AD-A047 408 NAVAL RESEARCH LAB WASHINGTON D C F/G 17/1
EXPERIMENTAL SYSTEM FOR RECIPROCITY - COUPLER CALIBRATION MEASU--ETC(U)
AUG 77 L P BROWDER
UNCLASSIFIED NRL-MR-3570 SBIE-AD-E000020 NL

1 OF 1
ADA047408

END
DATE
FILMED
1 -78
DDC

(12)

AD-E000020

NRL Memorandum Report 3570

AD A047408

Experimental System for Reciprocity-Coupler Calibration Measurements

LYNN P. BROWDER

Materials Section
Standards Branch
Underwater Sound Reference Division
P.O. Box 8336, Orlando, FL 32806

August 1977

DDC
RECEIVED
DEC 12 1977
B

AD No. ____
DDC FILE COPY

NAVAL RESEARCH LABORATORY
Washington, D.C.

Approved for public release: distribution unlimited.

(14) NRL-MR-3570

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NRL Memorandum Report 3570 ✓	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER (9) Interim rept.,
4. TITLE *(and Subtitle)* (6) EXPERIMENTAL SYSTEM FOR RECIPROCITY — COUPLER CALIBRATION MEASUREMENTS		5. TYPE OF REPORT & PERIOD COVERED ~~Interim report~~ on a continuing NRL problem.
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) Lynn P. Browder		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory (Washington, D.C. 20375) Underwater Sound Reference Division P.O. Box 8337, Orlando, FL 32806		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NRL Problem M05-05
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE (11) Aug[redacted] [redacted]77
		13. NUMBER OF PAGES ~~20~~ (12) 21p.
14. MONITORING AGENCY NAME & ADDRESS *(if different from Controlling Office)*		15. SECURITY CLASS. *(of this report)* UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution unlimited.

(18) SBIE

(19) AD-E000 020

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

Electronic system
Semiautomatic reciprocity-coupler
Calibrate underwater sound transducers
Switching matrix controller
Piezoelectric ceramics
Computer calculations

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

An electronic system for calibrating underwater sound transducers at hydrostatic pressure using the reciprocity-coupler method is described. The system includes a relay switching matrix and controller to make prescribed interconnections with speed and reliability. A calculator program is outlined and formulas provided to compute the reciprocity calibration data.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

251950

CONTENTS

ACCESSION for
NTIS White Section ☑
DDC Buff Section ☐
UNANNOUNCED ☐
JUSTIFICATION
BY
DISTRIBUTION/AVAILABILITY CODES
Dist. AVAIL. and/or SPECIAL
A

EXPERIMENTAL SYSTEM FOR RECIPROCITY-COUPLER CALIBRATION MEASUREMENTS

Introduction

This report describes an experimental system developed to facilitate data acquisition of the effects of stress on the piezoelectric and dielectric properties of lead zirconate-titanate ceramics or other piezoelectric materials. The system, which is based on the coupler reciprocity theory, is directly applicable to rapid and accurate automatic calibration of underwater sound transducers in the low-audio frequency range. Reciprocity-coupler calibration is one of a family of methods used to obtain primary calibrations of standard underwater sound transducers [1], particularly where hydrostatic pressure and temperature are controlled. The system is described with detail on the switching matrix and reciprocity calculations so that it may be expanded for more general usage or refined for specialized application.

Background

The reciprocity coupler is a tool that has been applied to various measurement needs in addition to its primary application as an acoustic calibrator. The reciprocity method of calibration has been well-documented [1]; therefore, the theory will not be repeated here. The reciprocity coupler was described in detail by Sims and Henriquez [2]. The technique for using the coupler in evaluating certain piezoelectric and dielectric parameters of piezoelectric ceramic materials subject to one-dimensional stress was developed by Meeks and Timme [3]. The speed of sound in castor oil as a function of pressure and temperature was also measured by Timme in the coupler [4].

