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A Simple Hydraulic Sinusoidal Pressure Calibrator

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A Simple Hydraulic Sinusoidal Pressure Calibrator

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FOREWORD

The work described in this publication was performed as part of a project on development of methods for the evaluation of electromechanical transducers. This project is currently supported by the Naval Air Systems Command, U. S. Navy. During the period of the performance of this work, the project leader was Paul S. Lederer.

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A Simple Hydraulic Sinusoidal Pressure Calibrator

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This paper describes a simple, accurate device for the sinusoidal calibration of pressure transducers. Calibration is achieved by vibrating a liquid tube on an electrodynamic shaker (vibration generator); the pressure transducer mounted at the base of the tube senses the sinusoidally varying pressure in the tube. The frequency range is 15 Hz to 2000 Hz with a maximum obtainable amplitude of 19.5 psi (134 kN/m^2) peak to peak. The transducer can easily be calibrated statically in the same device, thus permitting precise correlation between static and dynamic calibrations. Agreement between static and dynamic calibrations to within 0.1% has been achieved.

Key words: Calibrator; dynamic; hydraulic; InterAgency Transducer Project; pressure transducer; sinusoidal pressure.

1. Introduction

The need to measure dynamic pressures has existed for many years. The ever increasing pace of technology in recent years, however, has intensified the need for, and complexity of, pressure measurements by means of electromechanical transducers. In order to assure that the quality of these dynamic measurements is adequate, it is necessary to know something about the dynamic characteristics of the transducer.

These characteristics are best described by the transfer function of the device, which is most useful when given as amplitude-frequency and phase-frequency response curves. To obtain such curves directly from the application of known sinusoidal pressures to the transducer is difficult because of the limitations of existing dynamic pressure calibration systems. Most of them cannot approach the amplitude, frequency, and accuracy requirements of many applications. A more serious problem associated with these systems is that many indicate amplitudes that cannot be independently established. This necessitates the use of a "reference" transducer with which the transducer under test must be compared. The hydraulic sinusoidal pressure calibrator described below is a simple and inexpensive adjunct to an electrodynamic shaker for obtaining amplitude-frequency response curves of pressure transducers. Pressure amplitudes generated by this device can be established from fundamental physical parameters. The experimental work described was limited to amplitude-frequency characteristics; phase frequency characteristics were not investigated. It is capable of sufficiently good accuracy for the devices to be calibrated over its amplitude and frequency ranges, particularly bio-medical pressure sensors. With the present setup pressures of 3.2 psi (22.4 kN/m^2) peak-to-peak have been generated over a frequency range from 25 Hz to 2000 Hz, and as much as 19.5 psi (134 kN/m^2) peak-to-peak between about 100 Hz and 300 Hz. Below 25 Hz, mechanical limits on shaker table displacement reduce the generated pressure amplitudes.

The hydraulic sinusoidal pressure calibrator consists of a rigid container holding a column of liquid mounted vertically on the table of an electrodynamic shaker. The pressure transducer under test is mounted near the bottom of the container, with its diaphragm in a vertical plane (to reduce the effect of the vibration on the transducer). All pressure transducers are sensitive to vibration. Flush diaphragm types generally generate a much smaller spurious output due to vibration than other types of pressure transducers. Also, the vibration sensitivity is usually much less when the vibration acts parallel to the plane of the diaphragm, rather than perpendicularly to that plane. The effect of vibration sensitivity would be to widen the margin within which static and dynamic calibrations can be correlated. With the shaker at rest, the static pressure acting on the transducer diaphragm is equal to the head of the liquid (the product of the vertical height of the column from diaphragm center to the top surface of the liquid and its density). If the column is vibrated sinusoidally in a vertical direction with a peak acceleration of exactly 1g, the pressure seen by the transducer will vary sinusoidally from a maximum of twice the head of the liquid to 0 psig.

There is a theoretical limitation on the pressure amplitudes generated; an acceleration level sufficiently high to reduce the liquid pressure to 0 psig can never be reached, but only some value near the vapor pressure of the liquid. Operation at a greater value of acceleration will produce wave shape distortion. The limitation on the practical frequency range of operation is imposed by the natural frequency of the liquid column-transducer system. This is treated in detail later on.

This device is a true calibrator, since the transducer can first be statically calibrated either with the precisely computable liquid head, or by the imposition of an additional accurately known gas pressure to the liquid. Following this, the dynamic calibration can be performed using the same setup and monitoring the applied acceleration with an accurate accelerometer mounted on or near the vibrating liquid column. Experimental data indicate that correlation between static and dynamic calibrations with this device can be as good as $\pm$ 0.1% with a stable and repeatable pressure transducer.

2. Theory

The dynamic properties of the liquid column, as well as those of the transducer to be calibrated, impose constraints on the dynamic calibration capability of the system. Experimental work was carried out to arrive empirically at an optimum system. The experimental work included tests of three different makes of transducers having different ranges, diaphragm sizes, and natural frequencies. Calibrators using liquid columns of different heights, diameters, and liquids were also tested. A theoretical investigation was undertaken which achieved reasonably good confirmation of the experimental results, as shown later. A brief account of the theoretical study follows.

2.1. Natural Frequency of Liquid Column

The theoretical value of the natural frequency of a liquid column can be obtained by considering the fact that stationary waves are set up in the column at resonance. The velocity of propagation of these waves is the velocity of sound in the medium. Waves at several harmonically related frequencies may exist, but only the lowest frequency is of interest. The system may be considered as a single degree of freedom system with a natural frequency equal to that of the lowest harmonic of column resonance. This is the resonance at which the column height (a tube closed at one end) is equivalent to a quarter wave length.

Based on this, and introducing numerical factors for the systems of units used, it can be shown that expressions for the natural frequency of the column are:

For metric units

$$(1)\quad f_n = 0.250 \left(\frac{kg.m}{N.s^2}\right)^{\frac{1}{2}} \quad \frac{1}{h} \sqrt{\frac{B}{\rho}}$$

For English units

$$(2)\quad f_n = 4.91 \left(\frac{in.}{s^2}\right)^{\frac{1}{2}} \quad \frac{1}{h} \sqrt{\frac{B}{\rho}}$$

The symbols stand for the following in both systems:

B = bulk modulus of liquid	N/m^2	$lb/in.^2$
c = velocity of sound in liquid	m/s	ft/s
ρ = density of liquid	kg/m^3	$lb/in.^3$
h = height of column	m	in.
f_n= natural frequency of liquid column	Hz	Hz

2.2. Effect of Transducer Diaphragm Stiffness

The relations given above are based on the assumption of an infinitely stiff container. In practice this is not true for several reasons; the most important one is the presence of the transducer. The diaphragm of the transducer has a finite stiffness, since most sensing elements require a certain amount of diaphragm deflection in order to actuate the electrical pickoff which produces an output signal in response to the pressure which acts on the diaphragm.

Since the diaphragm is deflected inward (toward the body of the transducer) with the application of pressure, an additional volume is created in front of the diaphragm which is filled up by liquid from the column. This results in an additional decrease in column height (deflection); the system appears softer than it would due to the liquid alone, and produces a lowered natural frequency.

Information on the equivalent volume change caused by the diaphragm deflection due to the application of full scale pressure can usually be obtained from the transducer manufacturer. For pressures other than full scale values, corresponding volume changes can be scaled proportionately with reasonable confidence.

The effect of this volume change on the value of natural frequency calculated for the liquid column alone can be computed, based on the following considerations.

A unit pressure change acting on the liquid alone will cause a volume change:

$$(3) \quad dv = \frac{V}{B}$$

V = volume of liquid in column
B = bulk modulus of liquid

The volume change due to the transducer diaphragm deflection for a unit pressure change can be designated as dv_t. The net change in fluid volume change is the sum of the two: $dv + dv_t$, and using this, one obtains a new equivalent value of bulk modulus.

$$(4) \quad B_t = \frac{V}{dv + dv_t}$$

This can be substituted in relations (1) or (2) to arrive at the value of natural frequency for a liquid column acting on a transducer with a known diaphragm deflection.

