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Space Shuttle Pogo Pressure Measuring System A Progress Report

Paul S. Lederer and John S. Hilten

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Institute for Applied Technology
National Bureau of Standards
Washington, D. C. 20234

March 1, 1975

Progress Report Covering Period
September 15, 1973 to December 15, 1973

Prepared for

NASA George C. Marshall Space Flight Center
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This is a progress report. The work is incomplete and is continuing. Results and conclusions are not necessarily those that will be included in the final report. Performance test data were obtained from one or two samples of several transducer types, and do not necessarily represent the characteristics of all transducers of a given type.

Prepared for
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Huntsville, Alabama 35812

U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

ABSTRACT

This progress report describes continuing development of methods for the dynamic calibration of pogo pressure transducers used to measure oscillatory pressures generated in the propulsion system of the space shuttle. The requirements are for the generation of a known (5% or better) sinusoidal pressure perturbation of 140 kPa (approximately 20 psi) peak-to-peak at bias pressures up to 55 MPa (approximately 8000 psi) over a frequency range of from 1 Hz to 100 Hz. Rotation of a mercury-filled column in the vertical plane at frequencies of 10 Hz and below has produced peak-to-peak pressures of 39 kPa (5.7 psi) at bias pressures of up to 55.4 MPa (8030 psi). Evaluation of some variable-impedance, semiconductor strain-gage, piezoelectric, and metallic strain-gage pressure transducer systems for suitability as pogo sensors is described.

Key words: calibration; dynamic; high pressure; orbiter vehicle; pogo; pressure; pressure transducer; sinusoidal; space shuttle.

SPACE SHUTTLE POGO PRESSURE MEASURING SYSTEM

Progress Report for the Period
From September 15, 1973 to December 15, 1973

to the

George C. Marshall Space Flight Center
NASA Order #H-02100A
NBS Project 4253448

Prepared by

Paul S. Lederer
and
John S. Hilten

1. INTRODUCTION

The objectives of this project include (1) the development of a dynamic pressure calibration method for pogo pressure transducers used to measure oscillatory pressures generated in the propulsion system of the space shuttle and (2) the procurement and evaluation of several commercial transducers to determine their suitability for the measurement of such pogo pressure perturbations. Specified is a full-scale range of 140 kPa (approximately 20 psi)* peak-to-peak at bias pressures up to 55 MPa (approximately 8000 psi) over a frequency range of from 1 Hz to 100 Hz. Transducers used for shuttle pogo measurements will be required to operate at temperatures within the range of from -253°C (-423°F) to about 480°C (900°F), depending on the final choice of their location within the propulsion system of the space shuttle orbiter vehicle. The definition of objectives will be suitably modified to take into account detailed environmental parameters for the transducers when these factors become known. Current efforts are therefore to develop a suitable dynamic pressure calibration technique for use at ambient laboratory temperature, as the most convenient working temperature within the specified range. The previous progress report covering the period from January 15, 1973 to September 15, 1973 [1]** described the selection and initial development of suitable dynamic pressure calibration techniques; this report discusses test results for four commercial transducer types, as well as some additional investigations of calibration methods.

2. TESTS PERFORMED

2.1 Transducer Systems Available for Testing

A variable-impedance pressure transducer system was received in early September 1973. Two piezoelectric pressure transducers were received in September 1973

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* 1 kPa = 0.145 psi, 1 MPa = 145 psi.
** Figures in brackets refer to references, section 7.

to be used with the piezoelectric pressure-sensing system and transducers already received, and two pressure-sensing systems based on strain gages were delivered in November 1973. One of these systems consists of semiconductor strain-gage transducers with an ancillary electronics package; the other is a metallic strain-gage transducer.

2.2 Tests on Variable-Impedance Transducer System

The variable-impedance pressure transducer operates on an eddy-current principle. Position of a metal diaphragm (which senses the pressure) relative to a coil energized by an alternating current determines the magnitude of eddy currents induced in the diaphragm. The eddy currents, in turn, reflect a change in impedance back into the coil, thus resulting in a variable-impedance transducer. The system tested has an additional coil and fixed metal plate to provide a second arm of an a-c bridge. An ancillary electronics package contains oscillator and demodulator circuits. The bridge is connected to the electronics with special cable; the portion adjacent to the pressure sensor is a rigid metal conduit about 50-cm long. The system is shown in figure 1.

As indicated in the previous report, an experimental dynamic calibration resulted in the expected output of about 1 mV for a 69-kPa peak-to-peak pressure fluctuation. More complete static calibration of the system has now been accomplished. Figure 2 shows one of the results of these static calibrations performed from 0 to 55.2 MPa. Linearity (maximum deviation from computed least-squares straight line for all points) was 0.9% maximum hysteresis observed was 1.0% full scale, and full-scale repeatability of the three consecutive calibrations was within about 0.1%. However, because of the fact that the measured sensitivity of this transducer system was only 0.0183 mV/kPa (0.126 mV/psi) resulting in a full-scale value only slightly greater than 1 volt, the dynamic calibration at a bias pressure of 55.2 MPa produced outputs heavily distorted by system noise. This can be seen in figures 3 and 4, which show the results of calibrations at 50 Hz and 100 Hz, and at acceleration levels of 40 g_n and 80 g_n peak-to-peak (corresponding to 52 kPa and 103 kPa, respectively). This calibration was performed using the vertical, closed, liquid-filled calibration tube on the electrodynamic vibration exciter.

The results of these tests, the constraints imposed by the length of rigid conduits, and the associated bulky system electronics do not recommend this pressure-measuring system for pogo pressure-measuring applications. Other sensors tested show greater promise to meet the pogo measurement system needs.

2.3 Tests on Semiconductor Strain-Gage and Amplifier System

The semiconductor strain-gage pressure measurement system consists of a pressure transducer using semiconductor strain gages as sensing elements and an electronics package. Both are shown in figure 5. The system produces two output signals. One is proportional to the bias pressure with a full-scale value of 5 V for the range 0 to 55.2 MPa; the other represents the pogo pressure fluctuations with a full-scale design output of about 5 V for 140 kPa peak-to-peak. The manufacturer of this sytem furnished three pressure transducers and one electronics package; tests were performed on all three transducers. In this case, also, the linearity of the calibration data was determined from the least-square straight line for all calibration points. The calibration curves of the three pressure transducers are non-linear. Figure 6 shows the characteristics of transducer E-3. The other two transducers are somewhat less non-linear and have smaller hysteresis also. Their calibrations are not shown. Performance parameters of transducers E-1, E-2, and E-3, respectively, are as follows: sensitivity, 0.0927, 0.0935, and 0.0908 mV/kPa (0.639, 0.0643, and 0.626 mV/psi) averaged over the entire range; linearity, 5.51, 3.99, and 6.27 % full scale; and hysteresis, 1.64, 2.04, and 7.55 % full scale.

Measures of repeatability obtained from three consecutive calibrations of each transducer at full scale are E-1, 0.25; E-2, 0.18; and E-3, 0.22 % full scale.

The dynamic calibrations were performed at two bias pressures, 7.1 MPa and 55.4 MPa, over a frequency range of from 20 Hz to 100 Hz. The results of these calibrations are shown in figure 7. During these calibrations, data were obtained simultaneously from a quartz crystal pressure transducer, A-3, which had been previously calibrated using the liquid-filled tube method on the vibration exciter. The data were analyzed and the results are compiled in table 1. In view of the relatively large non-linearity observed, transducer sensitivity was determined at the two ends of the full-scale range. These data are also given in table 1. The values of static sensitivity supplied by the manufacturer under these conditions are within +0.7% of the measured calibration values.

The manufacturer did not supply performance figures based on dynamic calibration but indicated that the output would be about ±2.5 V for dynamic pressure levels of 140 kPa peak-to-peak, or about 0.036 V/kPa. Experimentally determined values were considerably larger, as can be seen in the table. More disturbing than this, however, was the large disagreement between dynamic calibration data obtained at the two bias pressures used in these tests. These disagreements ranged from 0.7% for E-3, to 10% for E-2, and to 37.4% for E-1. Part of the disagreement may be due to the non-linearity of the transducer's static calibration characteristics, as shown in this table also. Smaller deviations from linearity in the static calibration characteristics seem to correlate with smaller amounts of dynamic non-linearity.

In these dynamic calibrations a piezoelectric transducer previously calibrated was also mounted in the test apparatus and exposed to the same pressures as the transducer under test. Although data obtained with this reference transducer showed a systematic error of about 6%, this data indicated that the dynamic pressure generated by the system is virtually unaffected by system bias pressure. Similar piezoelectric transducers previously tested had shown variations in sensitivity of about 2% to 4% with bias pressures from 6.9 MPa to 55 MPa; the particular reference transducer used in this test showed a maximum observed variation of 2%.

During the dynamic calibrations of the transducers, the maximum noise level observed was about 34 mV rms, corresponding roughly to an equivalent pressure of 2.6 kPa peak-to-peak, or about 2% of the expected full-scale range of the transducers. The results from dynamic calibration at frequencies of from 20 Hz to 100 Hz are shown in figure 7.

Conclusions about the semiconductor strain-gage system are (1) this approach appears to have potential for pogo measurements, but (2) further development is required to reduce the observed variation in sensitivity with bias, and (3) the electronic circuitry will require repackaging for flight rating.

2.4 Strain-Gage Differential Pressure Transducer

A metallic strain-gage transducer was ordered and received in November 1973. The transducer, shown in figure 12, consists of two pressure chambers connected through an adjustable leak and separated by a diaphragm which responds to the pressure difference between the chambers. The manufacturer stated that "...any steady pressure applied to the transducer will, in time, equalize in the two pressure chambers and no reading will be obtained. However, if a dynamic component is superimposed on the steady pressure, it will not have time to leak through and will appear as a pressure difference across the diaphragm." Thus, this transducer's frequency response is not flat down to zero frequency; the low-frequency characteristics are controlled by the adjustable-leak valve. In view of its design principle and its large size (note the scale in figure 12) and mass of 2.8 kg (6.3 lb.), this transducer type is judged as being not likely to offer any advantages over the other systems tested. Only a limited number of tests will, therefore, be performed on this transducer.