Coupler Reciprocity Measurements

A reciprocity calibration requires basic measurements of voltage, current, time (or frequency), mass (or density), and length. The reciprocity coupler is a small stainless-steel acoustic chamber containing three transducers. Transducer A is a reciprocal transducer that serves both as a projector and a hydrophone, while transducer B serves only as a projector, and transducer C serves only as a hydrophone. The latter may be a standard hydrophone that is to have its receiving sensitivity measured or a piezoelectric ceramic material that is to have its characteristics measured. The coupler is filled with DB grade castor oil which is the coupling medium between transducers. The reciprocal transducer A is driven as a projector, and the output voltage e_{CA} from transducer C, is measured. Then, transducer B is driven and the output voltages e_{AB} from transducer A and e_{CB} from transducer C are measured. Also measured is the driving current to transducer A. From these electrical

---

Note: Manuscript submitted July 20, 1977.

measurements the receiving sensitivity of transducer C may be calculated using the formula

$$M_C = \left(\frac{\omega V R e_{CA} e_{CB}}{\rho c^2 e_A e_{AB}} \right)^{1/2} .$$

This is a reciprocity calibration where ω is the angular frequency, V is the volume of the reciprocity coupler, R is the resistor in the current measuring circuit, ρ is the density of castor oil in the coupler, and c is the speed of sound in castor oil. The quantities e_{AB}, e_{CA}, and e_{CB} are the output voltages noted before while e_A is the voltage developed across R by the driving current in transducer A. A comparison calibration of its receiving sensitivity may be calculated using the formula

$$M_A = \frac{M_C e_{AB}}{e_{CB}} .$$

If the voltage e_{BA} is measured and transducer B is also reciprocal, the receiving sensitivity of B may be calculated from the formula

$$M_B = \frac{M_C e_{BA}}{e_{CA}} .$$

Each of the receiving sensitivities must be corrected for the stray-line capacitance loading when the results are to apply to the hydrophone sensor or the piezoelectric sample alone.

The properties of castor oil, c and ρ, have been measured as a function of pressure and temperature and fitted with empirically determined equations. Timme [4] measured the relative sound speed at temperatures from 0 to 40°C and atmospheric pressure to 110 MPa. The data were fitted with the empirical equation

$$\tau = a_0 + a_1 T + a_2 T^2 + a_3 Tp + a_4 p + a_5 p^2$$

where τ is the relative speed of sound, and

$a_0 = 1.000$,
$a_1 = -2.15 \times 10^{-3} / {}^\circ\mathrm{C}$,
$a_2 = 4.0 \times 10^{-6} / ({}^\circ\mathrm{C})^2$,
$a_3 = 2.5 \times 10^{-6} / ({}^\circ\mathrm{C} \cdot \mathrm{MPa})$,
$a_4 = 2.22 \times 10^{-3} / \mathrm{MPa}$,

$a_5 = -3.0 \times 10^{-6}/(\mathrm{MPa})^2$,

T is temperature in degrees Celsius, and

p is pressure in megapascals.

The absolute speed of sound is represented by:

$$c(T,p) = 1570\ (a_0 + a_1T + a_2T^2 + a_3Tp + a_4p + a_5p^2)$$

where 1570 m/sec is the measured sound speed at 0°C and atmospheric pressure. Stallard [5] determined the density ρ as a function of temperature and pressure. The result is the empirical equation

$$\begin{aligned} 1/\rho = {} & b_1 + b_2T + b_3T^2 + b_4T^3 + b_5p + b_6pT \\ & + b_7pT^2 + b_8pT^3 + b_9p^2 + b_{10}p^2T \\ & + b_{11}p^2T^2 + b_{12}p^3 + b_{13}p^3T, \end{aligned}$$

where ρ is the density,

T is temperature in degrees Celsius,

p is pressure in megapascals, and

$b_1 = 1.027$ $\mathrm{cm^3\ g^{-1}}$

$b_2 = 7.038 \times 10^{-4}$ $\mathrm{cm^3\ g^{-1} \cdot (°C)^{-1}}$

$b_3 = 9.659 \times 10^{-7}$ $\mathrm{cm^3\ g^{-1} \cdot (°C)^{-2}}$

$b_4 = 3.045 \times 10^{-9}$ $\mathrm{cm^3\ g^{-1} \cdot (°C)^{-3}}$

$b_5 = -4.909 \times 10^{-4}$ $\mathrm{cm^3\ g^{-1} \cdot MPa^{-1}}$

$b_6 = -2.633 \times 10^{-6}$ $\mathrm{cm^3\ g^{-1} \cdot MPa^{-1} \cdot (°C)^{-1}}$