2.3. Effect of Change in Container Volume

The pressure due to the head of liquid in the container will tend to increase the volume of the container by a small amount. It can be shown for a thin-walled, circular, right cylinder that the average change in volume, dv_c, is given by the following relation:

$$(5) \quad dv_c = \frac{\pi}{16} \frac{d^3h^2\rho}{qE}$$

where d is the diameter of the container, h the height, q the wall thickness, ρ the density of the liquid, and E the modulus of elasticity of the container material.[1] For other than extremely thin walled cylinders, the container volume change will usually be so small compared to other volume changes due to pressure that it can safely be neglected.

2.4. Other Factors Affecting Values of Natural Frequency

The effect of absorbed air or other gases on the value of natural frequency can be considerable, although it is not readily predictable. Accordingly, the liquid used should always be carefully evacuated for at least fifteen minutes. This will not only remove most of the absorbed gases, but also gas bubbles in narrow passages, corners, threads, etc. Also, there may be volume changes due to the pressure acting on O-rings, threads sealers and similar elastic materials used in the mounting of the pressure transducer under test.

Finally, it should be noted that the handbook values of bulk modulus and density may not be the exact ones for the particular liquid used, due to uncertainty of composition, dilution, or adulteration. These factors may account for the discrepancies noted between calculated and observed values of natural frequencies for various transducers.

3. Description of the Hydraulic Sinusoidal Pressure Calibrator

The simple hydraulic sinusoidal pressure calibrator described below evolved as a result of a number of experiments. All tests described in this report, with the exception of the series on the effect of calibrator tube diameter, were run using the calibrator shown in Figures 1 and 2. Figure 1 is a drawing of the basic configuration. Figure 2 shows the dynamic calibrator as it is mounted on the electrodynamic shaker. The basic configuration was found to be the optimum one for transducer calibrations using water as the liquid medium.

A 10 in. long brass tube with an inner diameter of 1.0 in. and a wall thickness of 0.063 in. was inserted and soft soldered into a counterbored hole in a square brass block. The square block was drilled and tapped for the mounting of the pressure transducer 0.5 in. from the bottom of the tube; the depth of the mounting hole was controlled so that the transducer diaphragm projected into the tube proper. The transducer was sealed into the block by means of plastic tape. The square block was attached with a screw to the shaker by means of a tapped 10-32 hole in the bottom of the square block.

This basic configuration with water as the liquid was used for the complete, accurate, dynamic calibration of the three pressure transducers reported on in detail below. The basic configuration was modified to explore the effects of column height, diameter, type of liquid, and damping characteristics. These tests are described later in this paper.

4. Dynamic Calibration of Three Pressure Transducers

Three different pressure transducers with full scale ranges of 5,

[1] "Resistance of Materials", Fred B. Seely, John Wiley & Sons, New York 1947.

15, and 50 psig (34, 103 and 345 kN/m^2 respectively) were calibrated with the sinusoidal pressure calibrator. Two were semi-conductors and one was a bonded strain gage device. All three were flush diaphragm types. Table I summarizes the pertinent instrument characteristics.

Table I

Instruments Tested

Pressure Trans-ducer	Range psig (kN/m^2)	Static Sensitivity mV/psi	Type of Strain Gage	Diaphragm Diameter in. (cm)	Manuf. Value of Natural Frequency Hz
A	15 (103)	1.80	Bonded Wire	0.63 (1.6)	5,000
B	50 (345)	10.00	Semiconductor	0.36 (0.91)	25,000
C	5 (34)	7.24	Semiconductor	0.14 (0.36)	70,000

4.1. Initial Procedures

A pressure transducer is mounted in the sinusoidal pressure calibrator with plastic tape to seal the threads and then the tube is filled with water. Because the water contains some entrapped air it is necessary to evacuate the calibrator (including the transducer) for about fifteen minutes. As the system is placed under vacuum, the air bubbles come to the surface so rapidly that some of the water is forced out of the tube; this loss is prevented by using a vented, inverted flask connected to the calibrator tube by means of a double rubber stopper. The sketch in Figure 3 shows this arrangement.

The calibrator is then attached to the shaker. The water level is adjusted to be 0.500 in. (within ± 0.003 in.) from the top of the tube. This is done by using a depth micrometer set at 0.500 inch and an eye dropper to add or remove water. The depth micrometer measurement is made at the center rather than at the edge of the tube because of the presence of a meniscus. Since the center of the pressure transducer is mounted 0.500 from the bottom of the tube, a static pressure head of 9.00 in. of water (0.32 psi or 2.24 kN/m^2) is developed using a 10 in. tube. In some cases it is necessary to vibrate the calibrator at its resonant frequency for a few minutes to bring any remaining bubbles to the surface. Entrapped air will cause waveform distortion and a lowered natural frequency. After these procedures are completed the calibration can begin.

4.2. Calibration Procedures

In those calibrations where a correlation with the static calibration at zero frequency was desired, a three point static calibration was performed before the start of the dynamic calibration. This was done by using a bellows to apply air pressure above and below ambient directly to the calibrator and transducer. The pressure level was read on a precision dial gage with a full scale range of 40 in. water. This was the value of the applied pressures: ± 1.45 psi (± 9.96 kN/m^2). The transducer output was measured with a precision potentiometer. The static calibration was repeated to assess instrument stability.

After completing static calibrations, dynamic calibration points were taken, at frequencies of 15, 25, 50, 75, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400, 1500 and 2000 Hz (unless otherwise noted). The level of acceleration was 2g peak-to-peak at 15, 25, and 50 Hz resulting in equivalent pressures of 0.65 psi (4.5 kN/m^2) peak-to-peak. The remaining points were taken at an acceleration level of 10g peak-to-peak resulting in equivalent pressures of 3.2 psi (22.4 kN/m^2) peak-to-peak. In the vicinity of resonance the applied acceleration was reduced, since the high Q of the system (sometimes over 100) made it necessary to reduce the acceleration input because of the danger of overranging the pressure transducer. The low frequency points were taken at an acceleration level of 2g peak-to-peak to prevent droplets of liquid from being thrown out of the calibrator; this characteristic is a function of the type of liquid and the vibration amplitude. A loose fitting 0.1 in. thick cork disc floating on the surface of the liquid in the calibrator was successfully used to increase the acceleration capabilities at low frequencies. The acceleration level (from the amplified output of a calibrated piezoelectric accelerometer mounted in the shaker head) and the pressure transducer output were both read on an ac rms differential voltmeter to within ± 0.1% of the range at any of the above frequencies. Frequency was monitored by an electronic counter, and distortion was checked with a distortion meter. The electrodynamic shaker used was a commercial device with a frequency range of 5 Hz of 10,000 Hz and an output rating of 300 pounds force (1330 newtons).

4.3. Results

Pressure transducer B was calibrated with the 10 in. calibrator using water from 15 Hz to 2000 Hz. The resonant frequency was found to be about 1350 Hz with a damping ratio of less than 0.01 of critical; the pressure transducer response was up 5% at 300 Hz. The Q was over 143. Figure 4 shows the frequency response data; this curve follows very closely the theoretical single degree of freedom frequency response curve for 1350 Hz and 0.01 damping.

Using the same calibration setup a series of 75 calibration points was run to determine (1) how well the dynamic calibration would correlate with the static calibration and (2) how linear the amplitudes were at selected frequencies. A precision decade amplifier with a gain of 10 ± 0.1% was inserted between the transducer and the ac voltmeter. The data obtained are given in Table II which shows the transducer output as actually measured in mV rms ×10 (due to the decade amplifier) and the equivalent transducer output corresponding to an acceleration level of 10g peak-to-peak. This was calculated from the data to permit convenient comparison over the entire frequency range. The correlation between dynamic and static calibrations was within 0.3% as shown in Figure 5. The procedure followed was to average all sensitivity values obtained from dynamic calibrations at frequencies from 15 Hz to 50 Hz and to compare this average with that of the static calibrations previously performed on the transducer. The 32 sensitivity values covering the 15 Hz to 50 Hz range described above had a maximum variation (scatter) of ±0.3%. Linearity is summarized in Table III.

