the use of one per data channel and provided a simple, straightforward interfacing scheme. A specialized FFT processor was selected versus a general-purpose microcomputer because of the computational speed requirement, cost advantage, and ease of interface.

5.2 Investigation of Frequency Components to 16 kHz and Continuous Monitoring

The requirement for investigation of frequency components to 16 kHz deals primarily with the digitizing rate of the A/D converter. The Nyquist sampling theorem dictates that to produce a 400-line spectrum (the industry standard) to 16 kHz, a digitizing rate of 40.96 kHz is required. Since 12-bit A/D converters operating at this speed are relatively inexpensive, MTI selected one A/D converter per data channel as the design approach. Since each digitized channel requires a filtered signal, one MTI-designed antialiasing filter per channel was included in the design.

The remaining key component required to produce the FFT is the computational machine. The most influential criterion here is the speed at which the FFT must run, which is also dependent on the requirement for continuous monitoring with no gaps in time domain data gathering. The steps in determining the FFT involve digitizing the signal, transferring the digitized data to the computational device, and calculating the FFT. This is a process that recycles continuously. If the portion of the cycle for transferring the data and calculating the FFT takes no more time than that required to digitize the signal, the FFT computation will be completed prior to the time required to begin calculating the FFT on the next block of acquired data. The process will then coincide with real-time data collection and no data will be lost. The FFT calculation requires 1024 samples at a 40.96-kHz sampling rate. Therefore, the acquisition time for the 1024 samples is 25 msec. If the data transfer and FFT calculation can be accomplished within the 25 msec, the process can be continuous with no data loss.

Possible implementation approaches range from one FFT calculator per channel to time sharing a very fast device with a number of data channels. In preparing the original proposal and during Phase I, MTI surveyed the available FFT devices. The processors evaluated fell into three groups (see TABLE 13). The Group A device did not meet the speed requirement; group B devices moderately exceeded the speed requirement; and the group C device, which far exceeds the speed requirement, was prohibitively expensive. In group B, the DSP Systems Corporation device had a strong design advantage in that it is compatible with the Intel MULTIBUS microprocessor architecture and provided a suitable approach for interface with the other supporting hardware. Also in group B, the IBM PC-based Ariel 523 device offered a cost advantage over DSP Systems but was less powerful and required a difficult interface approach. It was therefore rejected. The group C device required sharing many data channels with one array processor for cost effectiveness. Such time-sharing of more than two channels with one FFT processor board results in many technical difficulties, including packaging, timing, and signal transmission. Considering these factors, the DSP Systems FFT-1 device was selected to time-share between two data channels. This resulted in a streamlined, cost-effective hardware implementation, with a modest margin for error in timing performance.

5.3 Accuracy of Warning and Alarm Condition Determinations

Use of the FFT assumes that the sampled input waveform is continuous in that one digitized waveform is representative of all the preceding data and the data that follow. In reality, a sampled waveform results in discontinuities at the end of each data block. The effect is a once-per-data-block modulation that introduces sidebands for any signal that does not contain an exact integer number of cycles in the data block. Data processing algorithms, termed "windows," have been developed to reduce the effects of such data discontinuities, with several types of windows developed for different data processing requirements. Both a Hanning window and a maximally flat window were considered by MTI in selecting a window type for inclusion in the alarm sensing module. TABLE 14 compares these window types with a "no window" case.

TABLE 13. FFT Processor Survey.

Group	Type of Device	Device Evaluated	Calculation Speed	Cost Comparison
A	Integrated Circuit	Texas Instruments TMS 32010	50 to 70 msec	Reference Cost
B	Microprocessor Board	Ariel 523	9 to 12 msec	2 × A
	Microprocessor Board	DSP Systems FFT-1	8 to 10 msec	4 × A
C	Array Processor	Marinco APB-3024M	~2 msec	8 × A

TABLE 14. Window Comparison.

Window Specification	No Window[1]	Hanning Window	Maximally Flat Window
Maximum Amplitude Error	36%	14%	<0.5%
Resolution for 16-kHz Spectra	40 Hz	64 Hz	160 Hz
Signal-to-Noise Ratio	4:1[2]	3.2:1	1:1

[1] Resolution estimated as 1 bin.
[2] 4:1 is assumed for comparison purposes.

Data processing with a Hanning window suppresses the modulation effect, reducing the sidebands and increasing the dynamic range. However, the use of a Hanning window widens the effective bandwidth of the FFT algorithm. Fig. 12 illustrates this and demonstrates the relationship between the effective filter shape and the amplitude accuracy obtained if a signal is not exactly in the center of the bin (the smallest frequency increment of the FFT).