$b_7 = -4.042 \times 10^{-9}$ $\mathrm{cm^3\ g^{-1} \cdot MPa^{-1} \cdot (°C)^{-2}}$

$b_8 = -8.772 \times 10^{-11}$ $\mathrm{cm^3\ g^{-1} \cdot MPa^{-1} \cdot (°C)^{-3}}$

$b_9 = 1.471 \times 10^{-6}$ $\mathrm{cm^3\ g^{-1} \cdot MPa^{-2}}$

$b_{10} = 9.181 \times 10^{-9}$ $\mathrm{cm^3\ g^{-1} \cdot MPa^{-2} \cdot (°C)^{-1}}$

$b_{11} = 3.591 \times 10^{-11}$ $\mathrm{cm^3\ g^{-1} \cdot MPa^{-2} \cdot (°C)^{-2}}$

$b_{12} = -3.634 \times 10^{-9}$ $\mathrm{cm^3\ g^{-1} \cdot MPa^{-3}}$

$b_{13} = -1.657 \times 10^{-11}$ $\mathrm{cm^3\ g^{-1} \cdot MPa^{-3} \cdot (°C)^{-1}}$.

Thus, the adiabatic compressibility of castor oil, $1/\rho c^2$, may be computed from the measured quantities of temperature and pressure. With the coupler, temperature is controlled by circulating fluid from a temperature bath, and temperature of the castor oil is measured using a calibrated thermister. Pressure of the castor oil is measured with a precision, temperature-compensated pressure gauge.

Volume of the coupler is determined prior to the tests by measuring the volume of methyl alcohol needed to fill the chamber with transducers in place. Other measurements needed to complete the sensitivity calculations are the transducer capacitances and stray-lead capacitances, which are measured using a capacitance bridge, and angular frequency of the acoustic signal that is determined by a frequency counter. The resistor R used to determine driving current is a pre-calibrated standard type.

Electronic Equipment

System Description

Figure 1 is a block diagram of the electronic system used to make the reciprocity measurements and obtain the calculated results. There is a high-voltage transmitting section, a low-voltage receiving section, and a capacitance bridge interconnected to the coupler transducers through a switching matrix. The switching matrix is operated by the switch controller which is manually activated to obtain the particular switching function desired. The digital readings from the receiving section voltmeter and the capacitance bridge are recorded in sequence into the memory of the programmable calculator. When the sequence is complete, the calculator automatically computes the desired hydrophone sensitivities and other parameters and may print or plot the results and record the data on magnetic tape for future processing.

Transmitting Section

Figure 2 is a block diagram of the transmitting part of the system. It contains an oscillator, power amplifier, matching transformer, and frequency counter. The oscillator should have a high order of short-term amplitude stability and good frequency stability. The frequency is continuously monitored by the counter. The power amplifier and matching transformer provide driving power to the reciprocity transducers in the coupler. The driving signal to the transducers should be a sine wave of high quality with low harmonic distortion, and with low hum and noise content. The relay K4 is part of the switching matrix and serves to remove the driving signal when necessary.

Receiving Section

Figure 3 is the block diagram for the low-voltage receiving section. It contains a low-noise receiving amplifier with an adjustable bandpass filter, a precision AC digital voltmeter, an oscilloscope, and the standard current-measuring resistor (1000 ohms). The relay K3-3 is part of the switching matrix, section B is activated in the part of the switching sequence that requires measuring the AC voltage developed by the standard resistor with transducer driving current flowing through it while section A is activated to measure the output voltage of the amplifier. The oscilloscope is included in the receiving section to give a visual indication of the measured waveform to ensure proper operation of the system so that noise and distortion are not present.

Capacitance Measuring Section

The capacitance-measuring capability is included in this system to determine the relative dielectric constant of piezoelectric ceramics as a function of pressure and temperature. The precision capacitance bridge uses its three-terminal measurement configuration in the system to avoid stray capacitance effects.