Table II

Pressure Transducer B Dynamic Calibration Data

Frequency Hz	Applied Accel. g peak-to-peak	Transducer Output x10 mV rms	Equivalent Output at 10g peak-to-peak mV peak-to-peak
15	2	22.95	32.46
17	2	22.95	32.46
19	2	22.96	32.47
21	2	22.95	32.46
23	2	22.97	32.48
25	2	22.98	32.50
25	4	45.90	32.46
25	6	68.84	32.45
25	8	91.66	32.41
25	10	114.70	32.44
27	5	57.52	32.54
29	5	57.56	32.56
31	5	57.43	32.49
33	5	57.37	32.45
35	5	57.36	32.45
37	10	114.70	32.44
39	10	114.80	32.47
41	10	114.72	32.45
43	10	114.83	32.48
45	10	114.89	32.50
47	10	114.80	32.47
49	10	114.90	32.50
50	2	22.96	32.47
50	4	45.90	32.46
50	6	68.92	32.49
50	8	91.89	32.49
50	10	114.92	32.50
50	12	137.76	32.47
50	14	160.70	32.47
50	16	183.78	32.49
50	18	206.72	32.48
50	20	229.78	32.50
55	10	114.82	32.48

Table II (Continued)

Pressure Transducer B Dynamic Calibration Data

Frequency Hz	Applied Accel. g peak-to-peak	Transducer Output x10 mV rms	Equivalent Output at 10g peak-to-peak mV peak-to-peak
60	10	114.93	32.51
65	10	114.95	32.51
70	10	115.00	32.53
75	10	115.10	32.56
80	10	115.14	32.57
85	10	115.20	32.58
90	10	115.27	32.60
95	10	115.33	32.62
100	2	23.11	32.68
100	4	46.16	32.64
100	6	69.27	32.65
100	8	92.31	32.64
100	10	115.34	32.62
100	12	138.35	32.61
100	14	161.63	32.65
100	16	184.64	32.64
100	18	207.65	32.63
100	20	230.81	32.64
100	22	253.90	32.64
100	24	277.06	32.65
100	26	300.00	32.64
100	28	323.30	32.66
100	30	346.32	32.65
100	32	369.21	32.63
100	34	392.24	32.63
100	36	415.31	32.63
100	38	438.20	32.62
100	40	461.14	32.61
100	42	484.62	32.64
100	44	507.21	32.60
100	46	530.32	32.61
100	48	553.45	32.61
100	50	576.77	32.63
100	52	599.52	32.61
100	54	623.07	32.64
100	56	646.20	32.64
100	58	670.00	32.67
300	2	24.53	34.69
300	10	122.70	34.70
300	20	245.00	34.65
300	30	366.34	34.54
300	40	487.31	34.46

Table III

Transducer B Linearity Characteristics

Frequency Hz	Acceleration Range g peak-to-peak	Maximum deviation of Sensitivity $\pm\%$
25	2 to 10	$\pm$ 0.2
50	2 to 20	$\pm$ 0.1
100	2 to 58	$\pm$ 0.1
300	2 to 40	$\pm$ 0.4

A thin cork disc was floated on the water to prevent splashing at the higher acceleration levels and at low frequencies. The maximum acceleration level of 58 g peak-to-peak generated an equivalent pressure of 19 psi peak-to-peak (130 kN/m^2); at this acceleration level it appeared that the electrical connector to the transducer was being affected by the vibration, causing poor waveform. Distortion was measured with a commercial distortion meter at 40g and 50g peak-to-peak at 100 Hz and was found to be 0.6% and 0.8% respectively. Scanning the frequency range of 100 Hz to 2000 Hz, distortions of sufficient magnitude to be seen on an oscilloscope were noted at 277, 462, 695 and 2003 Hz. Consequently, such points were avoided during actual calibration runs.

Transducer A was calibrated in a similar fashion except fewer points were taken. The resonant frequency was found to be about 1310 Hz with a damping ratio of less than 0.01 of critical. The dynamic calibration agreed with the static calibration to within 1.6%, as shown in Figure 5. This relatively large discrepancy, compared to the results from calibrations of the other two transducers, may be due to the fact that this transducer's voltage output was very small in amplitude compared to the other two tested, and quite noisy. Deviations from linearity as measured at 25, 50, 100, and 300 Hz were within $\pm$0.4%, $\pm$0.4%, $\pm$0.1% and $\pm$0.4% respectively. Since the actual sensitivity of Transducer A is 1.8 mV/psi, about one-fifth of that of the other two transducers, the presence of electrical noise lowers the accuracy of the measurements at low acceleration levels (2g peak-to-peak). Consequently, these data are not shown in the graph in Figure 5.

Transducer C was calibrated in a similar fashion to Transducer B except that fewer calibration points were taken and the maximum applied acceleration was limited to 30g peak-to-peak to prevent generating pressure amplitudes so large as to overrange the transducer. The resonant frequency of this system was found to be about 1410 Hz with a damping ratio of less than 0.01 of critical. The correlation between dynamic and static calibration was within 0.1%, as shown in Figure 5. Deviations from linearity as measured at 25, 50, 100 and 300 Hz were within $\pm$0.1%,

±0.1%, ±0.2%, and ±0.3%, respectively.

Table IV summarizes the results of the calibrations for the three transducers. The correlation between dynamic and static calibrations is shown as a ratio. The maximum deviation from the average in the dynamic calibrations represents the scatter of the experimental data. The bottom half of the table presents information on the deviations from linearity obtained for the three transducers at various frequencies and acceleration (pressure) levels.

Table V shows the estimated uncertainty of the of the dynamic calibration at an acceleration level of 10g peak-to-peak and a calibration frequency of 50 Hz, the optimum combination of level and frequency for the experimental setup described. The uncertainty, expressed as the root-sum-square error, is estimated to be ± 3.28%, ±1.12%, and ±1.34% for transducers A, B, and C, respectively.

As shown in the section on theory, the frequency response characteristics are determined by the parameters of the liquid column as well as the transducer. Thus the natural frequency of a column of water 9.0 in. high, taken by itself in a perfectly rigid container without absorbed air, can be calculated to be about 1590 Hz. Information was supplied by the transducer manufacturers on the volume changes of the transducers due the application of full-scale pressures. The corresponding changes due the pressure of a 9.0 in. column of water were calculated to be 0.43 x 10^{-6} in.^{3}, 0.13 x 10^{-6}in.^{3}, and 0.0051 x 10^{-6} in.^{3}, for transducers A, B, and C. respectively. Based on this, theoretical values of system natural frequency, for liquid column and transducer were calculated to be 1470 Hz, 1560 Hz, and 1590 Hz. This compares to experimental values of the resonant frequency (highest output at constant acceleration level) of 1310 Hz, 1350 Hz, and 1410 Hz. It was not practical for the computations to take into account effects of remnants of absorbed gas, the stiffness of container and sealants, all of which would tend to result in lowering the computed value of natural frequency to some extent. Accordingly, the agreement found between calculated and experimental frequency values is considered satisfactory.

TABLE IV

Comparison of Static-Dynamic Calibration, Resonant Frequency, and Linearity

Transducer	Frequency Hz	Acceleration Range g peak-to-peak	Number of Dynamic Calibration Points	Ratio, Dynamic/Static	Maximum Deviation From Average (Dynamic) ±%	Resonant Frequency Hz
A	25-50	4 - 20	14	0.984	0.5	1310
B	15-50	2 - 20	32	0.997	0.3	1350
C	15-50	2 - 20	21	1.000	0.3	1410
A	25	4 - 10	4		0.4	
A	50	4 - 20	6		0.4	
A	100	10 - 60	6		0.1	
A	300	10 - 60	6		0.4	
B	25	2 - 10	5		0.2	
B	50	2 - 20	10		0.1	
B	100	2 - 58	29		0.1	
B	300	2 - 40	5		0.4	
C	25	2 - 10	5		0.1	
C	50	2 - 20	7		0.1	
C	100	2 - 30	4		0.2	
C	300	2 - 30	4		0.3	

TABLE V

Estimated Error for Dynamic Calibration at 50 Hz and 10g Peak-to-peak, 9.0 in. Water Column, 1.0 in. ID