If a signal's frequency is close to or at the edge of a bin, then a 36% amplitude error is introduced by using no window function. The Hanning window reduces this error to 14%, while a flat window results in a negligible error. Although the flat window results in a dramatic reduction in possible error, it is inappropriate in some cases. The penalty for using the flat window is that the effective filter widens from one bin to over four bins, thus reducing frequency selectivity. Use of the flat window not only reduces resolution but also reduces the signal-to-noise ratio for discrete frequency signals containing a random noise background.

After consideration was given to the trade-offs involved in selecting a window for the alarm sensing module, MTI concluded that the Hanning window offered the best compromise. Its resolution and signal-to-noise ratio are quite close to the no window case, while the maximum possible amplitude error is reduced by a factor of over 2.5. Although there is the possibility of a 14% amplitude error in the data, since the error is 0 to -14% and not ±14%, any FFT amplitude reported could be greater than reported but not smaller. This fact could influence limit selection, but it is expected that set limits would not be so precise that a 14% error would be serious.

A requirement also existed for providing an FFT analyzer function on the host computer. For this feature, all three window options were available and were easily implemented in the system software on the host computer.

5.4 Time Domain and Frequency Domain Limit Checking

The contract requirements stipulated that both time domain and frequency domain limit checking was required for a substantial portion of the data channels. TABLE 15 summarizes the limit checking requirements and indicates the type of signal processing required when limit checking in the time domain is applied. Note that for some channels, such as static strain gages, the time domain limit is based on a dc level after the signal is filtered at a frequency response of 0 to 10 Hz. For accelerometers, limit checking is based on the peak level after the signal is filtered (averaged) at a frequency response of 0 to 16 kHz.

The challenge was to design an economical approach to the time domain limit checking. This requirement was addressed by implementing two filters (0 to 10 Hz and 0 to 16 kHz) for each data channel. The output of the desired filter is selectable by software and connected to an analog circuit that determines the sum of the maximum positive signal plus the maximum negative signal divided by two for an accurate representation of the peak value. The peak detection, in turn, is connected to an analog threshold comparator. The reference level for the threshold comparator is provided by a digital-to-analog (D/A) converter that is programmed from the host computer. The D/A converter provided a means of programming the required threshold value and the use of analog circuits for the balance of the function was an economical solution. Further, MTI decided that both functions should be implemented on all boards, since to implement both functions only on certain boards would have prevented complete interchangeability of the boards. As a result, all channels have the capability of simultaneous time and frequency domain monitoring in the SGMS design.

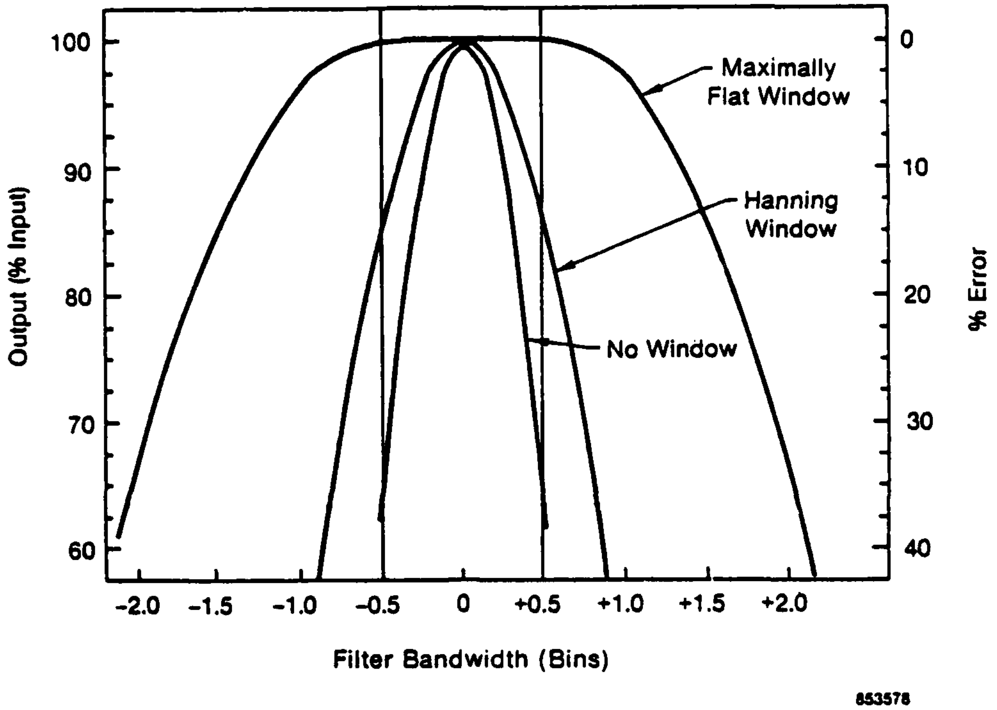


Figure 12. FFT effects versus window selection.