Switching Matrix Section

A schematic diagram of the switching matrix is shown in Figure 4 and includes connections to the coupler and capacitance bridge. The relays are of the coaxial type having individual driving coils for each switch contact, except for the relay at the power amplifier input, K4, which is a conventional SPDT type.

The switching matrix is composed of two main parts, the first of which is made up of relays K1 and K2. This part directs the transmitting drive signal to transducer A or B and routes the receiving signal from transducer B or A to the receiving section as required to make the reciprocity measurements. The second part contains the relay K3 which directs the receiving signal from transducer C to the receiving section, connects the capacitance bridge to transducer C, or routes the measured current signal to the digital voltmeter. The contacts of relays K1, K2, K3, and K4 are energized in groups simultaneously by the switching controller to perform the required measurement function.

The electrical requirements for relays K1 and K2 are that they shall apply the driving signal from the transmitting section to transducer A or B and the receiving signal from transducer B or A to the receiving section with a minimum of electrical cross talk from the transmitting section to the receiving section. To apply the transmitting signal to transducer A and receive from transducer B, contacts K1-1B, K1-3B, K1-2B, K1-4B, K2-1, and K2-2 are energized to close. The double break contacts of K1-1A, K1-2A, K1-3A, and K1-4A with the grounding action of contacts K2-1 and K2-2 effect a high level of electrical isolation between the transmitting and receiving sections. Conversely, to drive transducer B and receive from transducer A, contact K1-1A, K1-2A, K1-3A, K1-4A, K2-3, and K2-4 are energized to close. Electrical isolation is provided by open contact K1-1B, K1-3B, K1-2B, and K1-4B with closed contacts K2-3 and K2-4. Measurements have shown that 100 volts on the transmitting side of the matrix will result in less than 10 microvolts on the receiving side, or approximately 140-dB isolation.

The relays K3 and K4 are used for signal routing and control purposes. To apply the received signal from hydrophone C to the receiving section, relay contacts K3-1A, K3-2A, and K3-3A are energized to close. At the same time, either transducer A or B must be driven by the transmitting section through the contacts of relay K1. The current flowing through transducer A is measured when the driving signal is applied and relay contact K3-3B is closed. The capacitance of hydrophone sensor C is measured by the capacitance bridge when relay contacts K3-1B and K3-2B are closed. Relay K4 is energized only when a driving signal to one of the transducers A or B is required.

Switching Controller Section

The switching controller activates groups of relay contacts to perform the required measurement functions. Figure 5 is a switching logic diagram of a controller that will make the sequence of measurements required to compute a coupler reciprocity calibration and to determine the relative piezoelectric and dielectric constants of the material of transducer C.

There are five AC-voltage measurements, a measurement of capacitance (and dissipation factor D), and a short-circuit operation to discharge the piezoelectric material before measurement. The logic diagram may be implemented using a manual switch and a diode matrix similar to that shown in Figure 6. The short-circuit operation occurs on alternate switch positions.

Modifications for Automatic Control

The system may be adapted readily to automatic operation of data acquisition and computation if a computer or programmable calculator with adequate interfaces is used. The following modifications to the basic system are required.

- Computer control of the switching matrix relays.
- Computer control of the oscillator frequency and output level.
- Read-in of BCD coded information from the digital AC voltmeter and capacitance bridge to the computer.
- Read-in of pressure and temperature information to the computer.

Calculations

The reciprocity calculations were made with a medium-power programmable calculator. The constants and variables used in the mathematical formulas were first stored in memory by the calculator program.

Then the computations were made and the results printed, plotted, or stored on magnetic tape for further use. The sequence of operations by the calculator is as follows:

Step 1 - Print paper tape heading including test date and special hydrophone data.

Step 2 - Enter and store in memory the constants needed by the formulas including coupler volume, V; current resistor value, R; amplifier gain, G; permittivity of free space, ε_o; capacitance of reciprocity transducers C_A and C_B; stray lead capacitances to transducers C_{LA}, C_{LB}, and C_{LC}; and effective area, A_c, and thickness, t_c, of the material in transducer C.