2.5 Tests on Piezoelectric Pressure Transducers

Two additional piezoelectric pressure transducer systems were purchased and received in November 1973. One of these systems is shown in figure 8. The instruments were calibrated dynamically using the liquid-filled closed tube on the vibration exciter. One of the instruments, A-4, showed a considerable low-frequency roll-off in its amplitude-frequency response. This is apparent from figure 9 which shows the amplitude-frequency response of this instrument and of A-3, which was previously received and calibrated. In addition, the dynamic sensitivity of transducers A-4 and A-5 varies with bias pressure. Values of sensitivity supplied by the manufacturers for A-3, A-4, and A-5 at 6.9 MPa (1000 psi) are 5.87 mV/kPa, 4.38 mV/kPa, and 4.51 mV/kPa, respectively. Calibration data are presented in table 2. The sensitivities at 55 MPa of both A-4 and A-5 are about 9% less than their sensitivities at 7.1 MPa. In contrast, A-3 shows only a 0.5% change in sensitivity at these respective bias pressures. Both graphs and tabular data show that the frequency response of A-4 rolls off considerably at low frequencies, falling at 20 Hz to about 80% of the 50-Hz values. The manufacturer suggested that moisture might have been absorbed by the sensor, thereby reducing the insulation resistance. The manufacturer's recommendation to bake the transducer at 100°C under vacuum for two hours was followed; recalibration after this treatment showed no improvement in the low-frequency response. Accordingly, transducer A-4 was returned to the factory for repair.

The piezoelectric type of pressure transducer appears to be the most suitable type evaluated for pogo application. This statement is made on the basis of the experimental results and on conclusions derived from tests to date and on the basis of considerable experience with pressure transducer evaluation and performance analysis. System size and availability and a predicted lower operating temperature in the cryogenic range also contribute to the suitability of piezoelectric designs for pogo application.

3. MEASUREMENT PROBLEMS AFFECTING CALIBRATION

Calibration test results for piezoelectric pressure transducers at various times have shown inconsistencies and lack of repeatability. Anomalous results have also been observed for strain-gage transducers. Experiments have indicated two possible sources of discrepancy, and some additional testing was done to explore the effects of cable location and power supply parameters.

3.1 Cable Position Effects on Transducer Output

The cable position, cable route, and the manner in which the cable connecting the transducer to the power supply is restrained have been observed to have an apparent effect on transducer sensitivity. Accordingly, tests were performed in which the flexible cable from transducer A-3 was secured in different ways. In all cases, a line-powered supply was used. The test results are compiled in table 3. The cable was first led out straight from the transducer (mounted on the liquid-filled calibration tube) to the shaker body, where it ran over a plastic foam mat. In other tests, a 12.7-cm length of cable was formed into a loop between the transducer and a point of attachment on the liquid-filled tube. Shorter loops were used in other tests. Results from these tests were not consistent enough to attribute changes to particular cable configurations, but only to indicate overall repeatability to be within about 1.5% at 100 Hz. However, results with the 7.6-cm loop (see table 3), for which an increase in sensitivity of about 4% was observed, are suggestive. In this case bending the cable into a tight loop caused a side force to be exerted on the connector end of the transducer, possibly changing the preloading condition on the piezoelectric crystal sensing element within the transducer. Observations made during earlier transducer tests tend to confirm this. Manual pressure exerted laterally on the connector end of the transducer causes the transducer output to change amplitude during a dynamic calibration with all other conditions unchanged.

On the basis of these results, a requirement for good measurement repeatability is that the cable from the transducer should be secured near the transducer but without exerting any significant force on the connector end of the transducer. This conclusion applies specifically to the piezoelectric transducer type tested but may be more general.

3.2 Power Supply Effects on Transducer Output

Concern was caused by discrepancies observed during various tests of the semiconductor strain-gage transducers in which the actual output of piezoelectric reference transducer A-3 was 4% to 7% greater than that computed from its previous dynamic calibration.

A series of short tests was conducted on transducer A-3. In these tests frequency response characteristics were run between 25 Hz and 150 Hz at bias pressures of 7.1 MPa and 55.4 MPa, and with the cable from the transducer to the power supply looped at the transducer and attached to the liquid-filled tube or led out straight and supported by foam plastic (the effects of cabling are discussed in section 3.1). Overall repeatability of calibration using the line-powered supply S-7 at both bias pressures and with the cable looped or straight was found to be within about 2%.

In two further sets of tests the effect on transducer output of varying selected power supply parameters was investigated. Transducer A-1 was used in each set of tests and was mounted in the base of an open oil-filled tube with about 30 cm of liquid head. In the first test a battery-powered supply, S-1, was used. After d-c supply current and d-c voltage at the transducer were measured with the vibration exciter at rest, transducer output at ±10 g_n and 100 Hz was measured. An electronically regulated voltage supply was substituted for the battery in S-1. Transducer supply current and voltage were measured and transducer output at ±10 g_n and 100 Hz recorded for ten values of supply voltage, from 15 V to 24 V. The results are plotted in figure 10. It can be seen that over the entire range of externally supplied voltage, transducer output changed only about 0.2%. Transducer supply current was observed to remain at 0.9 mA over this range of voltages. It is interesting to note that transducer output was from 0.5% to 1% higher with a battery-powered supply, even though transducer supply current and voltage fell within the range of values obtained with the electronically regulated supply.

In another series of tests, line-powered supply S-6 was connected to the same transducer A-1 and measurements were made at ±10 g_n and 100 Hz. In these tests, the d-c current was measured and set; the results are shown in figure 11. It can be seen that in this case transducer output varies inversely with supply current, changing about 4% over the range of from 2 mA to 20 mA. Repeatability of this characteristic was within about 0.5%. Use of another line-powered supply, S-7, also resulted in a similar straight-line characteristic, but differed by about 1.2% from that of figure 11 at all current levels. Additional investigations of the effects of power-supply parameter variations on transducer output are planned.

The work described above shows that the use of a particular power supply may have a marked effect on the apparent sensitivity of a piezoelectric pressure transducer. Since the manufacturer does not indicate the type of power supply used in his calibrations, it is difficult to make valid comparisons between calibrations by the manufacturer and by NBS. The instruction books furnished with the specific transducer used in these tests indicate that both the power supplies are essentially constant-current sources, with the battery-powered supply set by the manufacturer to deliver 2 mA. The line-powered supply, on the other hand, can be adjusted to deliver currents between the recommended limits of 2 mA and 20 mA. The manufacturer states in his instruction book: "...often, when driving long lines or loads which require heavier currents, it is found that it is desirable to increase transducer current up to a maximum of 20 mA. On the other hand, noise and stability criteria dictate lower currents, in the 2 to 4 mA range." No further information is given on the level of current to use for any given application.

3.3 Summary of Measurement Problems

A summary of observed measurement problems affecting calibration follows. Variations of as much as 7.6% in the output of a particular transducer were observed when different power supplies were used and with all other dynamic calibration conditions unchanged and the system in an as-received state. When a transducer was used with a particular supply with a known or controlled current level, the range of transducer output values for a given set of measurement conditions was observed not to exceed 1.2%. Effects of cable position except for extremely tight loops appear to affect piezoelectric transducer output less than 1%. The mechanism responsible is probably a preloading of the sensitive element.

4. DEVELOPMENT OF DYNAMIC PRESSURE CALIBRATION TECHNIQUES

4.1 Tube Mass Effects

Following one of the early windmill-apparatus experiments, the calibration tube in which the transducer was mounted was removed from the windmill apparatus and attached to the vibration exciter for a corroborative dynamic calibration. A systematic difference was found between the data obtained from this calibration procedure and the data from the windmill apparatus. The observed discrepancies appear to stem from deviations in behavior from the implicitly assumed perfect rigidity of the tube material and the tube closure. Vibrational modes are excited in the tube by the vibration exciter, and these modes couple into the fluid via associated changes in tube volume.

For an experimental investigation, a symmetrical closed tube was constructed with identical mounting blocks at each end and with the filling connection located midway on the tube. Two similar piezoelectric pressure transducers, A-1 and A-2, were used, one mounted at each end of the tube. A number of 100-g weights were fabricated to be attached individually or in combination at the free end of the tube. The tube was filled with oil and pressurized to the desired bias pressure, 7.1 MPa or 55 MPa, attached by one end to the vibration exciter, and driven at 50 Hz with an amplitude of 5 g_n. Outputs of the two transducers were read for a series of loadings of the free end of the tube accomplished by adding weights in increments of the order of 100 g up to a 600-g total added mass. The tube was then reversed end-to-end, and the measurement procedure was repeated. The entire procedure was performed at each of the two bias pressures. The resulting data are plotted in figure 13.

The results of the experiments are qualitatively consistent with excitation of an axial compression mode in the tube. The pressure seen by the transducer under calibration is the sum of the component generated by acceleration of the pressurizing fluid and a component generated by volume changes of the tube, which are in turn the result of acceleration of the tube.

For a tube of uniform cross section and wall thickness, and considering only the axial mode and neglecting the mass of the closure plug and of the monitor accelerometer, the compressive force will be the product of half the tube mass and the acceleration, since the mass is assumed to be distributed uniformly over the length. The change in volume is proportional to the compliances of the tube and of the fluid. The contribution of tube vibration for frequencies sufficiently far below resonance is in phase with the fluid acceleration component of pressure at the tube end proximal to the shaker and, consequently, out of phase at the distal end. The components will, therefore, add and subtract, respectively, at the two ends. At the midpoint of the tubes, where the component contributed by tube acceleration is zero, only the component contributed by the fluid acceleration is present to a first-order approximation.

Adding additional mass at the distal end of the tube increases proportionally the compressive forces acting on the tube (at twice the rate of an equal change in distributed tube mass). In figure 13 the outputs of the transducers are plotted against the computed compressive forces (the product of acceleration and the sum of half the distributed mass and the added mass). The indication of the proximal transducer increases linearly with increasing mass and that of the distal transducer decreases at the same rate with increasing mass, consistent with the analysis. If the readings are extrapolated to lower mass, the two curves intersect at zero mass at a pressure reading corresponding to the pressure component generated by the fluid acceleration alone, again consistent with the analysis.

Other vibrational modes such as flexure and radial distension modes, which are much more difficult to analyze, can be suppressed in practice by increasing wall thickness. Increased wall thickness also has the effect of adding mass to the tube end, but to a first-order approximation greater thickness does not change the contribution of the distributed mass. Further work is planned to confirm the findings reported here sufficiently to permit reliable application of appropriate corrections when the closed-tube method of calibration is used.

4.2 Dynamic Calibration of Piezoelectric Pressure Transducer on Windmill Apparatus and Electromagnetic Vibration Exciter

The windmill calibration apparatus described in the previous progress report [1] was used with some modification to calibrate piezoelectric pressure transducer A-3. This transducer had been calibrated previously on this apparatus using a closed oil-filled tube at zero bias pressure. The length of the original tube was limited by space constraints, and with oil filling the maximum pressure generated was 5.9 kPa, peak-to-peak.