TABLE 15. Time Domain and Frequency Domain Alarm Requirements.

Type of Signal	Maximum Number of Signals in Category	Time Domain Limit Checking	Frequency Domain Limit Checking
Dynamic Strain Gage (ac Coupled)	108	None	Required
Static Strain Gage (dc Coupled)	12	dc Level (0 to 10 Hz)	Required
Accelerometer (ac Coupled)	24	Average Peak (0 to 16 kHz)	Required
High-Response Pressure Transducer			
(ac Coupled)	60	None	Required
(dc Coupled	60	dc Level (0 to 10 Hz)	Required
High-Response Thermocouple (dc Coupled)	24	dc Level (0 to 10 Hz) Average Peak (0 to 16 kHz)	Required

Notes: Time domain limit checking function controls two filter cutoffs - 10 Hz and 16 kHz.
The frequency domain checking function has eight sample rates and eight low-pass filter cutoffs.

5.5 Alarm Message Transmission

Once the distributed FFT processors compute overlimit data, the data must be transmitted to the host computer for routing to the alarm display and placement in a data logging file. The challenge was to provide a fast communications interface between the 108 alarm modules and the host computer.

MTI considered two methods for communicating the overlimits from the alarm sensing module to the host computer. The first method, included in MTI's original proposal, was based on the Intel BITBUS™, a high-speed serial bus that provides communication between Intel single-board computers. As the detailed system design progressed, however, it became apparent that the BITBUS could not maintain a sufficient data transmission rate and that an alternative method was required. It was also found that BITBUS was expensive and cumbersome to use. To remedy this, MTI designed a parallel data communications method, extending the capabilities of the existing host computer parallel data input/output controller. This alternative approach proved successful in maintaining high data rates and data integrity and has demonstrated the ability to convey alarm messages within the required 0.25 sec.

5.6 Selection of Host Computer

The system requirements dictated that the host computer support computations, system control, and data presentation while providing a single point of interface (graphics display terminal) for the system operator. Given these requirements, the MASSCOMP was selected as the host computer. The MASSCOMP obtains high system performance by using a triple bus architecture, thus allowing parallel computation, graphics display, and data acquisition. *It accepts Intel single-board computers without any modification*, facilitating interface to the 108 alarm modules. Further, with the addition of a front end processor for data acquisition, the required spectrum analyzer function could be incorporated into the host computer and its graphics terminal used for spectral displays.

The host computer selected not only needed to satisfy current computational needs but also be flexible for future expansion. The MASSCOMP can use multiple processors or array processors if more computational throughput is needed and more memory can be added. The use of standard buses and the endorsement of software standards, such as the Graphics Kernel System, indicate MASSCOMP's commitment to a smooth upgrade path for its customers. Therefore, in one machine, MTI was able to address the needs for powerful data acquisition, computation, control, and graphics display.

5.7 Four-Channel Spectrum Analyzer Function

MTI had the option of supplying the required spectrum analyzer function either as a separate unit controlled by the host computer or as equipment integral to the host. Since the spectrum analyzer was expected to have high usage by the system operators, MTI felt that it was important to integrate this function into the same display terminal used for system control and viewing of system data and status information. To meet this requirement, MTI added the data acquisition processor as a front end to the MASSCOMP CPU and used the MASSCOMP display terminal for graphics output.

This choice provided several advantages over the use of a separate spectrum analyzer. First, the operator is given only one piece of equipment, the MASSCOMP, to focus on when an engine is under test. Second, the graphics display terminal benefits greatly from tight integration with the main CPU. For example, configuration file information, such as alarm profiles, may be overlaid on the spectral displays, and this would be very difficult to do using a separate spectrum analyzer. Third, the signal processing algorithms that provide data for the spectrum analyzer display are implemented in the MASSCOMP software. This provides a great deal of flexibility in deciding what may be included in data presentation. Because the MASSCOMP utilizes separate graphics and data acquisition processors, it readily handles the implementation of the spectrum analyzer function in addition to its user interface and data logging duties.