Source of Error		±%	Error Squared
Height of liquid column		0.03	0.0009
Density of liquid		0.1	0.01
Noise, pressure transducer	Transducer A 3.1%	see left	9.6
	Transducer B 0.3%		0.09
	Transducer C 0.8%		0.64
Repeatability of static calibration, pressure transducer	Transducer A 0.01%	see left	0.0001
	Transducer B 0.20%		0.0400
	Transducer C 0.14%		0.0196
Output voltage measurement, pressure transducer		0.1	0.01
Power supply variation, pressure transducer		0.05	0.0025
Calibration of amplifier used with pressure transducer		0.05	0.0025
Voltage measurement, acceleration level meter		0.1	0.01
Noise, acceleration measuring system		0.3	0.09
Calibration of acceleration level meter with precision servo accelerometer		1.0	1.00

Total estimated limit of error	Transducer A	±4.84%	
	Transducer B	±2.23%	
	Transducer C	±2.67%	
Root-sum square error (assuming sources of error to be independent)	Transducer A		±3.28%
	Transducer B		±1.12%
	Transducer C		±1.34%

5. Effects of Parameter Variations on Calibrator Performance

5.1. Effect of Liquid Column Height and Diameter on Frequency Response

The regular calibration test was run on transducer B with the calibrator filled to within 0.5 in. of the top; this represented a static head of 9 in. of water (0.32 psi or 2.2 kN/m^2). Two additional calibration tests were run where the 10 in. calibrator tube was filled to within 3.5 in. of the top (0.22 psi or 1.51 kN/m^2 head) and to within 5.5 in. of the top (0.11 psi or 0.71 kN/m^2 head).

The approximate natural frequencies observed were 1350 Hz for the 9.0 in. column of water, 2025 Hz for the 6.0 in. column of water and 3600 Hz for the 3.0 in. column of water. The frequency response curves were flat to within about 5% to 300 Hz, 400 Hz and 700 Hz respectively. At an acceleration level of 10g peak-to-peak the generated pressures were 3.2, 2.2 and 1.1 psi peak-to-peak (22.4, 14.9, and 7.5 kN/m^2) respectively. The Q in all three cases was about 150. The data is presented graphically in Figure 6.

Two other calibrators were made up, one with an inner diameter of 1.5 in. and one with an inner diameter of 0.63 in. to study the effect of diameter on frequency response. Calibrations of transducer B using the new calibrators plus the existing 1.0 in. diameter calibrator showed only a slight change in the natural frequency with diameter. The natural frequencies noted were approximately (measured in 25 Hz increments) 1375, 1350 and 1300 Hz for the 0.63 in., 1.0 in., and 1.5 in. calibrators respectively. The graphical data is shown in Figure 7.

5.2. Experimental Attempts to Increase Damping

It was shown in provious calibrations that the damping was less than 0.01 of critical and the pressure transducer output was up about 5% at 300 Hz (approximately 20% of the natural frequency). The next series of tests was aimed at increasing the damping of the system to approximately 0.6 of critical; the frequency response would thus be flat within ±4% to approximately 80% of the natural frequency. The approach was twofold: (1) increasing the surface area and (2) increasing the viscosity of the liquid.

The first of the series of tests was a control calibration using transducer B which was run from 15 Hz to 2000 Hz using water.

In the second test the surface area of the calibrator was increased by taking twelve 0.25 in. diameter (0.005 in. wall) 8.5 in. long, stainless steel tubes and packing them into the calibrator; this "honey comb" calibrator was then filled with water and the standard frequency response test run.

For the third test the water was removed from the calibrator and the tube dried and its insert tubes refilled with SAE 140 weight oil and the standard frequency response test run.

For the fourth test the 0.25 in. tubes and the 140 weight oil were removed and the calibrator degreased; the calibrator was then repacked with forty-eight 0.125 in. diameter tubes. A frequency response test was again run using water.

The fifth test was similar to the fourth except 140 weight oil was used.

The Q (dynamic response/static response, as measured at resonance) was found to be as shown in Figure 8 and summarized below:

	Q
Test (1) water, no tubes	143
Test (2) water, twelve 0.25 in. tubes	61
Test (3) 140 weight oil, twelve 0.25 in. tubes	2.6
Test (4) water, forty-eight 0.125 in. tubes	24
Test (5) 140 weight oil, forty-eight 0.125 in. tubes	1.2

The Q of 1.2 represents a damping ratio of 0.44 of critical. While no particular difficulty was encountered in using the oil filled calibrator with twelve 0.25 in. tubes, it required special care to remove the entrapped air from the calibrator when using the forty-eight 0.125 in. tubes. In both cases the oil was heated to 100°C to facilitate air removal by vacuum. When using the oil in conjunction with an environmental test chamber it was shown that the proper damping could be readily achieved by simply chilling the 140 weight oil to an appropriate temperature.

Since the use of an environmental chamber is an undersirable complication, additional tests were performed. Worthy of note is the test where three 0.50 in. diameter tubes were inserted in the calibrator and a petroleum oil designated as P 29 was added (this is an NBS viscosity standard with a viscosity of 452 stokes at 30°C and a viscosity of 201 stokes at 40°C). Calibrations were run at 34.5°C, 29.0°C and 26.7°C and the damping at 29°C gave the desired results. Figure 9 shows the data graphically. The significant change in damping over a range of less than 8°C points out the desirability of using a liquid whose viscosity change with temperature is more moderate. Silicone based fluids were not tried but would appear useful in this regard.

5.3. Experimental Calibration Using Liquids Other Than Water

A regular calibration was run from 15 Hz to 2000 Hz using transducer B, first with glycerin and then with ethyl acetate. It was hoped to correlate the physical characteristics of these liquids (bulk modulus, density, viscosity, surface tension, vapor pressure, etc.) with the calibration system. While it is obvious that a denser liquid would apply a correspondingly higher pressure for a given acceleration level or that a more viscous liquid would provide more damping, it is difficult to predict the effect of these characteristics on the natural frequency.

Experimental values of natural frequency for the system were approximately 1360 Hz with glycerin and 1120 Hz when using ethyl acetate. Calculated values of natural frequency were 1780 Hz and 1050 Hz respectively. The Q was 8 and 47 respectively. The output amplitude of transducer B at the same acceleration level was proportional to the density of the liquid in both cases. Experimental values of resonant frequency for these liquids did not agree as well with calculated values, as did such values for water. Part of this may be due to the fact that different values of bulk modulus are given for these liquids in the different references consultated.