Step 3 - Print the formula constants on paper tape.

Step 4 - Enter and store in memory the test variables needed by the formulas including frequency, f; pressure, p; temperature, T; capacitance of transducer C, C_c; and the reciprocity voltage measurements e_A, e_{BA}, e_{CA}, e_{CB}, and e_{AB}.

Step 5 - Print the test variables on paper tape.

Step 6 - Compute $1/\rho c^2$ using the formulas from reference [4] and the values of p and T.

Step 7 - Compute the receiving sensitivity of transducer C, M_c, using the formula:

$$M_c = \left(\frac{2\,\pi\, f\, V\, R\, e_{CA}\, e_{CB}}{\rho c^2\, e_A\, G\, e_{AB}} \right)^{\frac{1}{2}} .$$

Step 8 - Compute the corrected receiving sensitivity of transducer C, M_c', using the formula:

$$M_c' = M_c \left(\frac{C_c + C_{LC}}{C_c} \right) .$$

Step 9 - Compute the corrected receiving sensitivity of transducer A, M_A', using the formula:

$$M_A' = \left(\frac{M_c\, e_{AB}}{e_{CB}} \right) \left(\frac{C_A + C_{LA}}{C_A} \right) .$$

Step 10 - Compute the corrected receiving sensitivity of transducer B, M'_B, using the formula:

$$M'_B = \left(\frac{M_c\ e_{BA}}{e_{CA}}\right)\left(\frac{C_B + C_{LB}}{C_B}\right) .$$

Step 11 - Compute the logarithmic receiving sensitivity of transducers A, B, and C in units of dB re 1 V/μPa using the formulas:

$$M_{ADB} = 20 \log M'_A - 120$$
$$M_{BDB} = 20 \log M'_B - 120$$
$$M_{CDB} = 20 \log M'_c - 120.$$

Step 12 - Print the computed values of M_{ADB}, M_{BDB}, and M_{CDB} on paper tape.

Step 13 - To compute the piezoelectric constants g_{33} and d_{33} and the relative dielectric constant K^T_{33} of the material in transducer C, use the following formulas

$$K^T_{33} = \frac{C_c\ t_c}{A_c\ \varepsilon_o} ,$$

$$g_{33} = \frac{M'_c}{t_c} \quad \text{V m/N, and}$$

$$d_{33} = g_{33}\ K^T_{33}\ \varepsilon_o \quad \text{m/V.}$$

Step 14 - Print the computed values of K^T_{33}, g_{33}, and d_{33} on paper tape.

Step 15 - Stop the computer program to examine the printed results and determine correctness.

Step 16 - Plot the computed results with an X-Y plotter, if desired.

Step 17 - Store the computed results on magnetic tape files together with pressure and temperature data if further machine processing is desired.

Step 18 - Return to step 4 and repeat the calibration measurement procedure for the next data point.

Steps 1, 3, 5, 12, 14 and 15 may be omitted for the purpose of increasing the program speed if printed data are not required and a simple X-Y plot of computed results is sufficient.

Measurement Results

This system was constructed and used with a series of measurements involving compressional stress on ceramic materials. Two transducers constructed of lead metaniobate were used in positions A and B with the test sample located in position C. Transducer A had been pressure stressed more than 50 times in the coupler, whereas transducer B was built from new material before the test series. The relative receiving sensitivities of transducers A and B during the test series is shown in Figure 7. The resolution of calibration points appears to be about ±0.01 dB. These curves do not give an indication of the calibration accuracy since this is dependent on the accuracy of the measurements of constants and variables used in the computations. The worst case analysis of the errors involved indicates a possible bias to the results of as much as ±0.12 dB and a random error of about ±0.05 dB. Most of the bias error is due to the uncertainty of the absolute speed of sound in castor oil at 0°C and atmospheric pressure. For further refinement of the system greater accuracy in the measurements of pressure, temperature, volume, frequency, and AC voltage would be required because each of these contributes about an equal amount to the bias and random error factors. Since these errors are small, the calibration accuracy is adequate for most practical measurements.