Although MTI's initial design decision was to use the integral spectrum analyzer, Phase II testing of the prototype revealed that a separate unit also has advantages. In the course of operating the system, the system exhibited much slower speed versus a stand-alone spectrum analyzer. This was overcome by selectively writing special software routines for selected functions. After the speed issue was addressed, the value of an integrated, single-point interface was confirmed, although there remained an interest in some of the advanced signal processing capabilities of the new four-channel spectrum analyzers. To use the advantage of the single point interface in tandem with the power of the stand-alone analyzer, the MASSCOMP implementation of the spectrum analyzer function was retained for those cases requiring high usage and coordination with other system status information. Additionally, a hardware interface was added to accommodate a stand-alone Scientific Atlanta four-channel spectrum analyzer for those less frequent cases requiring analysis functions not included with the SGMS.

6.0 SYSTEM ENHANCEMENTS

As MTI refined its understanding of how the SGMS would be employed in the CRF, several opportunities arose for system enhancements. The following subsections highlight enhancements that were implemented during the contract as well as options for potential future enhancements.

6.1 Implemented Enhancements

Enhancements implemented during this contract, described in the following subsections, include:

- Programmable sample rates and antialiasing filters
- Support for time domain diagnostic capability
- Data logging reports
- Fast plot
- MASSCOMP performance enhancement package.

6.1.1 Programmable Sample Rates and Antialiasing Filters

The RFP required monitoring to a maximum frequency of 16 kHz. However, obtaining frequency resolution greater than 40 Hz at low frequencies required the addition of programmable sample rates and antialiasing filters. These enhancements will also be important if time domain analysis is added. Since the sample rate clock is programmed directly from the MASSCOMP, altering the sample frequency for different frequency ranges was a simple matter of expanding the clock control software. In addition, a four-way antialiasing filter that is set by the system software for either 1-, 5-, 10-, or 16-kHz operation replaced the original fixed frequency filter design.

6.1.2 Support for Time Domain and Diagnostic Capability

As a result of Phase I activity, the capability for time domain diagnostic analysis was added during Phase II. Crucial to the system's diagnostic capability is the ability to put an extra classifier CPU with each alarm sensing module board set. These classifier CPUs would examine phase and time data and would perform the initial steps in classifying monitored phenomena. Since these CPUs would have to be located next to the FFT board for this operation, 18 extra slots were included in the TCASM cabinet. In addition to the extra slots and their related wiring, increased power supply capability was added to accommodate the extra CPU circuit board.

6.1.3 Data Logging Reports

During Phase II implementation of the SGMS data logging feature, MTI proposed the addition of a series of function-key-driven reports. This proposal was reviewed with the Air Force in July 1986. Since the printer would not be able to keep up with all overlimits during times of frequent overlimits, it was decided that the original method of sending all overlimits to the printer was not practical. In addition, there was no way for an operator to determine current overlimit amplitudes. Therefore, function keys were defined to produce three data logging reports. The first report produces a snapshot of the current system status; the second report details overlimits that have occurred during the past 60 sec; the third report allows the user to select the channels and time range that will be used to produce the report. Collectively, these techniques enhance the presentation of overlimit data.

6.1.4 Fast Plot

During Phase II, a performance issue arose in that the plots on the graphics screen for the four-channel spectrum analyzer function were too slow. The plot package being used was produced by Creare, Inc., and was a good, general purpose software package. However, as is often the case with general-purpose tools, the results were disappointingly slow. One spectral plot with the Creare software took about 13 sec to acquire the data, perform the analysis, and plot the result, with most of the 13 sec taken by the plot package. However, although it was slow, the plot package did provide advantages with respect to output quality and support of a large number of hard-copy devices. In order to address the problem of plotting speed, MTI presented alternative approaches to the Air Force in May 1986. The approach selected had MTI produce a special-purpose fast spectral plot in addition to the other, existing "slow" plots. This optimized plot made extensive use of low-level MASSCOMP graphics routines and resulted in a 10-times performance increase.

6.1.5 Performance Enhancement Package

During Phase III, the Air Force funded a Performance Enhancement Package (PEP) which provided the following upgrades to the MASSCOMP:

- Upgrade in the main CPU from a Motorola 68010 to a 68020
- Upgrade in the main memory from 2 to 4 megabyte
- Addition of a larger power supply and an increased number of slots to improve future SGMS upgrade potential
- Increase in CPU speed and memory for higher performance
  - Increase in CPU throughput by a factor of 2 to 3
  - Increase in throughput of floating point calculations by a factor of 2 to 4.

TABLE 16 summarizes net performance gains due to implementation of the PEP.