A new tube was made of stainless steel of adequate strength to withstand the desired bias pressures. The tube was filled with 29.2 cm of mercury, topped by 7.6 cm of oil. The oil served to isolate the mercury from oil in the piston gage which was used to generate the bias pressure. With mercury, pressures of 39 kPa peak-to-peak were achieved on the windmill apparatus. Subsequently, the tube was detached and mounted vertically on the vibration exciter. Sinusoidal pressures with amplitudes up to 140 kPa were recorded.

These tests were performed with the tube pressurized to a bias pressure of 7.1 MPa, and, for a final windmill test, to 55.4 MPa. The tube was pressurized while mounted on the windmill apparatus, the tube was sealed off, and the piston-gage pressure generator disconnected from the tube. This technique proved satisfactory in that no significant drop in bias pressure was observed during any test run. The test results are shown in figure 14 and indicate a very satisfactory agreement between calibration points from the two different calibration methods. These calibrations covered a frequency range of from 2 Hz to 5 Hz on the windmill apparatus, and from 15 Hz to 100 Hz on the vibration exciter. As indicated earlier, the windmill apparatus is restricted to operation above about 2 Hz by drive limitations, and below about 5 Hz by balancing problems.

The use of mercury was also successful in part, in that its higher density (compared to oil) permitted generation of much larger pressures. One major discrepancy observed was that the actual pressures obtained were about 20% greater than those calculated based on a closed-tube system. The discrepancy is thought to result from the compliance of the oil, which causes the system behavior to shift in the direction of that of an open-tube system. If the calculation is based on an open tube containing the same amount of mercury, the measured results are about 8% smaller than calculated. The use of two liquids with significantly different compressibilities resulted in a calibration tube that behaved as some combination of the behavior theoretically predicted for both open and closed tubes for a given liquid.

The results of these tests demonstrates the feasibility of the mercury-filled windmill calibration method. In view of the observed anomalous behavior, redesign of the tube and filling system is indicated to ensure that no oil is inside the tube.

A new windmill apparatus is under construction to provide better low-frequency operation (down to at least 0.5 Hz), to improve balancing capabilities for better high-frequency operation (up to at least 15 Hz), and to improve signal-to-noise characteristics through the use of improved slip rings.

Use of a mercury-filled tube on both the windmill calibration apparatus and on the electrodynamic vibration exciter has been selected as the method best suited to meet the pogo pressure calibration requirements.

5. TRANSDUCER PROCUREMENT

Two additional piezoelectric pressure transducers are on order to replace A-3 and the defective A-4; these transducers will be designed to withstand a higher rate of bias pressure build-up of 110 MPa/s. Also, low-frequency response will be 3 dB down at 0.5 Hz instead of at 1 Hz as in earlier versions.

Two low-impedance piezoelectric pressure transducers with external combination amplifier-power supplies are on order with a pressure capability of up to 103 MPa and a sensitivity of 0.15 mV/kPa.

6. FUTURE PLANS

Tasks for the Reporting Period December 15, 1973 to June 15, 1974 are the following:

(1) Completion of windmill calibration apparatus.
(2) Development of an improved method for filling calibration tubes.
(3) Calibration of four commercial transducer types over the frequency

range of from 0.5 Hz to 100 Hz and at bias pressures up to 55.4 MPa. Calibrations will be performed with a mercury-filled calibration tube on both the windmill apparatus and electrodynamic vibration exciter.

(4) Feasibility study of calibrations at temperatures both higher and lower than laboratory ambient. The timing of this task depends on prior verification of satisfactory calibration methods at laboratory ambient.

(5) Monitoring advances in the pressure transducer art, in particular the introduction of new commercial types. Samples of systems or transducers judged to be suitable for pogo application will be procured following consultation with the sponsor.

7. REFERENCES

[1] Hilten, J. S., and Lederer, P. S., Space Shuttle Pogo Pressure Measuring System -- Progress Report for the Period January 15, 1973 to September 15, 1973, NBSIR 74-562 (July 1974).

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TABLE 1

Transducer Sensitivities and Other Data for Tests on Transducers E-1, E-2, and E-3, with A-3 as Control

Characteristics	Data			
	E-1	E-2	E-3	A-3
Static Calibration Sensitivity According to Manufacturer (mV/kPa) [mV/psi]*				
range: 0 to 14.5 MPa [0 to 2100 psi]	0.122 [0.843]	0.112 [0.774]	0.106 [0.731]	5.87** [40.5]
range: 43.4 to 57.9 MPa [6300 to 8400 psi]	0.0783 [0.540]	0.0770 [0.531]	0.0769 [0.530]	5.77** [39.8]
Measured Static Sensitivity (mV/kPa) [mV/psi]				
range: 0 to 14.0 MPa [0 to 2030 psi]	0.123 [0.845]	0.112 [0.769]	0.105 [0.726]	--
range: 48.5 to 55.4 MPa [7030 to 8030 psi]	0.0800 [0.552]	0.0772 [0.533]	0.0774 [0.534]	--
Measured Dynamic Sensitivity (mV/kPa) [mV/psi]				
at 7.1 MPa [1030 psi]	132 [909]	84.1 [580]	81.3 [561]	5.42 [37.4]
at 55.4 MPa [8030 psi]	82.5 [569]	75.7 [522]	80.8 [557]	5.39 [37.2]
Ratio of Sensitivity at 55.4 MPa to that at 7.1 MPa [8030 psi to 1030 psi]	0.626	0.900	0.993	0.995
Transducer-Calibrator System Natural Frequency (Hz)				
at 7.1 MPa [1030 psi]	2040	2040	2025	--
at 55.4 MPa [8030 psi]	2290	2290	2285	--

* English unit equivalents in brackets.
**This transducer cannot be calibrated statically. Values given are obtained from dynamic calibrations.

TABLE 2

Transducer Sensitivities and Other Data for Tests on Transducers A-4 and A-5, with A-3 as Control

Characteristic	Data		
	A-4	A-5	A-3
Sensitivity According to Manufacturer (mV/kPa) [mV/psi]*			
at 6.9 MPa [1000 psi]	4.38 [30.2]	4.51 [31.1]	5.87 [40.5]
at 55.2 MPa [8000 psi]	4.38 [30.2]	4.42 [30.5]	5.77 [39.8]
Measured Dynamic Sensitivity (mV/kPa) [mV/psi]			
at 7.1 MPa [1030 psi]	4.41 [30.4]	4.26 [29.4]	5.42 [37.4]
at 55.4 MPa [8030 psi]	4.02 [27.7]	3.87 [26.7]	5.39 [37.2]
Ratio of Sensitivity at 55.4 MPa to that at 7.1 MPa [8030 psi to 1030 psi]	0.911**	0.908***	0.995***
Ratio of Frequency Response at 50 Hz to that at 20 Hz			
at 7.1 MPa [1030 psi]	0.85	1.02	1.00
at 55.4 MPa [8030 psi]	0.75	1.03	0.98

*English unit equivalents in brackets
**Value at 50 Hz
***Average of values from 20 Hz to 50 Hz

Table 3

Effects of Cable on Sensitivity of
Transducer A-3

Cable Length (cm)	Loop Length (cm) and Attachment Mode	Average Output at $\pm 10 g_n$ Acceleration (mV)		Relative Output	
		50 Hz	100 Hz	50 Hz	100 Hz
274	18, Fastened to Shaker Body	109.6	112.0	0.979	1.000*
84	18, Fastened to Shaker Body	109.6	111.8	0.979	0.998
274	6.3, Fastened to Shaker Body	111.5	112.6	0.996	1.005
274	12.7, Fastened to Liquid-Filled Tube	109.5	111.8	0.978	0.998
274	10.2, Fastened to Liquid-Filled Tube	109.5	111.8	0.978	0.998
274	7.6, Fastened to Liquid-Filled Tube	115.0	116.4	1.027	1.039