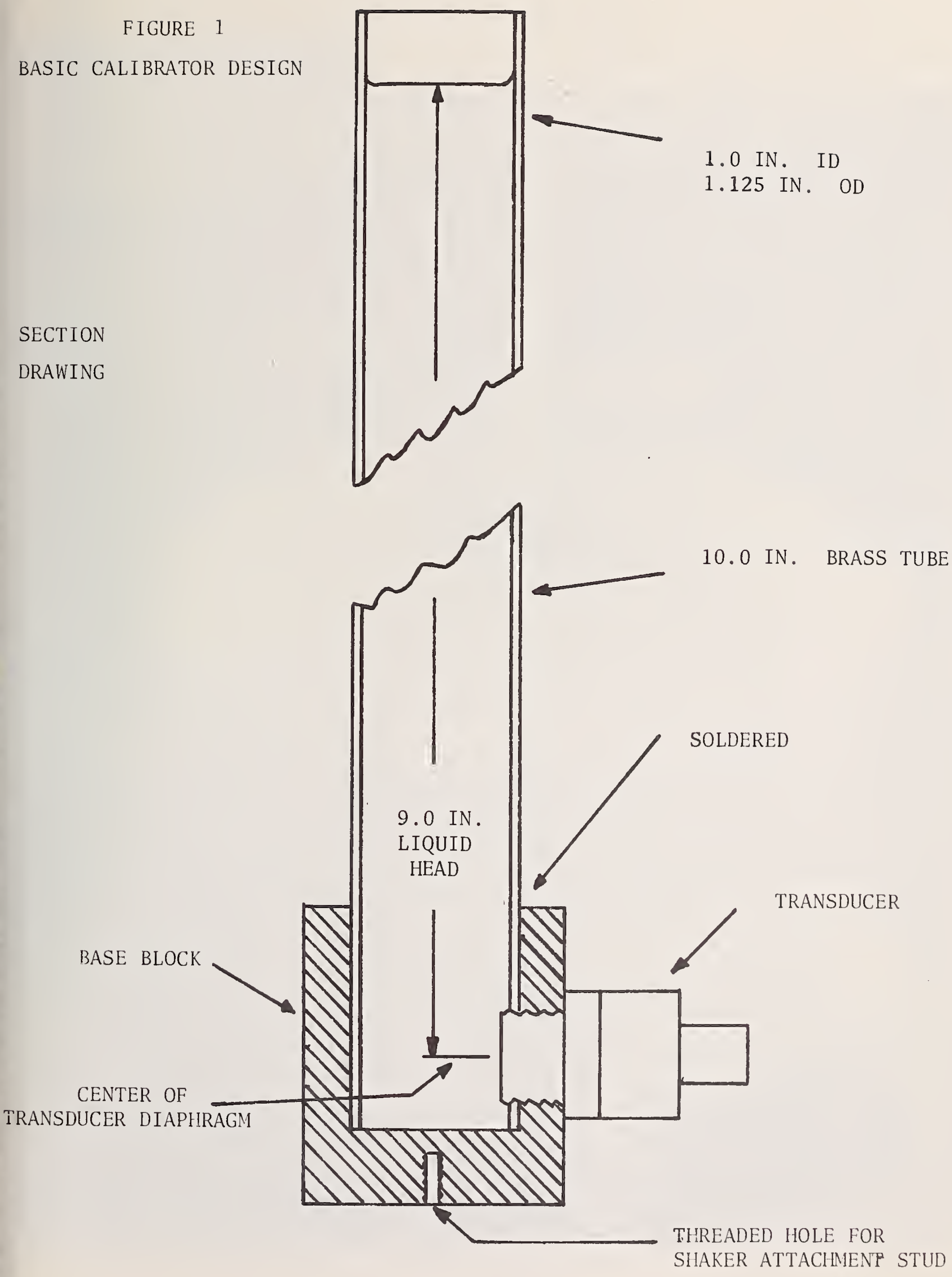
6. Conclusions and Recommendations

The hydraulic sinusoidal pressure calibrator has been found to be a simple, accurate device and an improvement in the state of the art for the dynamic calibration of many pressure transducers. Static and dynamic calibration data has been obtained from 15 Hz to 2000 Hz with pressure levels up to 19.5 psi (134 kN/m^2) peak-to-peak. The amplitude and frequency capabilities of this calibrator should make it particularly suitable for the dynamic calibration of bio-medical pressure transducers.

Additional efforts to investigate the use of other liquids with improved damping characteristics and configurations suitable for the generation of greater pressure amplitudes would further enhance the usefulness of this type of dynamic pressure calibrator.