The Versatec video plotter was also added to the system during the PEP upgrades. This plotter allows for a black-and-white hard copy of any screen on the MASSCOMP graphics terminal. Although the plotter can also resolve the screen colors into gray scales, the extra several seconds it takes to produce gray scales is not usually worth the marginal improvement in the resulting plot.

6.1.6 Audible Alert

The first hardware enhancement was a device called the audible alert, which emits a distinct tone for either warning or alarm whenever a channel moves into an overlimit situation. This tone frees the operator from keeping visual contact with the alarm display. The audible alert contains a volume knob and an "alarms only" or "warnings/alarms" switch.

6.1.7 Software Enhancements

Several enhancements were made to the monitoring software. One enhancement added the warning and alarm profiles to the fast plot. The most significant enhancement, however, was an automuxing feature. Four BNC jacks were added to the SGMS to allow an external, Scientific Atlanta four-channel spectrum analyzer to use the SGMS multiplexers. If the software is put in automuxing mode while it is displaying the fast plot, data channels with the latest 10 warning and alarm events are queued. These events are

TABLE 16. Net Performance Gains (Time in seconds).

Function	Pre PEP[1]	Post PEP
System Start-Up	75	25
System Shutdown	20	2
One Slow Plot	13	5
One Fast Plot	1.2	0.7

[1] Performance Enhancement Package.

held in a visible queue until the operator acknowledges the event. The acknowledge causes the multiplexer to automatically select the next channel in the queue. The channel's display appears on the MASSCOMP fast plot and also on the external analyzer. The automuxing mode successfully couples the SGMS to an external piece of equipment. The advantages of the SGMS queuing and multiplexer control work hand-in-hand with the advantages of the external analyzer (fast updates and an extensive set of additional analysis features).

6.2 Future Enhancement Options

In addition to the enhancements that were implemented, MTI has presented ideas for future SGMS enhancements. The following subsections summarize these options.

6.2.1 300-Megabyte Disk Drive

The hard disk delivered with the system is 70 megabytes in size. Approximately 50 megabytes are taken up by system-related utilities, leaving approximately 20 megabytes free for data logging and configuration files. The addition of a 300-megabyte Eagle disk drive would allow for much more disk space, and the disk itself would be much faster. With more free disk space, the data logging files could be stored on disk until they could be organized and backed up on auxiliary storage.

6.2.2 Array Processor Option

The time it takes to update a spectrum analyzer display on the MASSCOMP graphics terminal requires time to organize the data, to perform the FFT, and to display the result. In continuous display mode, the data acquisition is performed in parallel with the FFT and display. Unless the data are being acquired slowly, the limiting factor on the display rate is generally the time to do the FFT. An array processor option available from MASSCOMP would reduce the time required to perform an FFT from 250 msec to 10 msec.

6.2.3 Color Plotting Device

The current hard-copy support for the SGMS graphics terminal is a monochrome screen dump using the Versatec video plotter, and another device would be required to produce color plots. Such a device would be useful since the use of color greatly enhances the results when portraying extensive data. The MASSCOMP supports two types of color plotting devices: the ink-jet plotter and the pen plotter. The ink-jet plotter is a Tektronix 4695 and has a significant disadvantage in that it requires a special adapter that inserts into the MASSCOMP MULTIBUS to serve as the plotter interface. A color pen plotter, such as the HP 7550, provides an alternative to the ink-jet plotter. The HP 7550 is an 8-pen, self-capping, graphics plotter that provides A- and B-sized plots. It produces excellent quality plots and has extensive software driver support. The HP 7550 also interfaces with the MASSCOMP through a standard serial port. Although far superior in quality of presentation, both the ink-jet and pen plotters would require additional software support and are far slower than the Versatec video plotter. If color hard copy is desired, MTI recommends adding the HP 7550 plotter.

6.2.4 Hardware Spares

The SGMS contains more than a half-million dollars of electronics hardware. At various points in the system hardware architecture, a failure could cause a substantial reduction in system capacity and/or performance. Therefore, obtaining spares of critical hardware elements is necessary to ensure reliable system operation. In January 1989, MTI submitted an itemized proposal to the Air Force to acquire spares for the hardware elements listed below.

- rpm calculator board
- 108-to-4-line multiplexer
- Input buffers
- Cluster CPUs
- Alarm interface
- Computer parallel interface.

Failures in other hardware areas of the system would result in localized failures and minor reductions in system throughput capacity.

6.2.5 Additional Alert Device

The alarm display and audible alert function are important mechanisms for warning CRF personnel of possible dangerous situations. Both of these devices were designed with the ability to add a second device with little extra work beyond the construction of the second unit. A second alerting device could be very useful in configurations where the test supervisory personnel are not located in one area.