Note: *Reference value for relative output

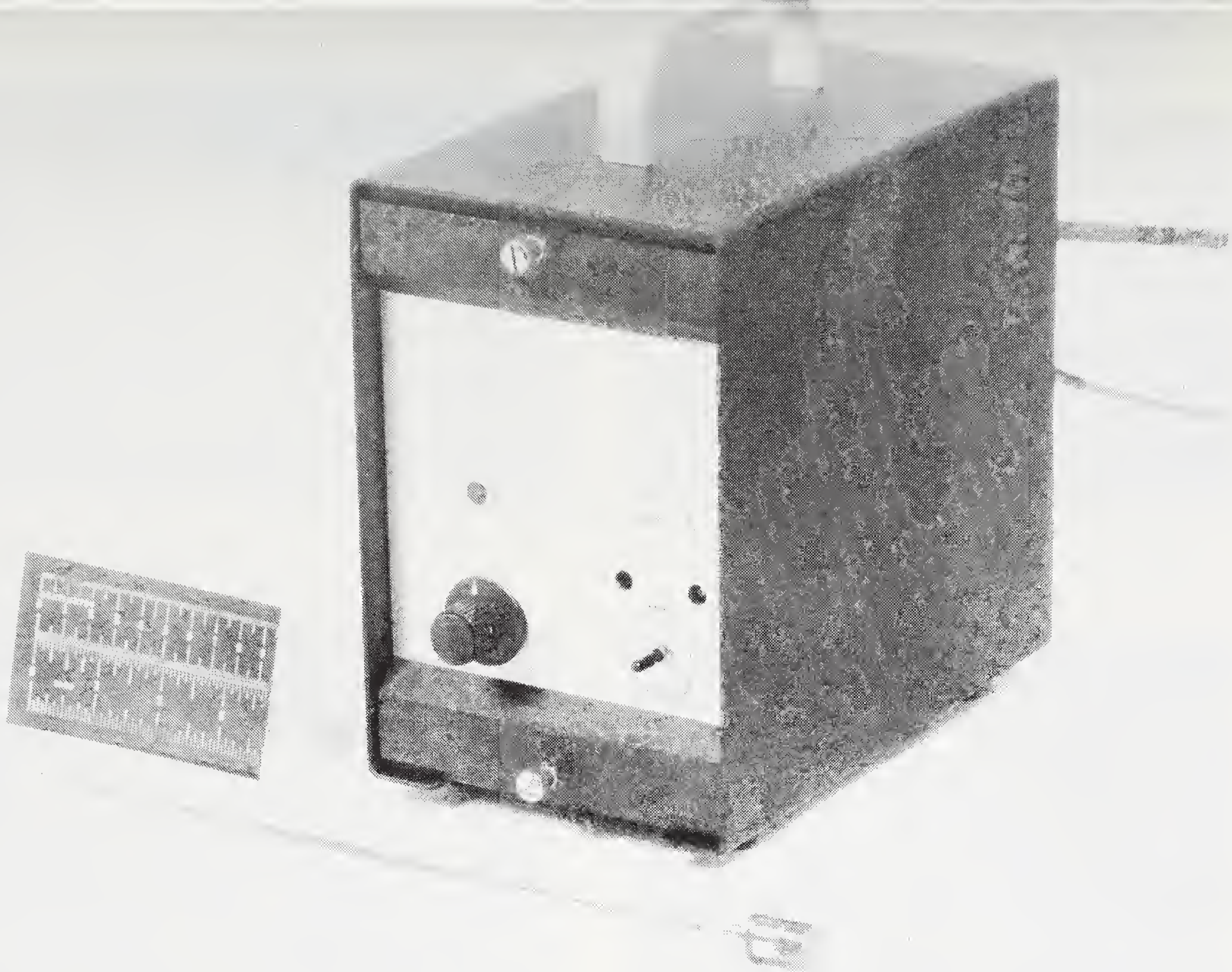


FIGURE I VARIABLE-IMPEDANCE PRESSURE MEASURING SYSTEM

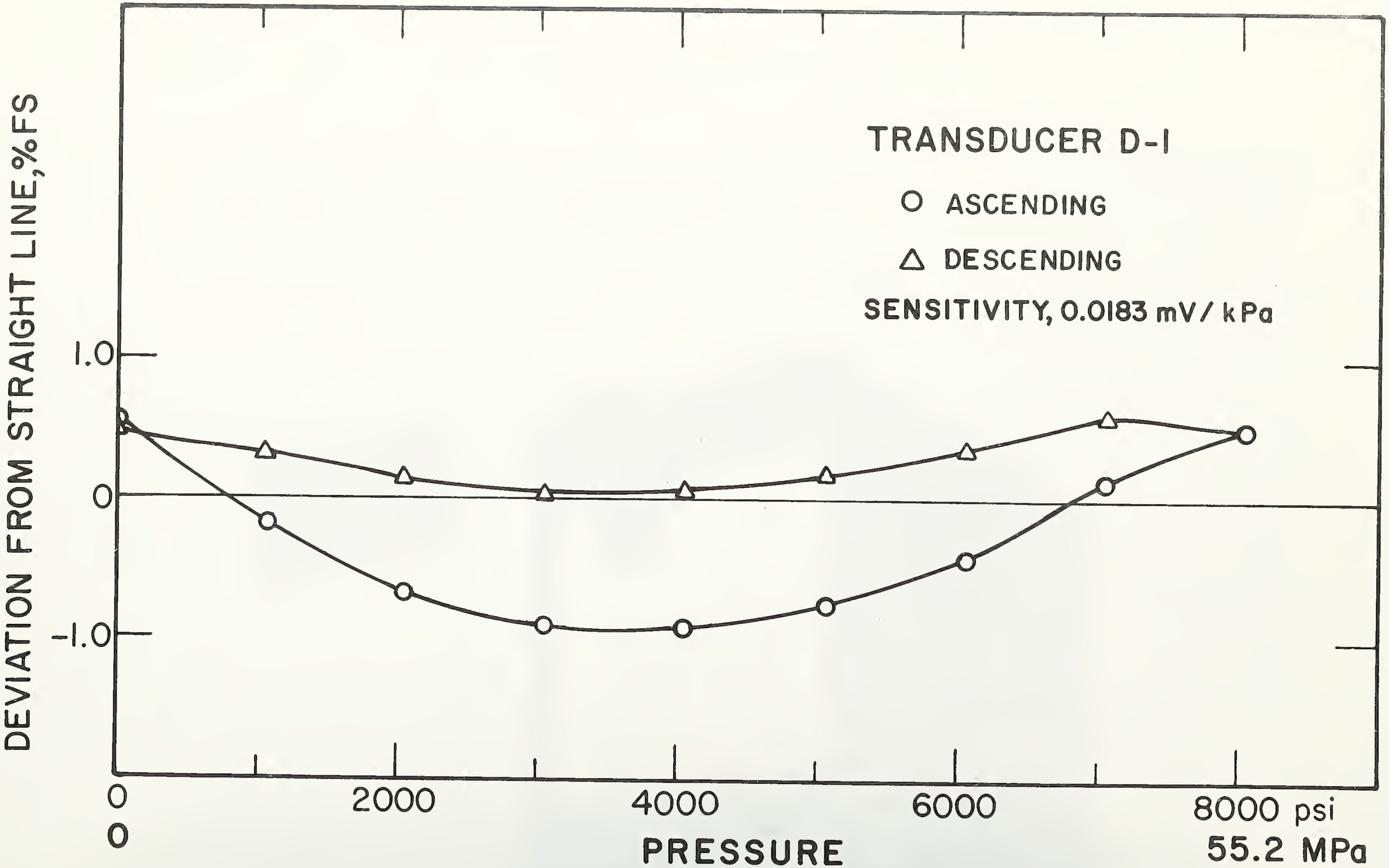
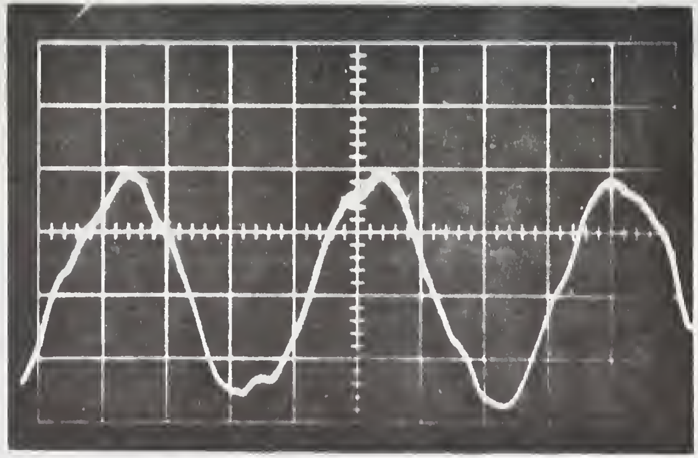
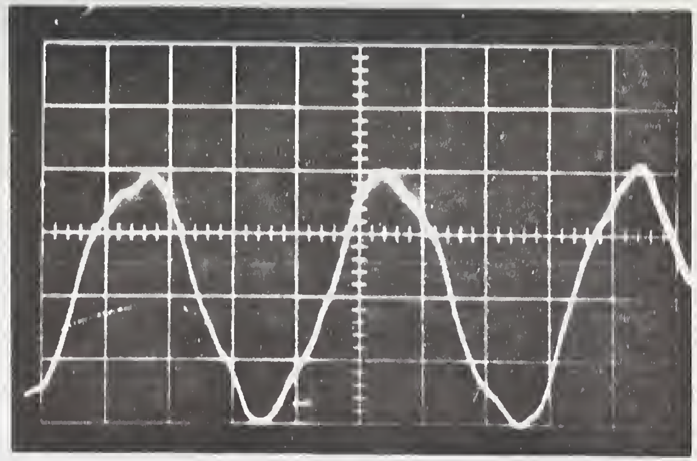


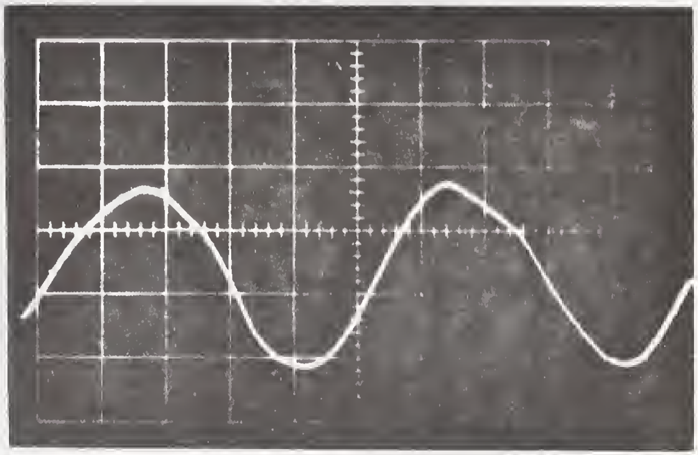
FIGURE 2 STATIC CALIBRATION CHARACTERISTICS OF VARIABLE-IMPEDANCE PRESSURE TRANSDUCER



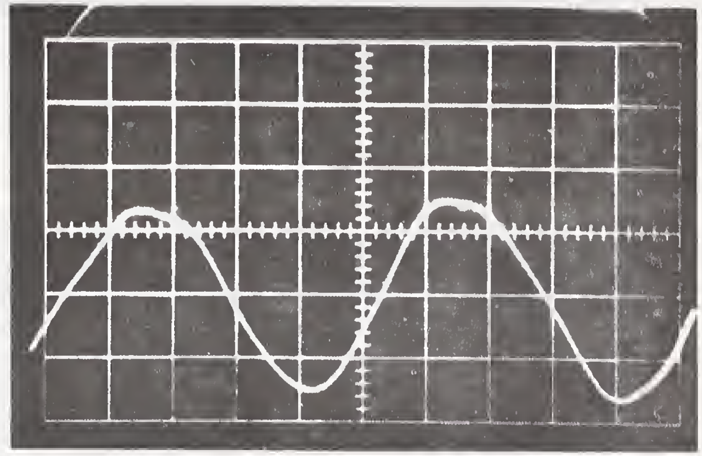
52kPa, PEAK-TO-PEAK; 7.1 MPa BIAS;
50 Hz; 0.2mV/cm; 5ms/cm.



52 kPa, PEAK-TO-PEAK; 55.4 MPa BIAS;
50 Hz; 0.2mV/cm; 5ms/cm.

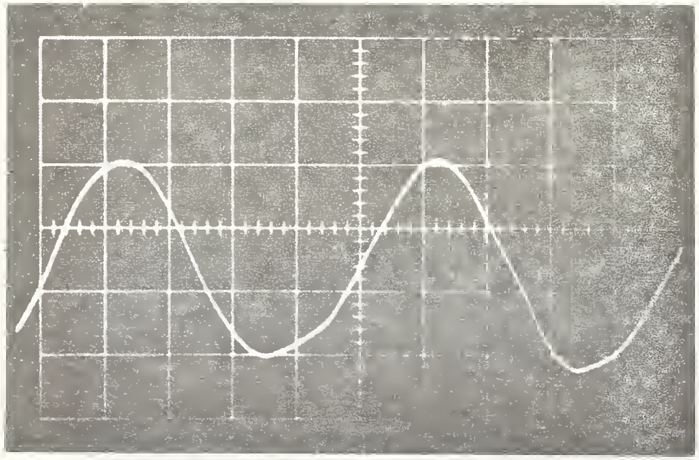


52 kPa, PEAK-TO-PEAK; 7.1 MPa BIAS;
100Hz; 0.2mv/cm; 2ms/cm.