FIGURE 1

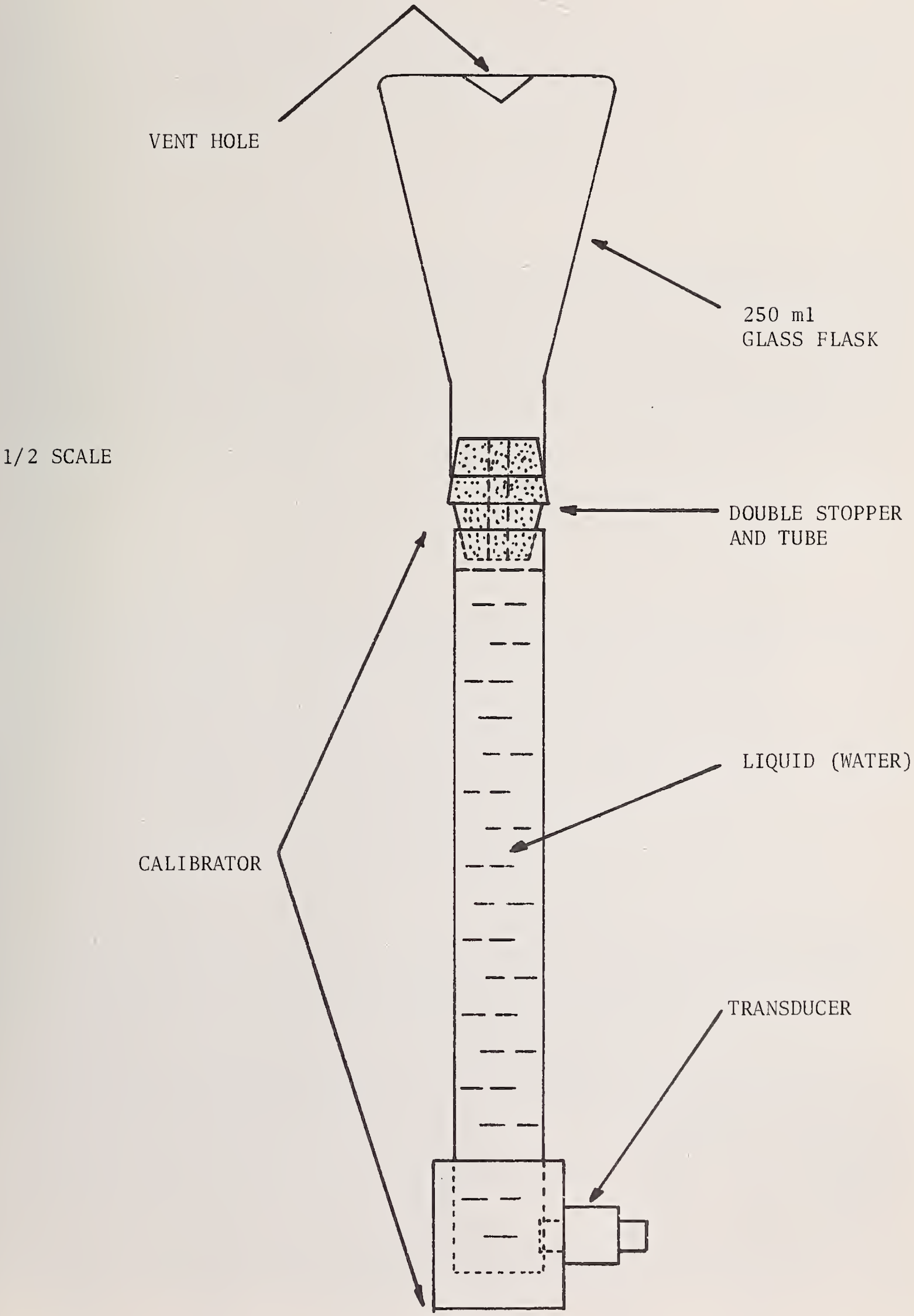
BASIC CALIBRATOR DESIGN

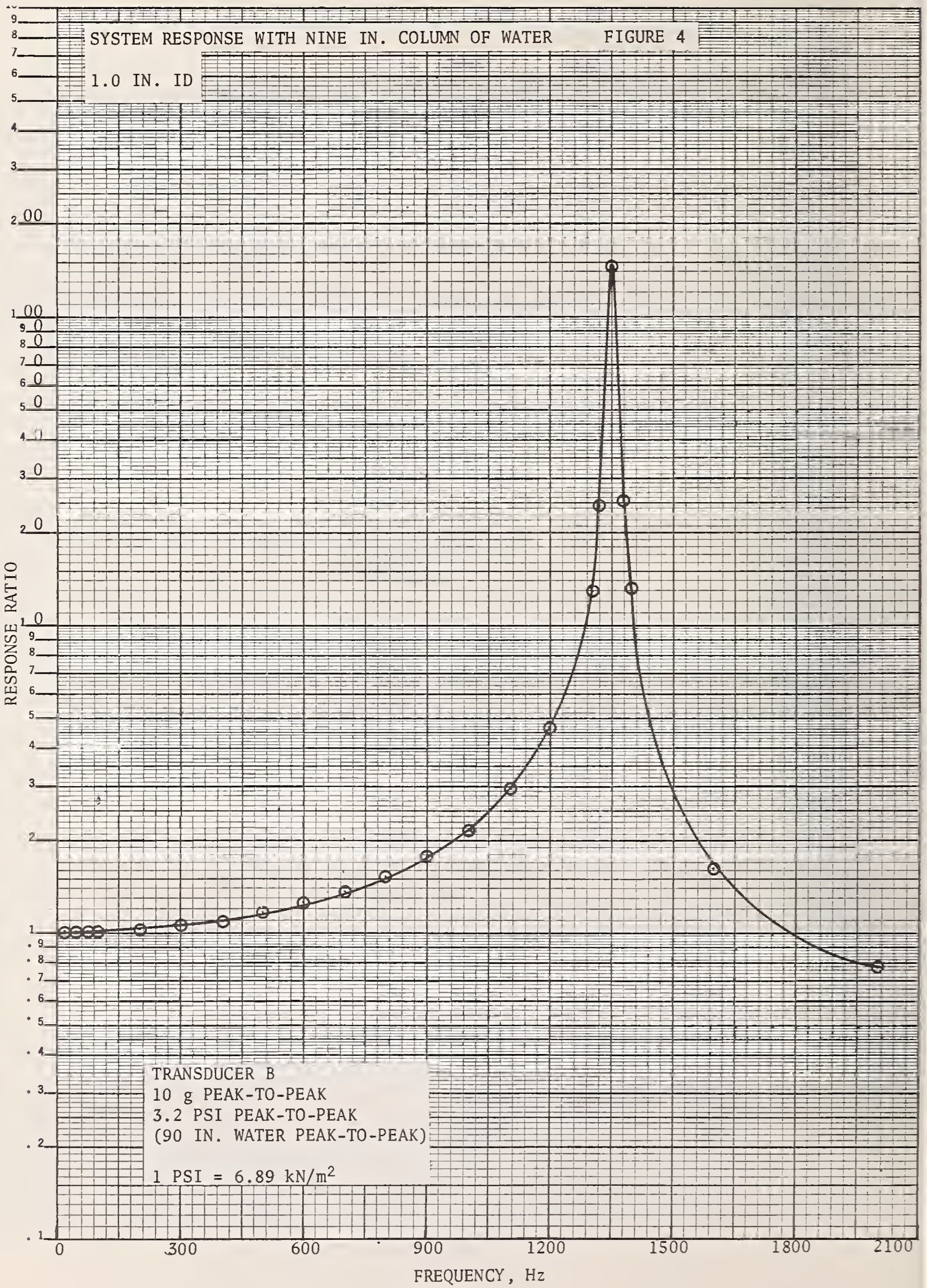


SINUSOIDAL PRESSURE CALIBRATOR MOUNTED ON AN ELECTRODYNAMIC SHAKER FIGURE 2

SETUP FOR DE-GASSING OF LIQUID IN CALIBRATOR

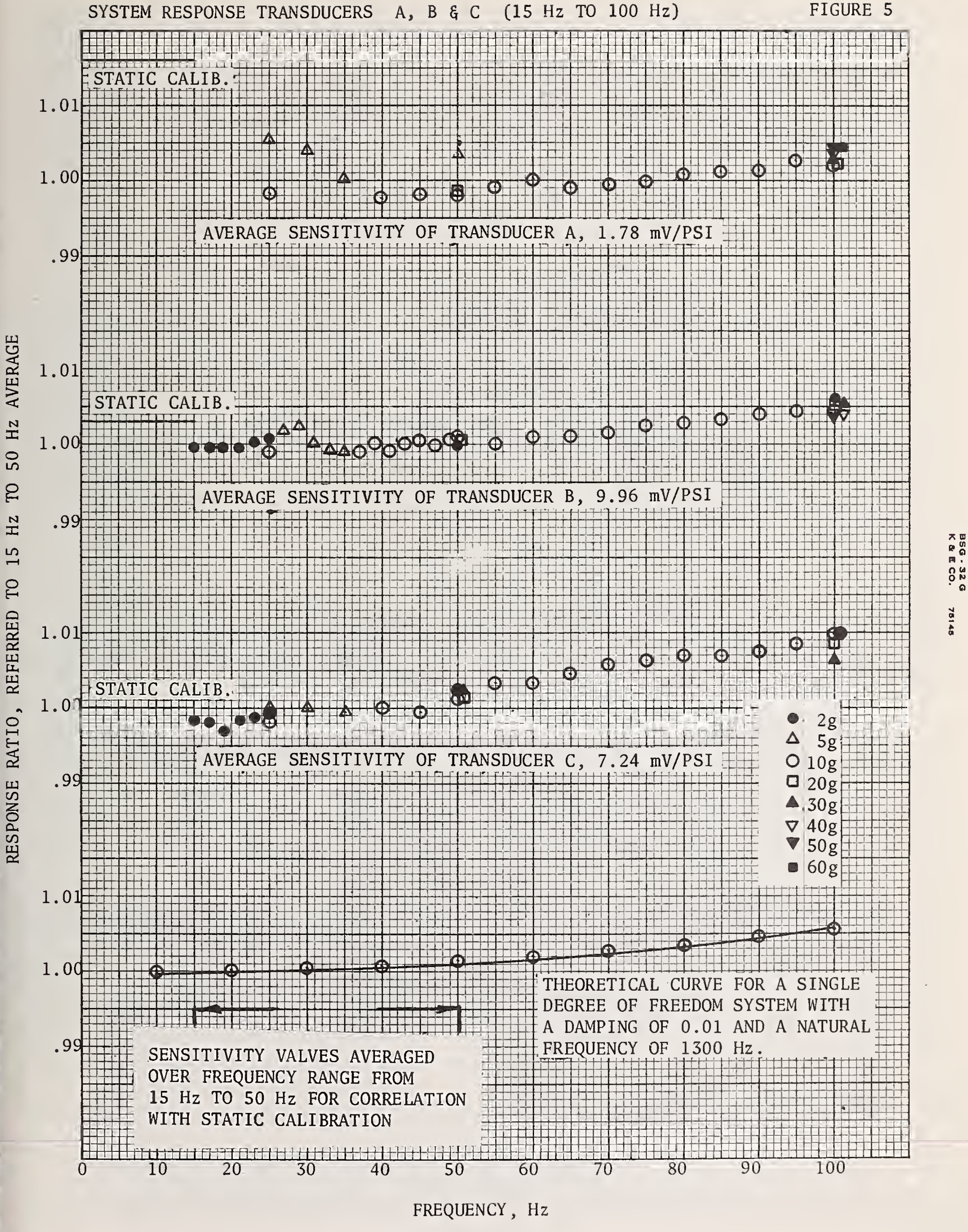
FIGURE 3