6.2.6 Trigger Signal

The CRF currently owns a special-purpose data acquisition and storage device (IDARS) that is based upon the MASSCOMP computer and is supplied by Creare Inc. This unit offers an ideal opportunity to connect or integrate the CRF equipment. If the IDARS unit could be told when to acquire data, the data acquisition process would be much more effective than the current routine of recording all channels. The SGMS could provide a triggering electrical signal, based on its alarm display output, that would be used to initiate the IDARS data acquisition. In this way, detailed analysis could be made in the time and frequency domain of a selected channel exceeding its programmed levels.

6.2.7 Additional TCASM

Although the system deliverable channels were reduced from 144 to 108, the SGMS was constructed to have full functionality in its software features. To bring the system back to 144-channel capability, another TCASM cabinet and its constituent circuit boards would have to be built and additional buffer and multiplexer capabilities would have to be added. The alarm display was built to house 144 channels and would only require addition of circuit boards for the remaining 36 channels.

6.2.8 Configuration Menu Consistency Check

Configuration menus allow the SGMS user to construct the total configuration on different screens, which must be complete and consistent when the system begins monitoring. However, since the system cannot distinguish between incomplete and inconsistent information at the time of data entry, it cannot notify the user of a possible problem until after monitoring begins. Therefore, a full consistency check, routinely done when the SGMS starts up, would enhance system operation by ensuring consistency of information before work begins.

6.2.9 Warning and Alarm Software Upgrade

It takes approximately one minute to go from monitoring mode back to configuration mode, make a change, and return to monitoring. As long as this one-minute interruption in the data logging file is acceptable, the current method is fine. However, changes to warning and alarm levels cannot currently be made while the system is monitoring. A substantial change to the monitoring software would be required in order to accommodate this option.

6.2.10 Data Logging Enhancements

The primary functions of the SGMS software are to monitor and alert. Data reduction and data logging are important, but secondary. The current data logging functions are straightforward representations of the collected overlimit data. As the Air Force builds an experience base in using the system, it is expected that new ideas for examining, querying, and reporting the overlimits will arise. These additional reports would not be difficult to add to the software. A special new report type is the automatic report. If the data logging files become large, then report times can run into minutes or even up to an hour. In those cases, automatic reports and plots that can run unattended become attractive.

6.2.11 Campbell Diagram

The dynamic Campbell diagram is a complex figure that can provide a trained observer with a wealth of information on a compressor's behavior at various speeds. The displayed peaks may be a result of an excitation, resonance, or a nonresonance. The Campbell diagram provides the ability to identify at a glance the excitation mechanism of the compressor and could be made available as an off-line diagnostic tool. Implementation of the diagram would require additional software. The data source would be the multichannel tape recorder. No warning and alarm indication or data logging features would be available while the plot is being made, since the SGMS would be dedicated to the data acquisition and the construction of the plot.

7.0 PROGRAM RESULTS

MTI's SGMS has achieved the overall goals of the program. The following subsections present program successes as well as challenges faced.

7.1 Program Successes

The SGMS architecture is one of the most successful aspects of the program. Originally proposed in 1985, this design has met program goals and remains the preferred approach for the following reasons:

- The architecture of the distributed microprocessor and special FFT board accommodates the need for real-time spectral analysis at a reasonable cost.
- Four years after the SGMS design, the DSP System's FFT boards remain MTI's choice, meeting the required FFT time and remaining relatively inexpensive, i.e., less than $800 per channel.
- The MASSCOMP has proven that it can control and accumulate the flow of information between the distributed processors, is supported by the manufacturer, and can be upgraded in the field.
- The MASSCOMP's open-bus architecture allows the SGMS project access to the internal MASSCOMP bus and provides high data rate access for the overlimit data.

The traditional MASSCOMP strengths — integrated data acquisition, graphics, and real-time support — have also proven beneficial to the program. Despite some difficulties encountered while using the MASSCOMP, it would still be MTI's choice for the host computer. The MASSCOMP used for this program has not experienced a single hardware failure in over 3 years.

The SGMS architecture has also met required performance specifications. The distributed alarm sensing function simultaneously accumulates samples from all channels. A double-buffering scheme allows the FFT boards to process a block of data while a new block is being accumulated. Overlimits are transmitted from the FFT boards to the MASSCOMP within 125 msec. Although the MASSCOMP does not have a predictable response time to the overlimits, it generally lights the LEDs at the alarm panel within 100 msec of being notified. Even under the most strenuous conditions, i.e., setting warning and alarm levels for all channels to zero and forcing all channels to be over limit, the SGMS maintains monitoring integrity until the hard disk fills up from overlimit records in the data logging file.