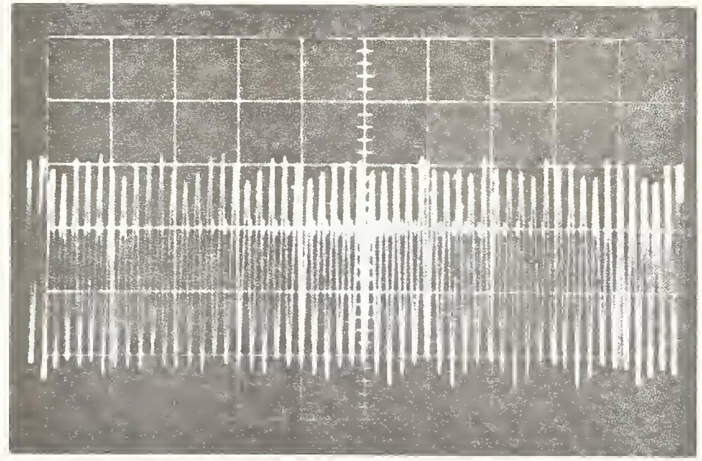


52 kPa, PEAK-TO-PEAK; 55.4 MPa BIAS;
100Hz; 0.2mV/cm; 2ms/cm.

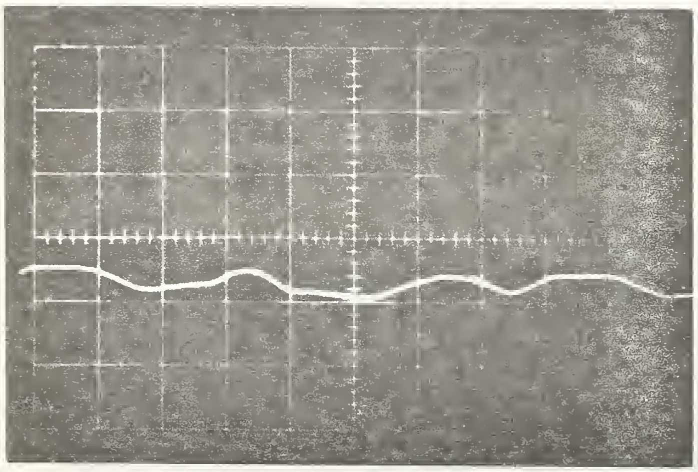
FIGURE 3 DYNAMIC RESPONSE OF VARIABLE-IMPEDANCE PRESSURE MEASURING SYSTEM



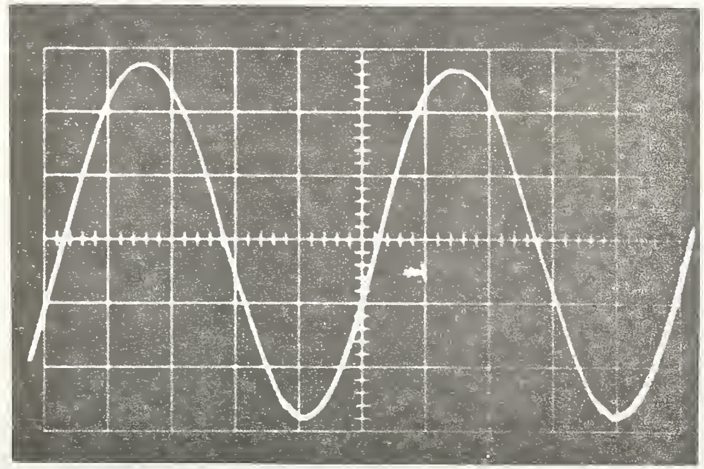
52 kPa, PEAK-TO-PEAK; 55.4 MPa BIAS;
100Hz 0.2 mV/cm; 2ms/cm.



52 kPa, PEAK-TO-PEAK; 55.4 MPa BIAS;
100Hz; 0.2mV/cm; 50ms/cm.



SYSTEM NOISE, NO PRESSURE INPUT;
0.2 mV/cm; 2ms/cm.



103 kPa, PEAK-TO-PEAK; 55.4 MPa BIAS;
100Hz; 0.2 mv/cm; 2ms/cm.