Conclusion

The calibration system described has been tested through use and found to provide calibration measurements with operational ease. The equipment has been shown to operate reliably and to give repeatable results.

References

[1] R. J. Bobber, *Underwater Electroacoustic Measurements* (Naval Research Laboratory, U. S. Government Printing Office, Washington, D. C., 1970).

[2] C. C. Sims and T. A. Henriquez, "Reciprocity Calibration of a Standard Hydrophone at 16,000 psi," J. Acoust. Soc. Am. 36, 1704-1707 (1964).

[3] S. W. Meeks and R. W. Timme, "Effects of One-Dimensional Stress on Piezoelectric Ceramics," J. Appl. Phys. 46, 4334-4338 (1975).

[4] R. W. Timme, "Speed of Sound in Castor Oil," J. Acoust. Soc. Am. 52, 989-992 (1972).

[5] J. M. Stallard, "Some Thermodynamic Properties of Castor Oil vs. Temperature and Pressure," NOLTR 66-68, Naval Ordnance Lab., White Oak, MD., April 1966.

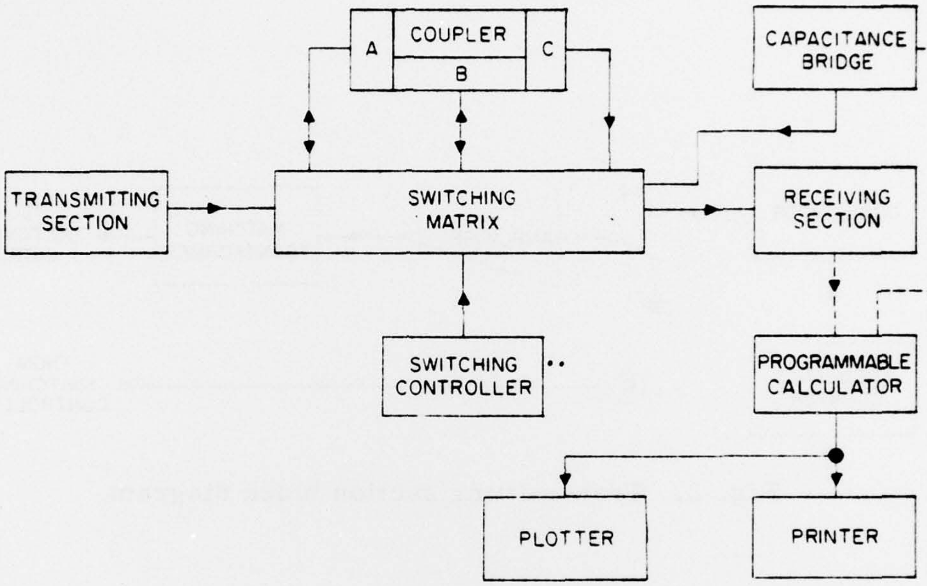

Fig. 1. System block diagram

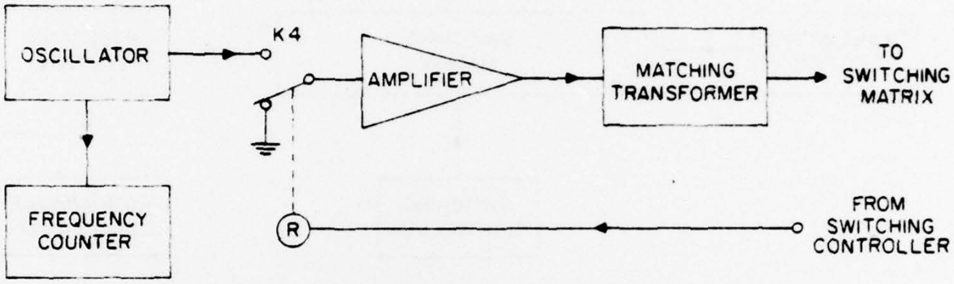

Fig. 2. Transmitting section block diagram

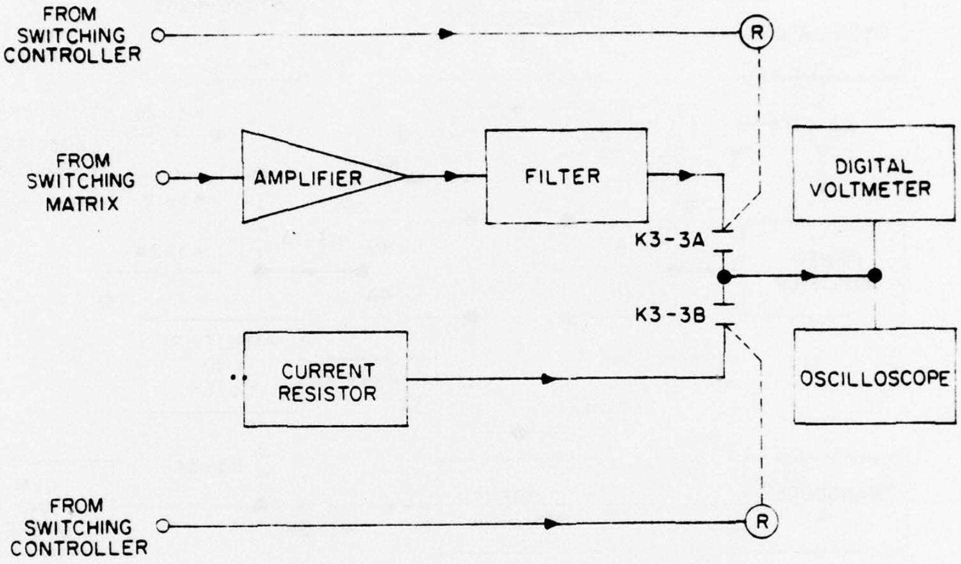

Fig. 3. Receiving section block diagram

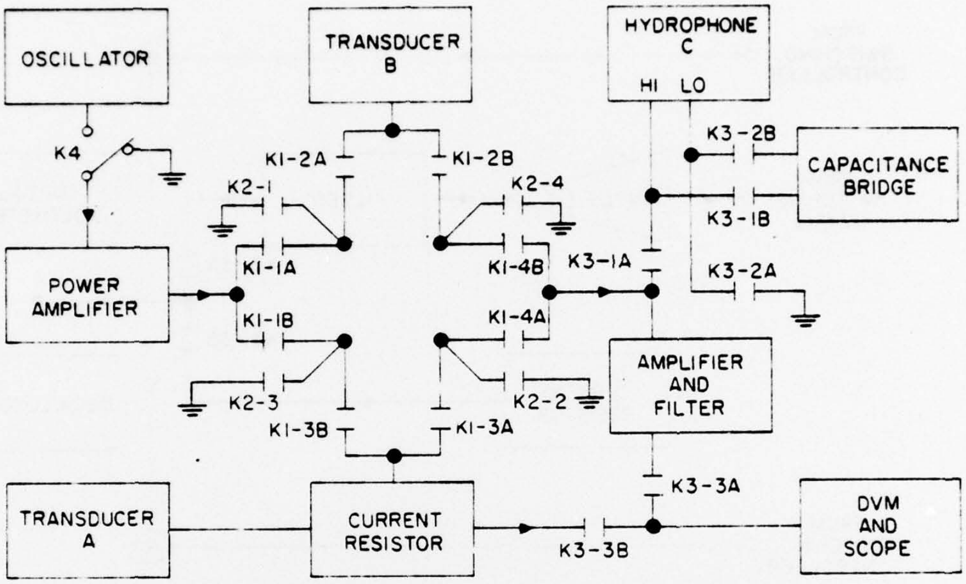

Fig. 4. Switching matrix schematic diagram

[illegible]EMENT	RELAY K1				K2		K3				K4
	1A 2A	1B 3B	3A 4A	2B 4B	1 2	3 4	1A 2A	1B 2B	3A	3B	
[illegible]			○	○	○		○				
2. e_{A}		○			○					○	○
3. e_{BA}		○		○	○				○		○
4. e_{CA}		○			○		○		○		○
5. e_{CB}	○					○	○		○		○
6. e_{AB}	○		○			○			○		○
7. C_{c}, D_{c}				○				○	○		