Another program success is the close working relationship MTI has developed with WPAFB program personnel. Problems that arose during the course of the program were often addressed quickly and to mutual satisfaction. The fast plot, described in Section 6.1.4, is an example of this cooperation. The list of enhancements discussed in Section 6.0 reflects MTI's maturing understanding of the project's application and our desire to produce a useful system that meets specification.

Finally, MTI's rigorous testing of the system helped to minimize problems after equipment installation in Phases II and IV. The Phase II prototype system was built to the 36-channel level, greater than the contract required, to allow complete checkout of one TCASM unit from the electrical, software, and environmental standpoints, MTI's up-front testing of the prototype allowed more enhancements to be added to the system during Phase III. Similarly, MTI's testing before Phase IV delivery was successful in shaking out the electronic failures causing early failure of circuit components.

7.2 Program Challenges

Despite achieving the overall goals of the program, MTI encountered several challenges in the hardware and software areas. The following subsections summarize these challenges and MTI's solutions.

7.2.1 Hardware Challenges

The first FFT board was tested early in Phase II. The board's actual performance, 20% slower than projections had indicated, was too slow for MTI's application. DSP suggested the board could be upgraded to run at 24 mHz. All FFT boards were purchased with a certification that they would operate properly at 24 mHz, which was suitable for MTI's application. This board upgrade eventually became a standard product enhancement for DSP. Phase II testing also revealed that the FFT board's returned amplitude was always 12% low, and could be attributed to the window function. Since DSP did not acknowledge that this error existed, MTI scaled the output appropriately to eliminate the constant 12% error.

Life testing, done during Phase II before the prototype was shipped to the Air Force, detected that the FFT board was sensitive to temperature and the level of the 5 V power supply. Fans were added to the TCASM cabinets to stabilize temperatures for the boards. Individual boards can still show temperature sensitivity. For this reason, it is recommended that the system be warmed up for 5 to 10 min before use.

The Phase IV version of the SGMS required 36 FFT circuit boards. Incoming inspection of the boards revealed a failure rate of about 25%, and several other boards failed after some use. MTI took several broken boards back to the DSP factory in September 1988 for testing, and concluded that the source of the high failure rate was poor quality control at the factory. Although the boards suffered from a design weakness in their bus interface circuitry, an engineering change from ALS to AS logic diminished this effect. Statistically, MTI has found that a particular board tended to fail only once. MTI upgraded DSP's test rig and improved their testing techniques. This upgrade substantially diminished cases of the board failing at MTI after appearing to work at DSP. As insurance for the Air Force, a copy of the board schematics, usually considered proprietary, was obtained. Therefore, should the need ever arise, MTI could affect a repair.

7.2.2 Software Challenges

The most challenging software in the SGMS was the assembly language firmware, located in the CPUs, that controls the alarm sensing module. This software, responsible for monitoring overlimits and communicating with the MASSCOMP, is under extreme time constraints and must handle several asynchronous hardware interrupts. However, the American Automation software development system used in the SGMS development could not successfully perform these required functions. Although MTI had success using this system with an INTEL™ 8088 microprocessor, using the INTEL 8086 seemed to cause intermittent behavior in the SGMS. American Automation attempted to help, but was not successful. MTI rectified this situation, but more work was required in this part of the program than was anticipated.

During Phase I, MTI decided to substitute a parallel I/O communication method for the BITBUS approach originally proposed. However, although the parallel method was fast enough to meet specifications, it was a challenge to implement. Since precise timing margins are required in hardware, making best use of the parallel method's speed required fine tuning of the software on both ends of the data link. Extensive tests were performed to reduce the likelihood of a single board jamming the entire bus. Although more work was performed in this area than anticipated, the result was a reliable, high-performance data link.

The MASSCOMP system software was a source of problems during the entire project. An occasional panic stop, or operating system crash, existed in the Phase II prototype. At that time, MTI suspected the problem was due to the MASSCOMP. The problems disappeared after the change in operating systems that took place during the PEP implementation, as described in Section 6.1.5. However, the new compilers that came with the PEP also had bugs, and beta test compilers had to be substituted.

Close to the time of Phase IV system delivery, MTI discovered another panic stop. Although a rare occurrence when doing a PF1 report, an operating system crash can disrupt monitoring for 10 min and could result in loss of the data logging information. After nearly eight weeks of analysis, MASSCOMP confirmed that they had seen this problem before, but did not have the solution. Given the choice of MASSCOMP making a special operating system patch or doing a work-around, MTI chose the latter. The work-around was made by adding a small spooler process to handle PF1 reports.