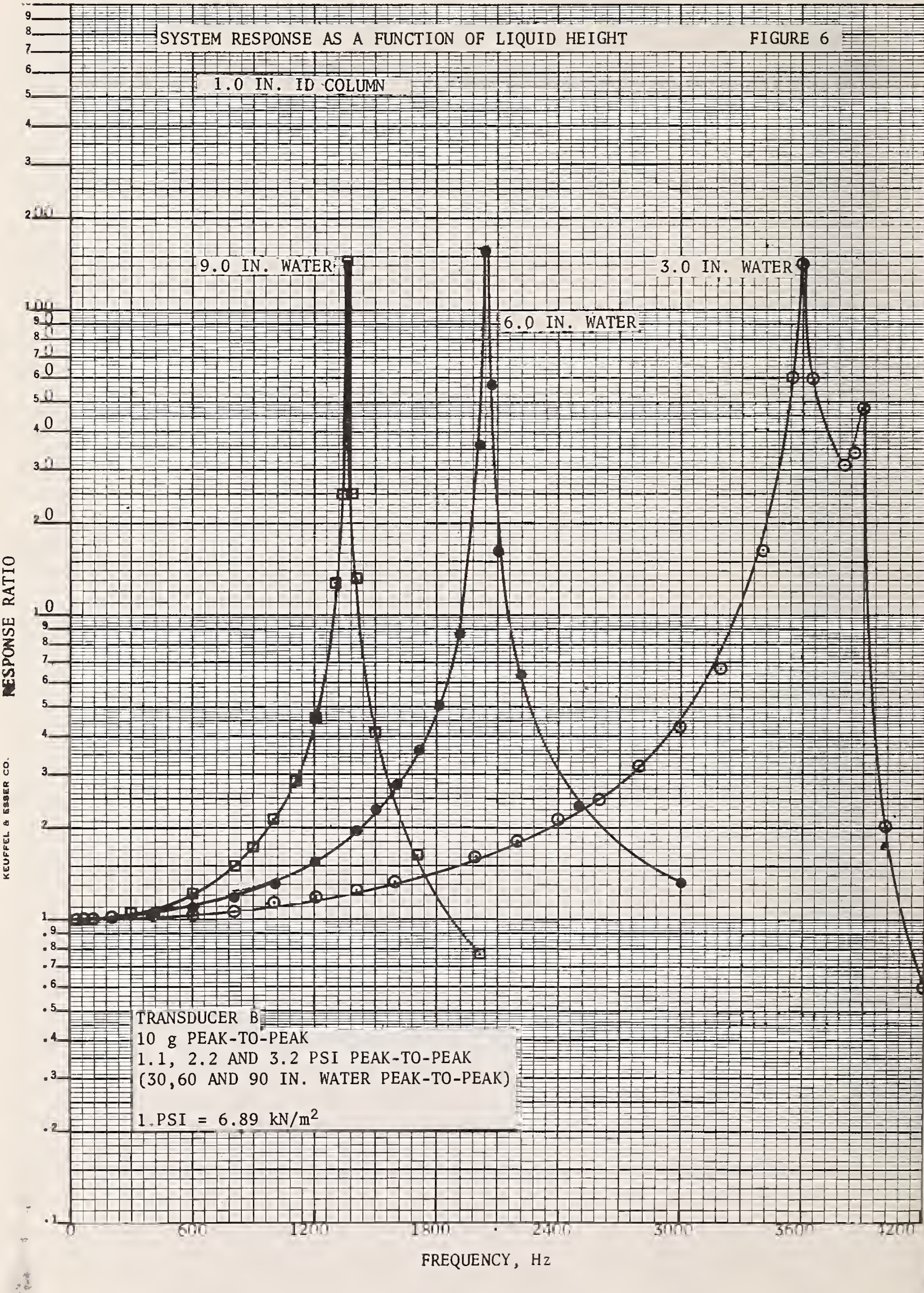


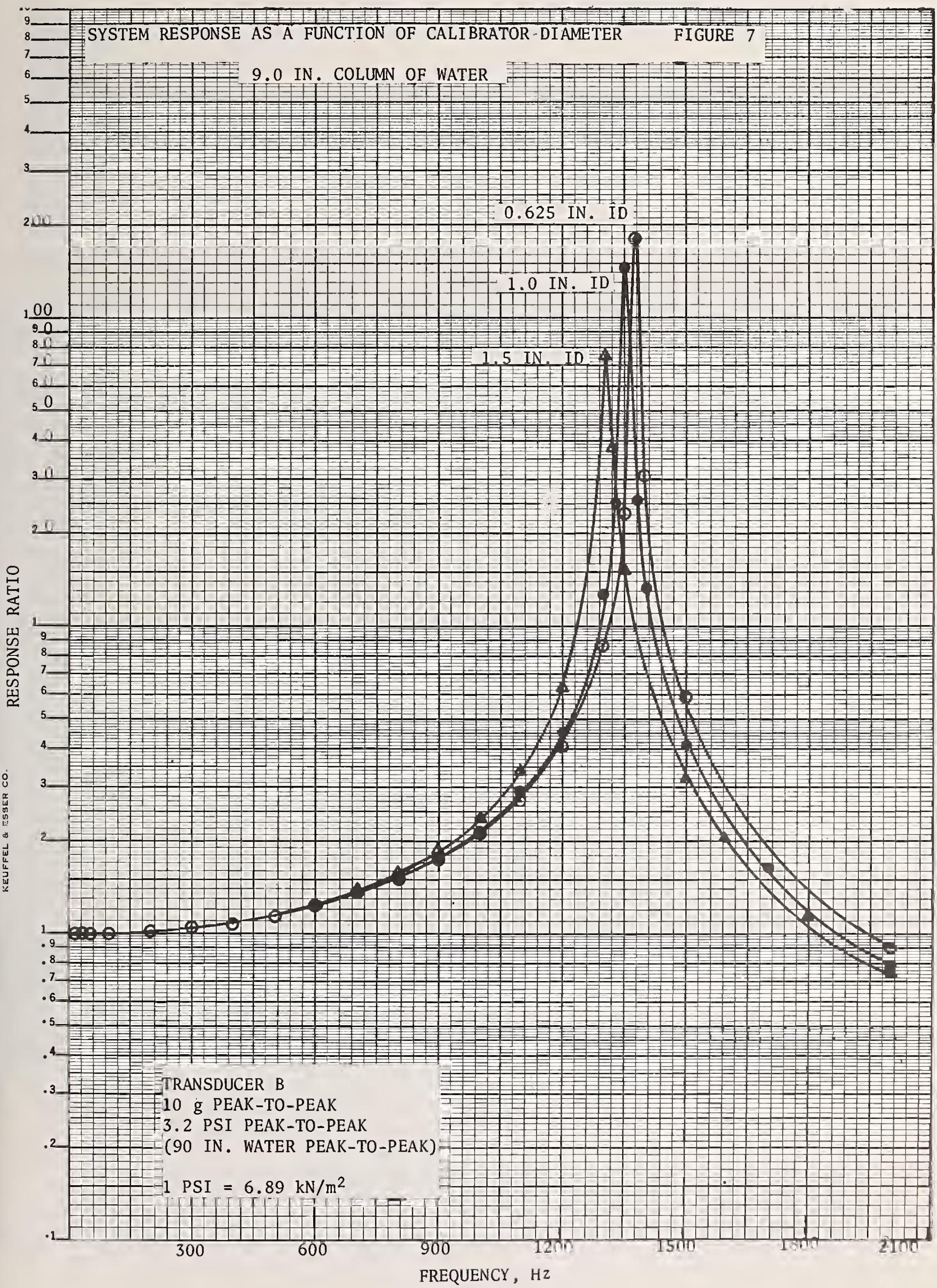
SYSTEM RESPONSE WITH NINE IN. COLUMN OF WATER
FIGURE 4
1.0 IN. ID
TRANSDUCER B
10 g PEAK-TO-PEAK
3.2 PSI PEAK-TO-PEAK
(90 IN. WATER PEAK-TO-PEAK)
1 PSI = 6.89 kN/m2
RESPONSE RATIO
FREQUENCY, Hz
0
300
600
900
1200
1500
1800
2100
100
10
1
.1