FIGURE 4 DYNAMIC RESPONSE OF VARIABLE-IMPEDANCE PRESSURE MEASURING SYSTEM

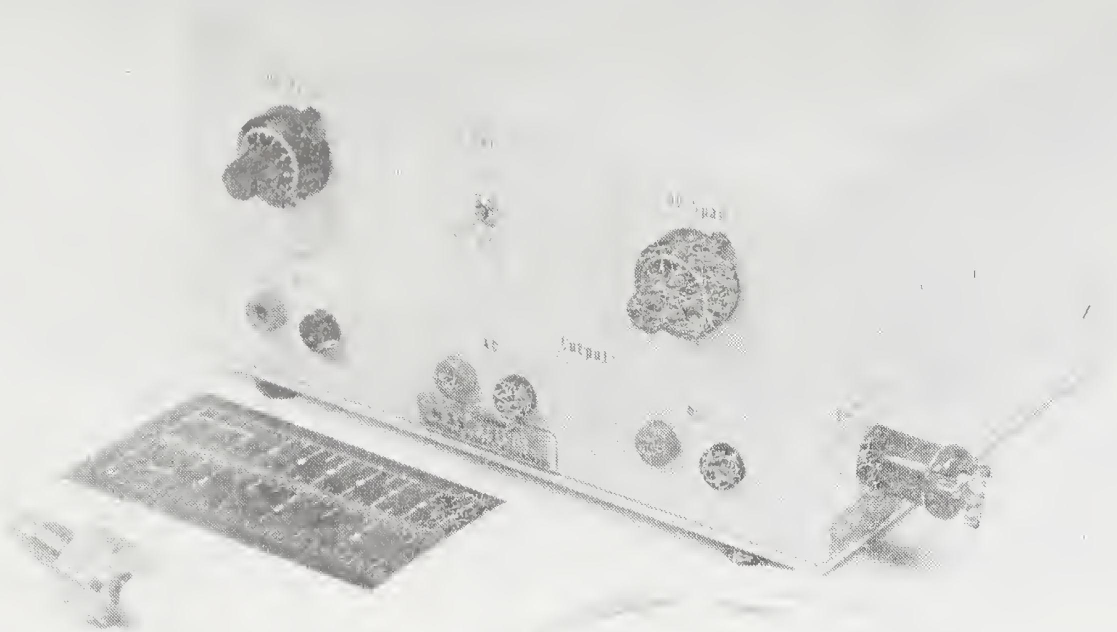


FIGURE 5 STRAIN GAGE PRESSURE TRANSDUCER SYSTEM

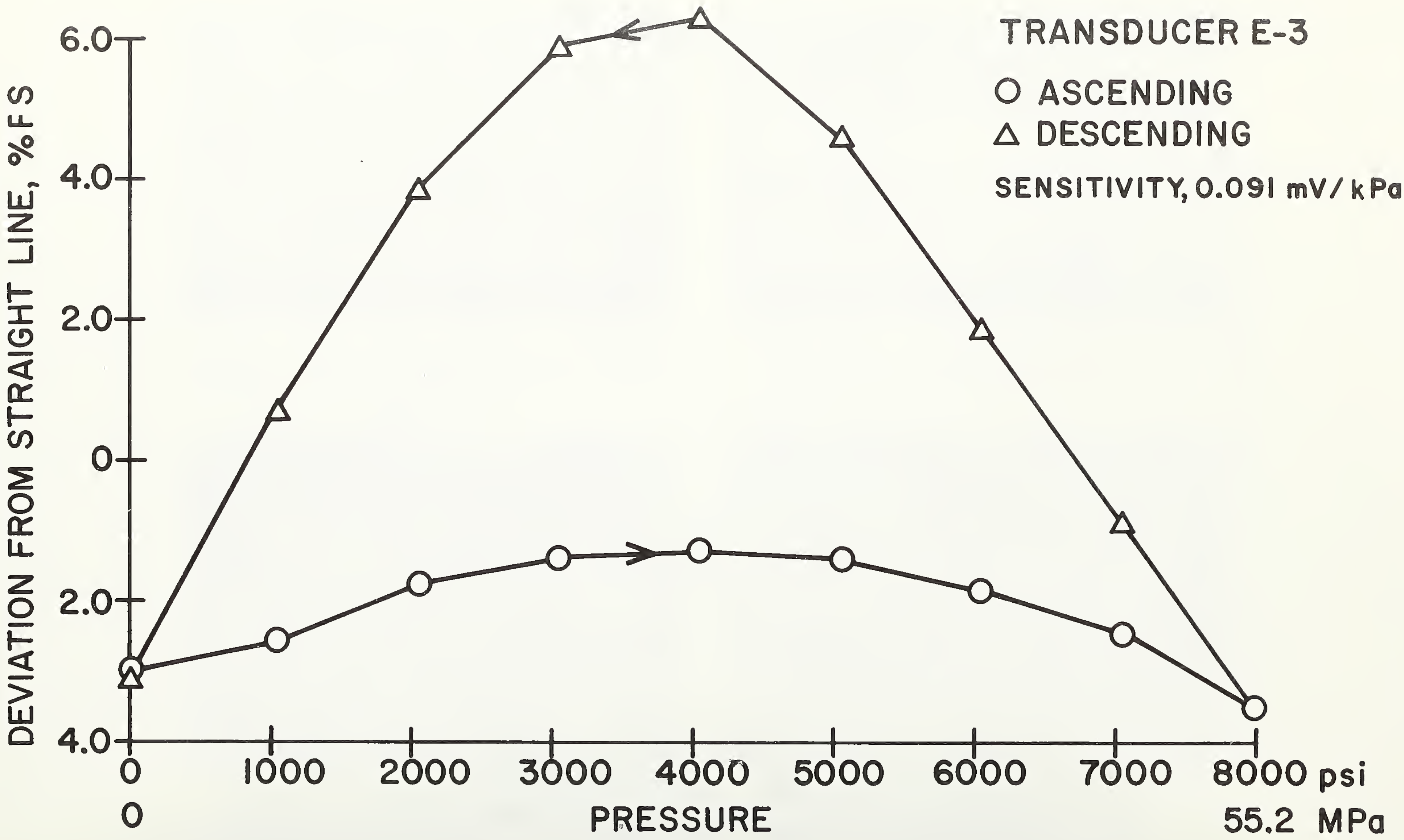


FIGURE 6 STATIC CALIBRATION OF STRAIN GAGE PRESSURE TRANSDUCER SYSTEM

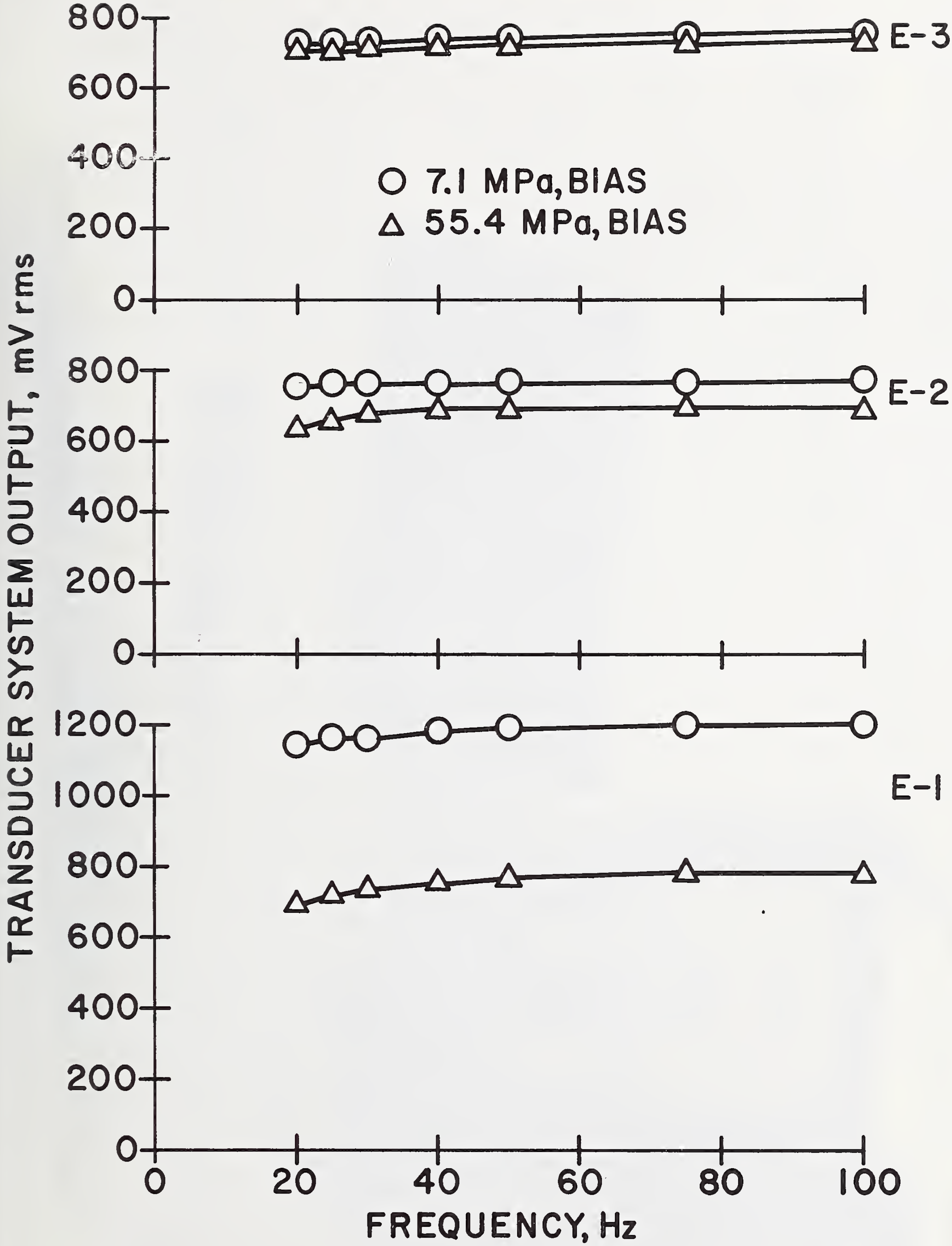


FIGURE 7 DYNAMIC CALIBRATION CHARACTERISTICS, STRAIN GAGE TRANSDUCERS

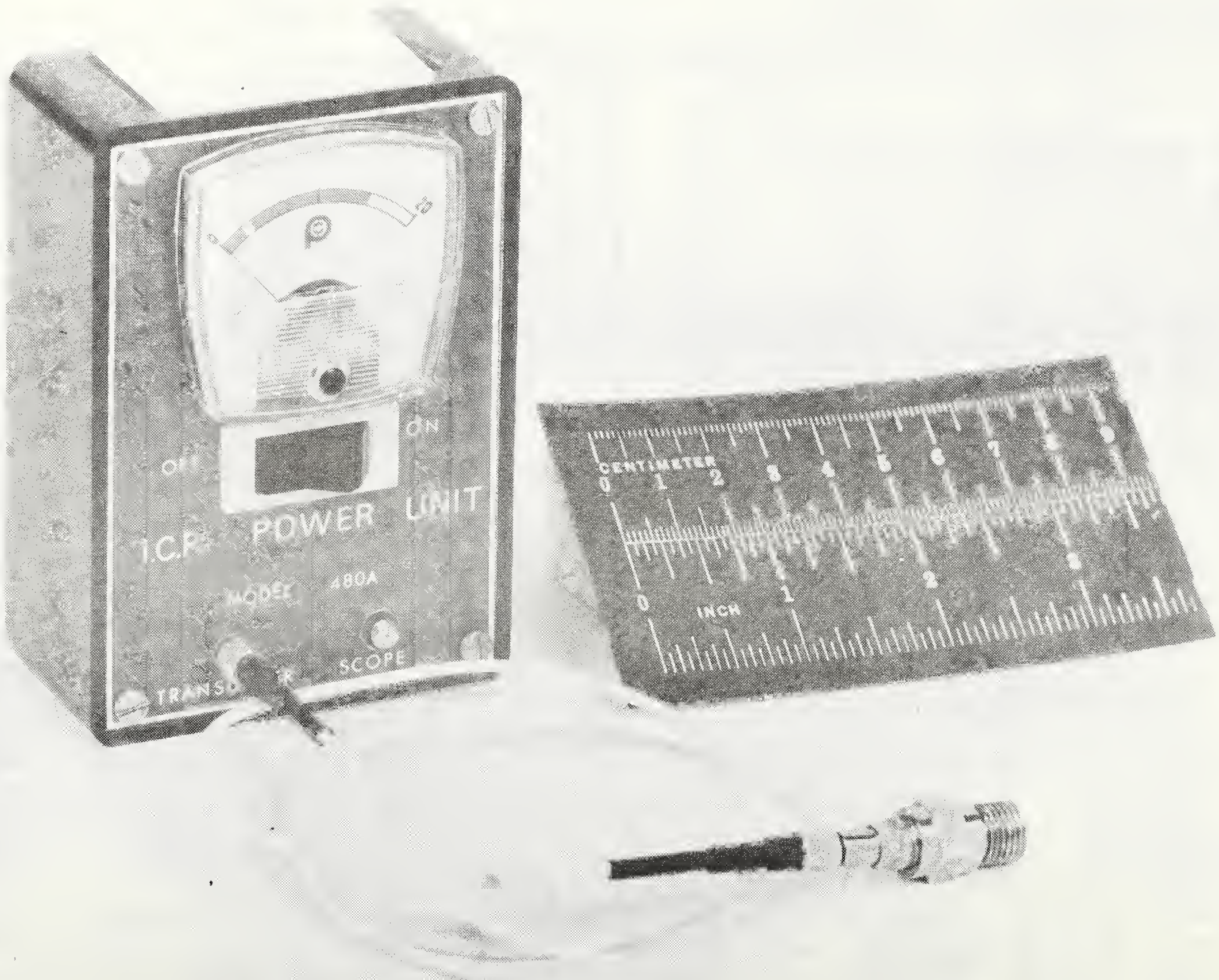


FIGURE 8 PIEZOELECTRIC PRESSURE TRANSDUCER SYSTEM

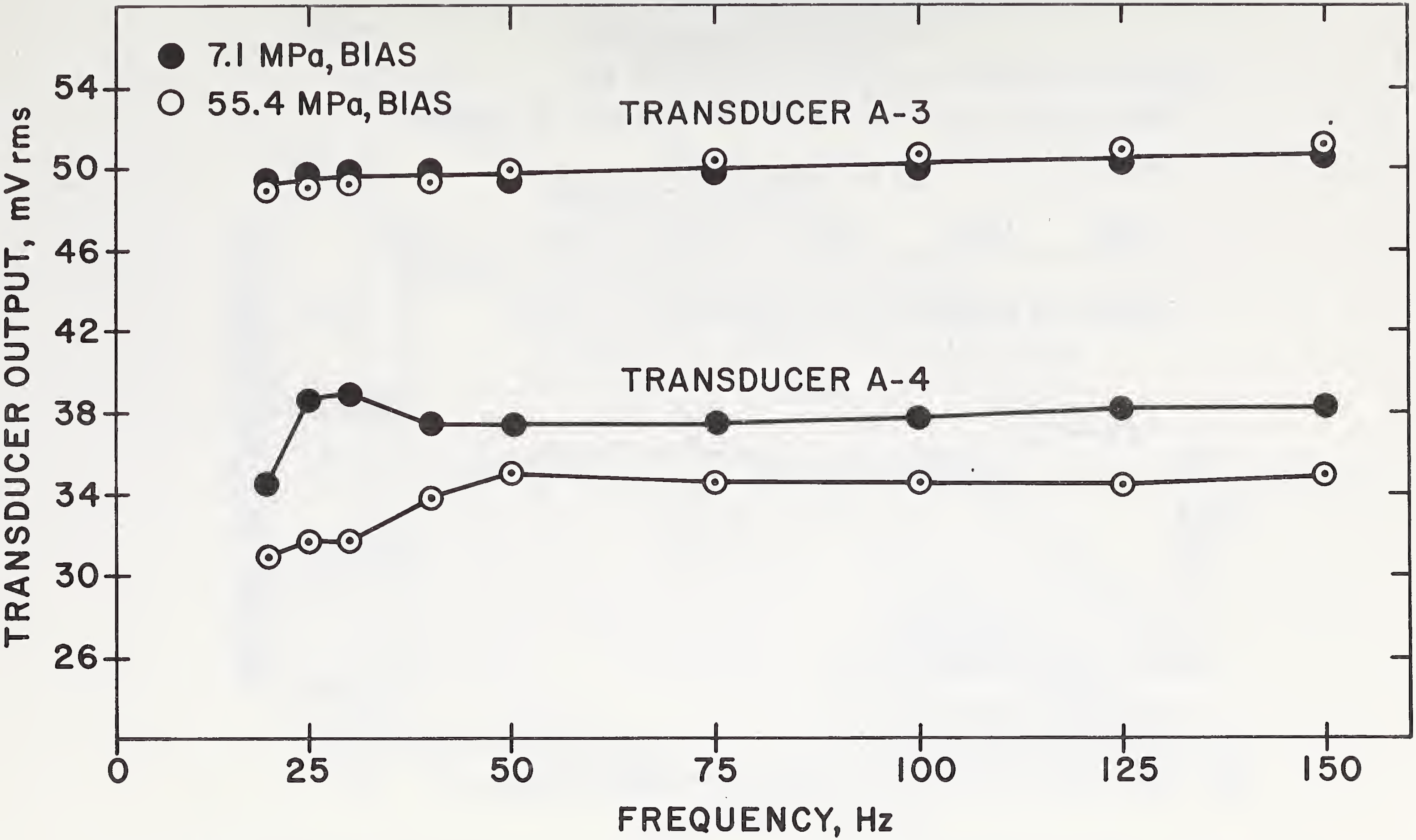


FIGURE 9 FREQUENCY RESPONSE OF PIEZOELECTRIC PRESSURE TRANSDUCER SYSTEMS AT TWO BIAS PRESSURES AND DYNAMIC PRESSURE OF 24 kPa, PEAK-TO-PEAK