Also near the time of Phase IV delivery, MTI discovered that the host computer would sometimes not be aware of the timer interrupt from the cluster CPU. MASSCOMP replied that the only way to guarantee the interrupt's arrival was to have the cluster CPU assert it, wait for the host computer to see it, and then deassert the interrupt. However, since the operating system has no guaranteed interrupt response time, the cluster would encounter unpredictable delays while generating the interrupt. This approach was not acceptable to the cluster CPU, which operates with submillisecond timing margins. As a work-around, the timing interrupt was moved to the host computer. Although the MASSCOMP timer is not as accurate as the cluster CPU timer, tests showed its accuracy to be adequate.

The program contract originally called for the MTI system to control the tape recorder sourcing data when in playback mode. Operations such as rewind, go to a specific time on the tape, and recycle were expected to be implemented. However, the Air Force had difficulty making the tape recorder control hardware work as expected. MTI met contract requirements as fully as possible by supplying the SGMS with a menu for tape control.

Although MTI encountered a number of technical challenges during the course of this program, all were overcome and no significant system deficiencies exist.

8.0 CONCLUSIONS AND RECOMMENDATIONS

MTI's SGMS has been installed and is fully operational at WPAFB. The system has improved the Air Force's capability to monitor the CRF by providing continuous real-time monitoring of all 108 strain gage channels in both the time and frequency domains. If an out-of-limit vibration occurs, the SGMS instantly alerts the operator so that attention is given to the condition prior to component failure. The system also offers the potential for reduced manpower coverage, allowing operators to devote their attention to more detailed analysis of the test data with assurance that no dangerous operational condition will be overlooked.

MTI's implementation of the SGMS has

- Achieved all functional requirements of the initial specification, with the exception of the tape recorder controller interface.
- Achieved all performance specifications of the initial specification.
- Provided additional utility due to funded enhancements.
- Provided a straightforward path for design expansion to include future advanced time domain monitoring techniques.
- Proven to be a very reliable system; there have been only limited component failures associated with the DSP FFT processors during the year since final installation and no failures during the past four years for the MASSCOMP computer.
- Provided the potential for future addition of software for extensive analysis of tape data. Once the tape recorder controller *difficulty* is resolved, data analysis requests could be configured, and the system could automatically conduct these analyses and produce text and graphical summaries.

MTI has reviewed the results of this program and makes the following recommendations for future directions.

First, the SGMS is a complex system containing in excess of one-half million dollars of electronic components. Although the system has been extremely reliable, MTI recommends that the Air Force improve the prospect of maintaining operation by purchasing the recommended critical spare parts, particularly spare FFT boards. DSP Systems does not stock spares, so turnaround on repairs for this critical system component usually takes weeks.

Second, the SGMS offers tremendous potential for automating the analysis of tape-recorded data. As operators gain experience using the system during live testing and post-test analysis, the value of automated analysis will become evident. MTI recommends that the technical difficulties encountered with the tape recorder controller be remedied and plans be made for including automated post-test data analysis.

Third, the Air Force expressed a desire to have a backup facility that would allow daily saves of the data logging files and configuration files to tape cartridge. This would require appending each day's data onto tape until the tape is full. Unfortunately, the tape drive provided with the MASSCOMP is designed for streaming operation and will not allow append operations. As delivered, the SGMS allows append-style backups only to floppy disk. During 1990, UniSolution Associates of Redondo Beach, California, is expected to have a software package that will allow the types of backups the Air Force wishes. Purchase of this additional software would significantly enhance system backup capabilities.

Finally, the GE and UTRC reports discussed in Section 3.2 indicate that potential exists for computer automation for real-time interpretation and characterization of time domain strain gage data as they relate to aeromechanical phenomena. MTI specifically expanded the SGMS design to accommodate future inclusion of these advanced signal interpretation techniques. The SGMS design provides an ideal platform for initial investigation of several techniques discussed in the above studies. Since the SGMS is integral to the support of the CRF, it is inadvisable to take the system off-line to further the design and evaluate these techniques. Therefore, MTI recommends that an additional subset of the SGMS, perhaps 16 or 32 channels, be constructed and the design expanded in hardware and software to include advanced time domain analysis capability. This smaller implementation of the SGMS could then be thoroughly evaluated using tape-recorded data of known aeromechanical phenomena experienced in the CRF. After this system proved its value and viability for analysis of time domain data, the SGMS at the CRF could be retrofit with the appropriate expansion hardware and software to include these new time domain analysis techniques.

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