(○) – CONTACT CLOSURE

Fig. 5. Switching logic diagram

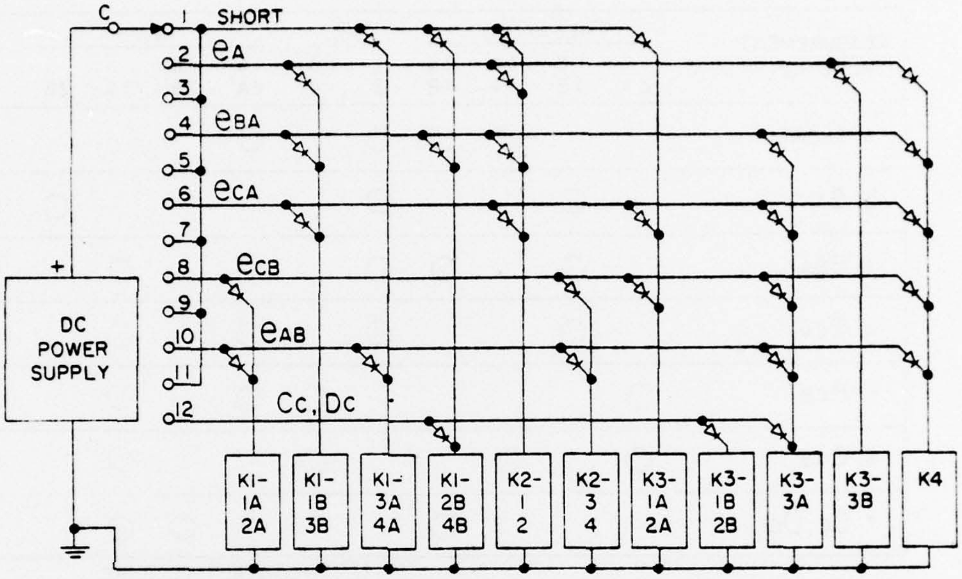

Fig. 6. Switching controller schematic diagram

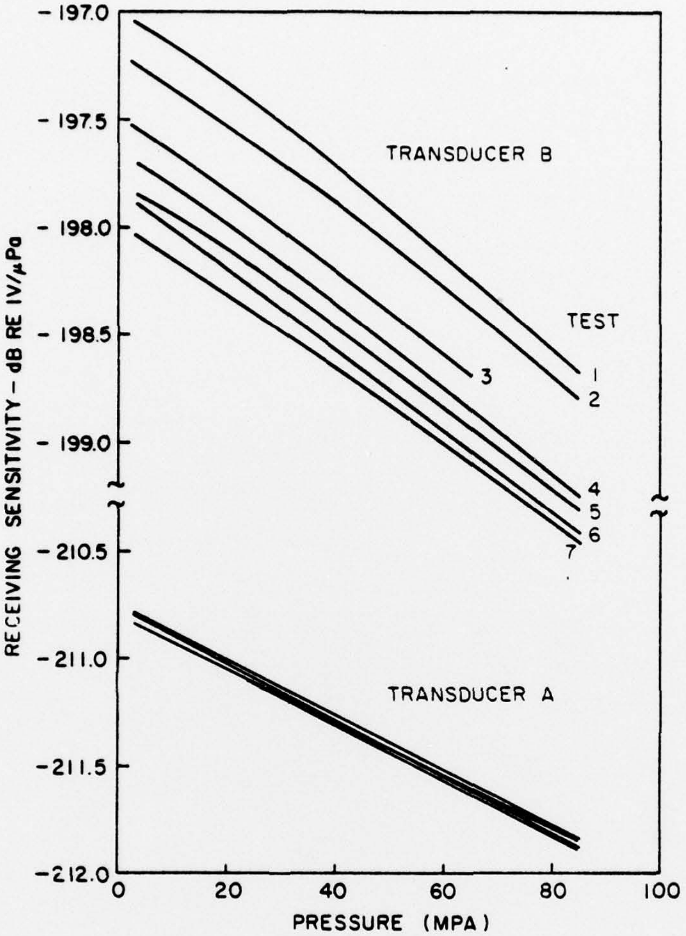

Fig. 7. Sensitivity under hydrostatic pressure