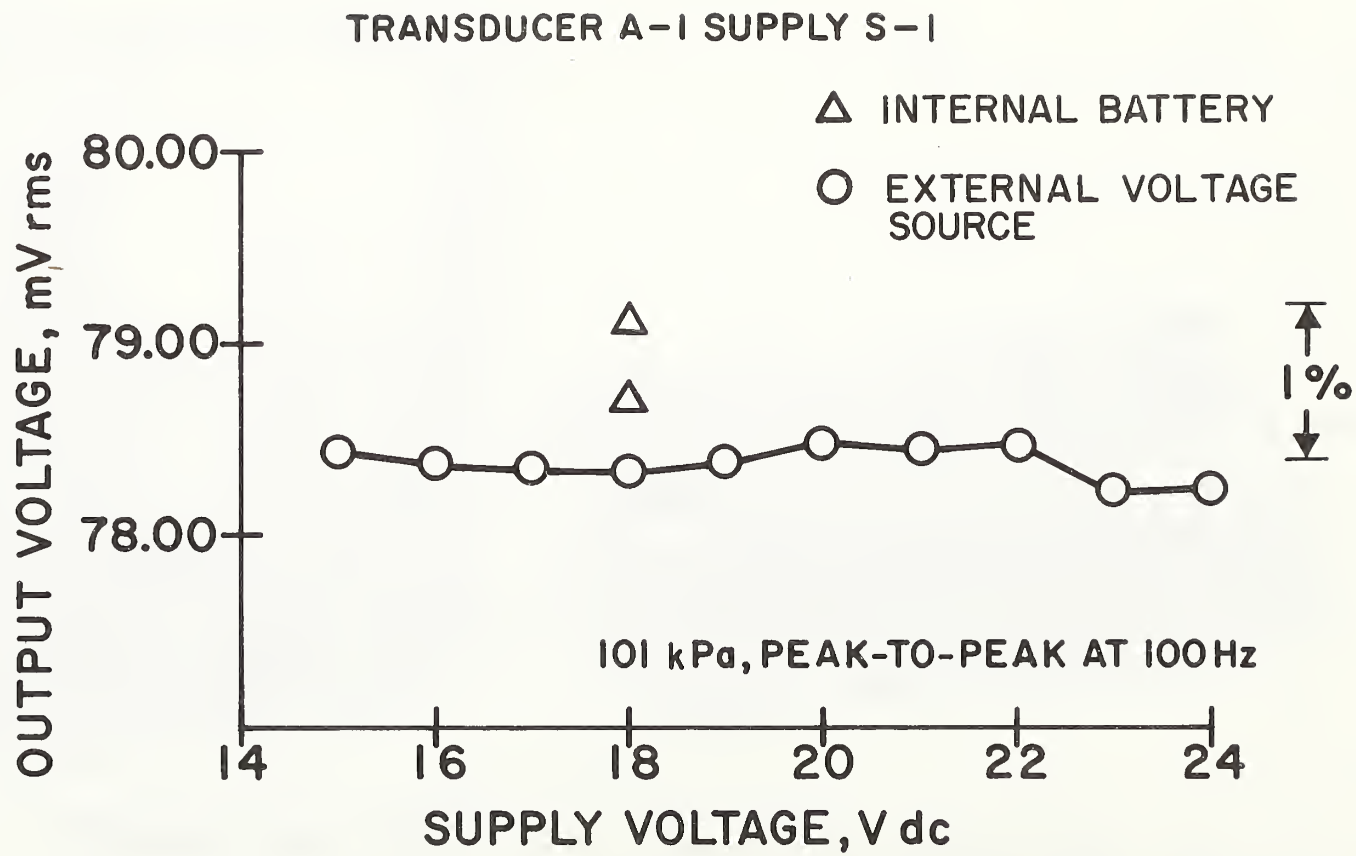


FIGURE 10 EFFECT OF SUPPLY VOLTAGE VARIATIONS ON OUTPUT OF PIEZOELECTRIC PRESSURE TRANSDUCER SYSTEM

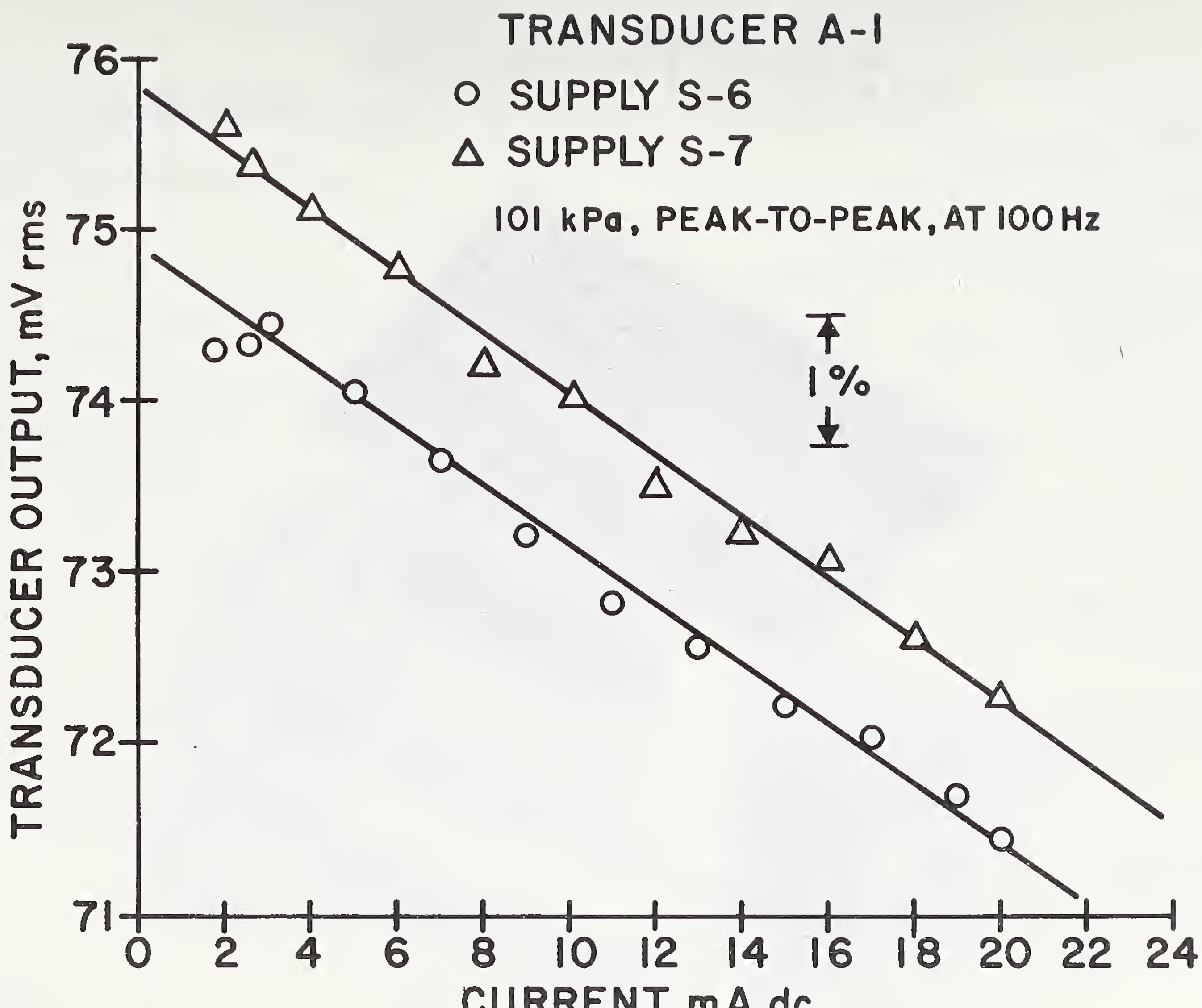


FIGURE 11 EFFECT OF CURRENT FROM LINE POWERED SUPPLY ON OUTPUT OF PIEZOELECTRIC PRESSURE TRANSDUCER SYSTEM

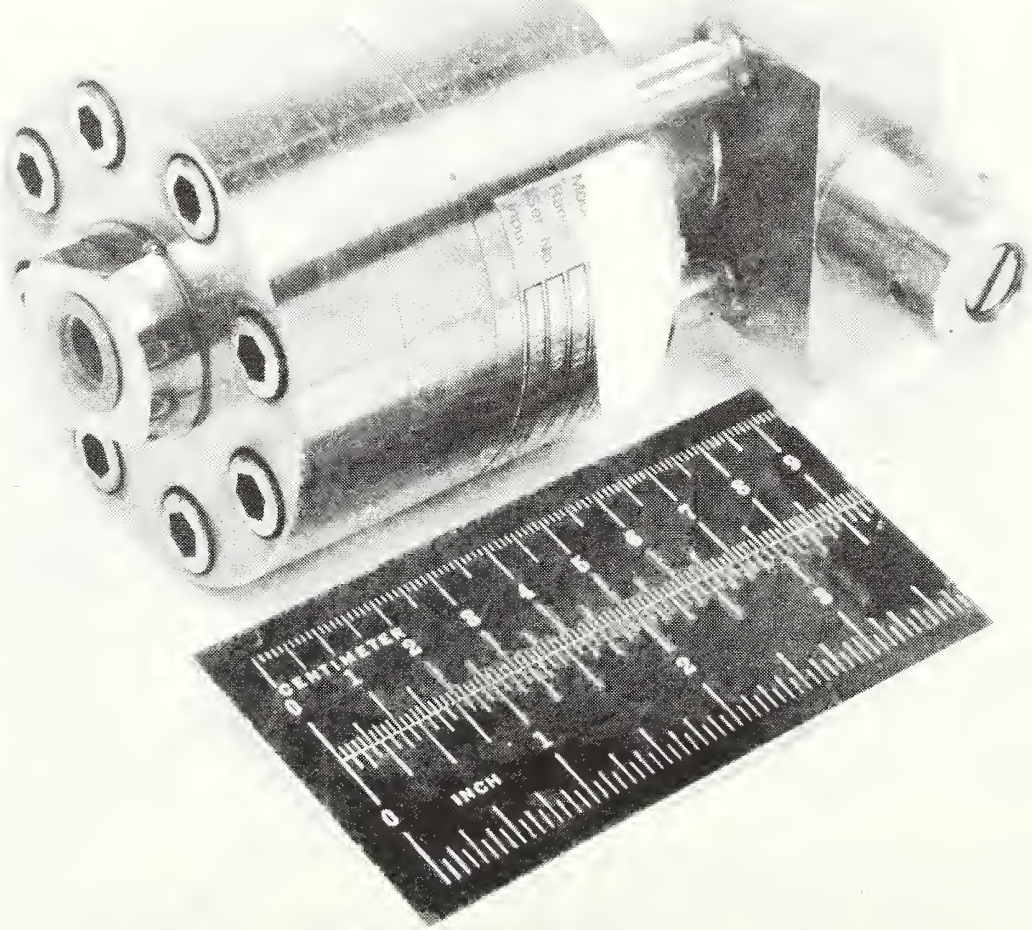


FIGURE 12 STRAIN GAGE DIFFERENTIAL PRESSURE TRANSDUCER

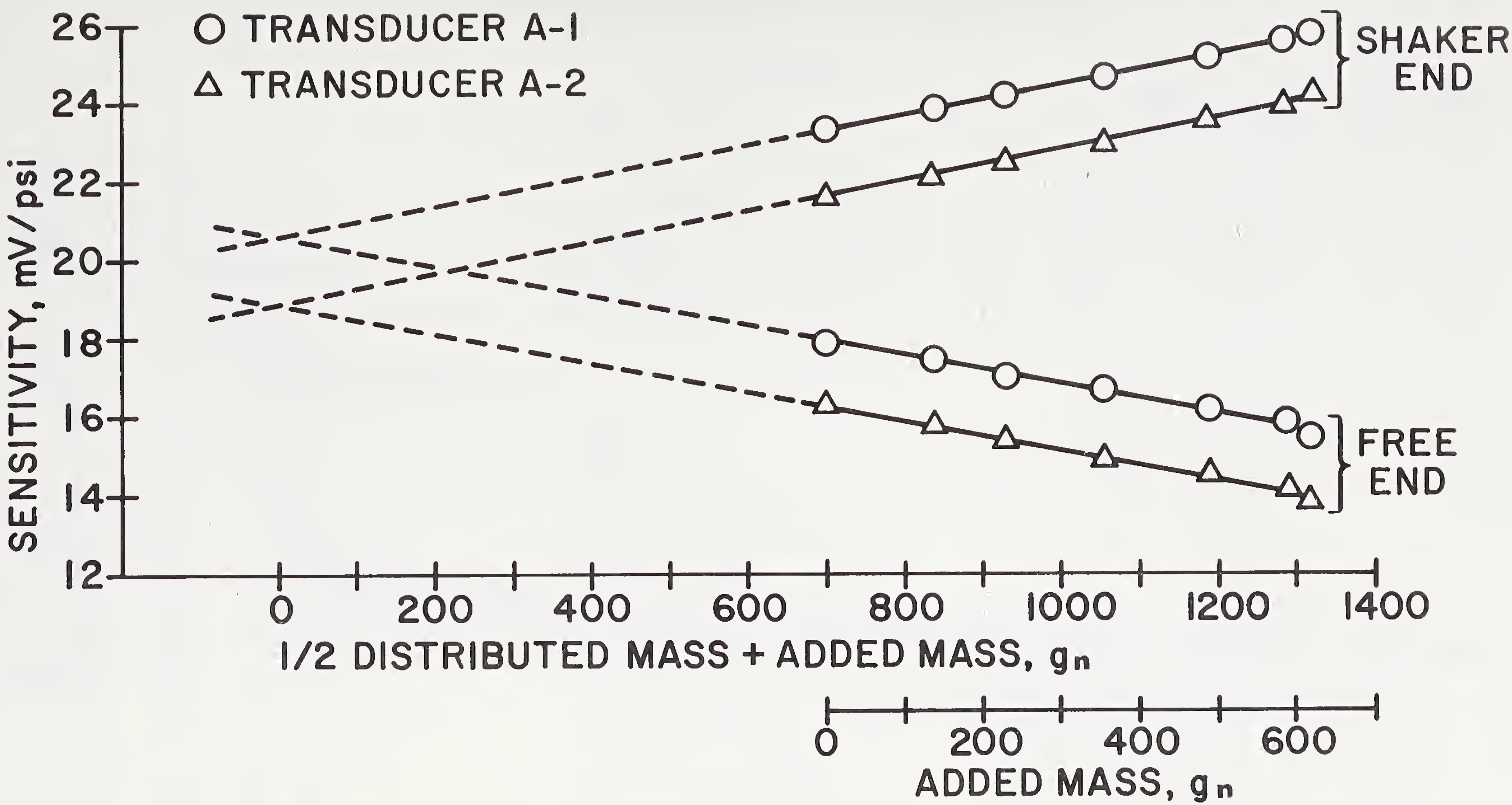


FIGURE 13 EFFECT OF TUBE MASS ON OUTPUT OF PIEZO ELECTRIC TRANSDUCER SYSTEMS

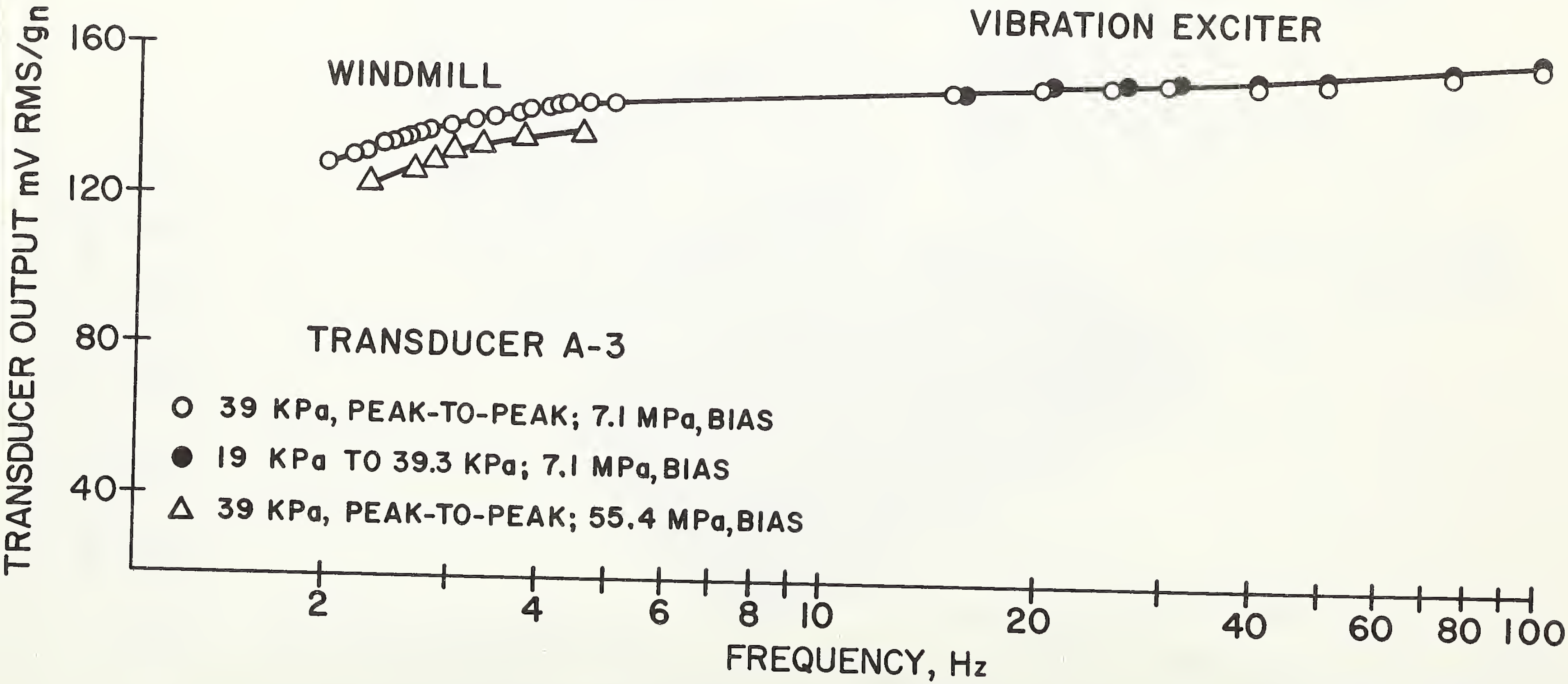


FIGURE 14 FREQUENCY RESPONSE OF PIEZOELECTRIC PRESSURE TRANSDUCER SYSTEM ON WINDMILL AND VIBRATION EXCITER, USING MERCURY OIL MEDIUM.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This progress report describes continuing development of methods for the dynamic calibration of pogo pressure transducers used to measure oscillatory pressures generated in the propulsion system of the space shuttle. The requirements are for the generation of a known (5% or better) sinusoidal pressure perturbation of 140 kPa (approximately 20 psi) peak-to-peak at bias pressures up to 55 MPa (approximately 8000 psi) over a frequency range of from 1 Hz to 100 Hz. Rotation of a mercury-filled column in the vertical plane at frequencies of 10 Hz and below has produced peak-to-peak pressures of 39 kPa (5.7 psi) at bias pressures of up to 55.4 MPa (8030 psi). Evaluation of some variable-impedance, semiconductor strain-gage, piezoelectric, and metallic strain-gage pressure transducer systems for suitability as pogo sensors is described.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Calibration; dynamic; high pressure; orbiter vehicle; pogo; pressure; pressure transducer; sinusoidal; space shuttle.

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