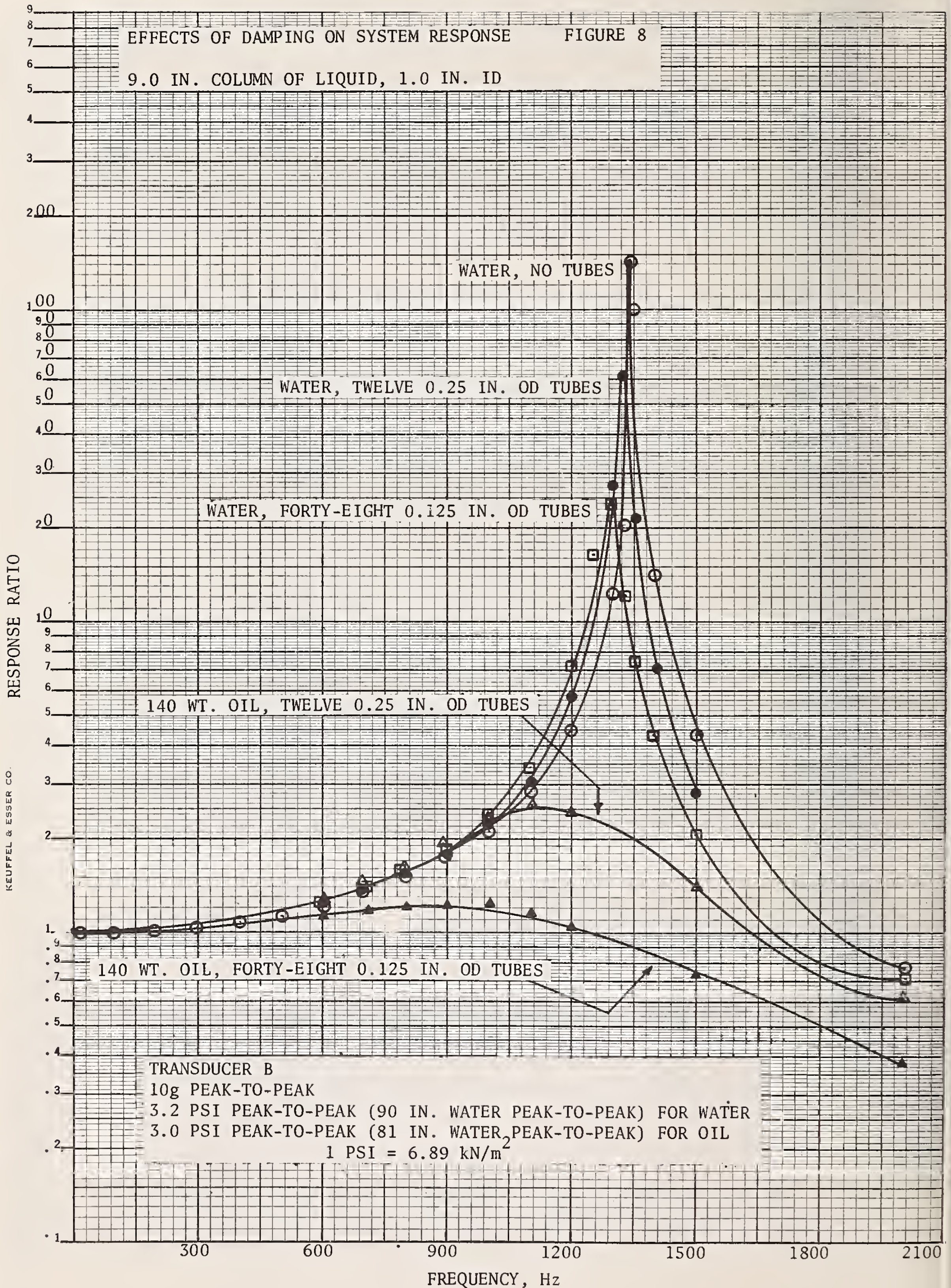
FIGURE 5

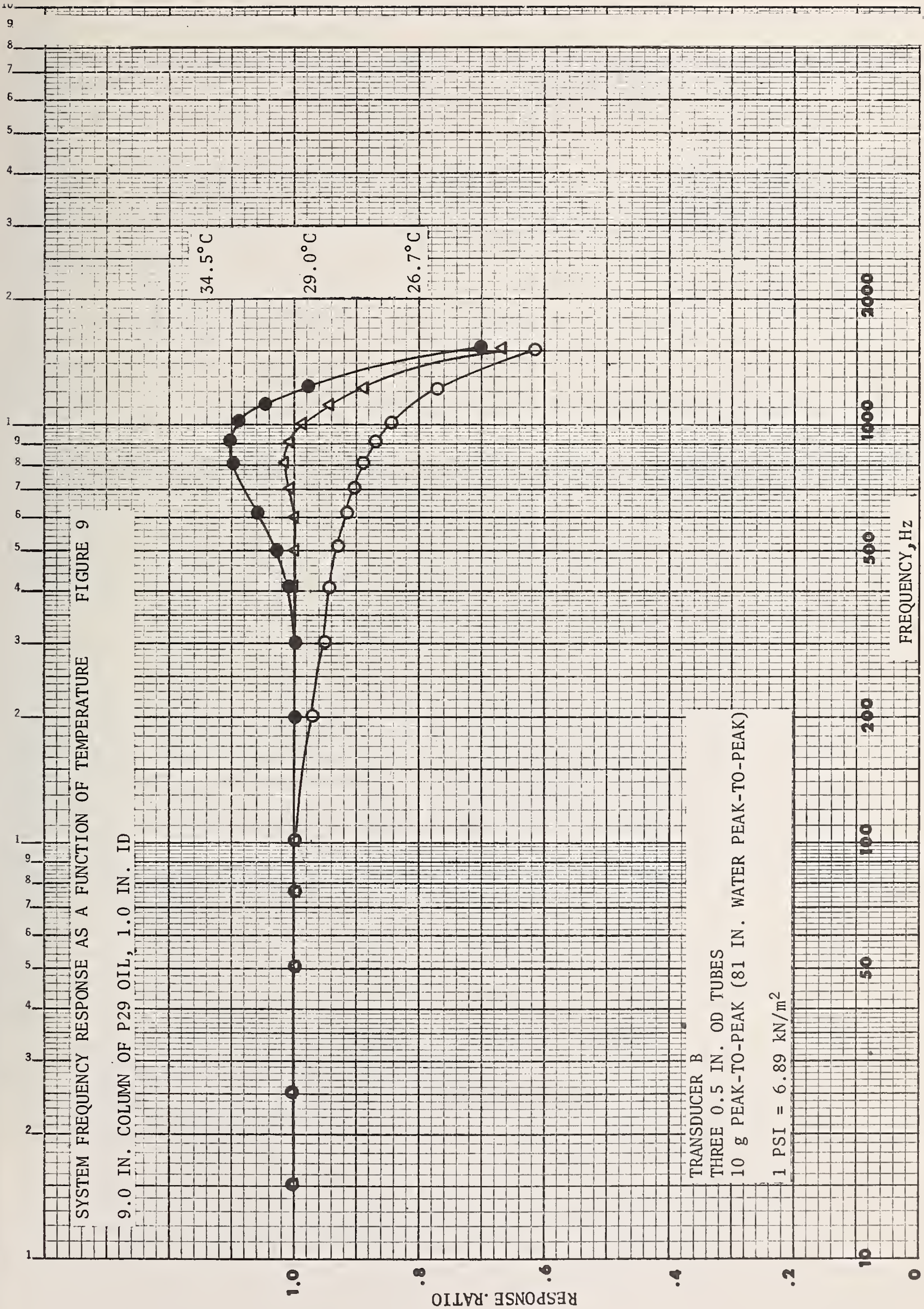


SYSTEM RESPONSE TRANSDUCERS A, B & C (15 Hz TO 100 Hz)
STATIC CALIB.
1.01
1.00
.99
AVERAGE SENSITIVITY OF TRANSDUCER A, 1.78 mV/PSI
STATIC CALIB.
AVERAGE SENSITIVITY OF TRANSDUCER B, 9.96 mV/PSI
STATIC CALIB.
AVERAGE SENSITIVITY OF TRANSDUCER C, 7.24 mV/PSI
2g
5g
10g
20g
30g
40g
50g
60g
THEORETICAL CURVE FOR A SINGLE DEGREE OF FREEDOM SYSTEM WITH A DAMPING OF 0.01 AND A NATURAL FREQUENCY OF 1300 Hz.
SENSITIVITY VALVES AVERAGED OVER FREQUENCY RANGE FROM 15 Hz TO 50 Hz FOR CORRELATION WITH STATIC CALIBRATION
RESPONSE RATIO, REFERRED TO 15 Hz TO 50 Hz AVERAGE
0
10
20
30
40
50
60
70
80
90
100
FREQUENCY, Hz
BSG-32G K&E CO. 75145


SYSTEM RESPONSE AS A FUNCTION OF LIQUID HEIGHT
FIGURE 6
1.0 IN. ID COLUMN
9.0 IN. WATER
6.0 IN. WATER
3.0 IN. WATER
RESPONSE RATIO
FREQUENCY, Hz
TRANSDUCER B
10 g PEAK-TO-PEAK
1.1, 2.2 AND 3.2 PSI PEAK-TO-PEAK
(30,60 AND 90 IN. WATER PEAK-TO-PEAK)
1 PSI = 6.89 kN/m^2
KEUFFEL & ESSER CO.


SYSTEM RESPONSE AS A FUNCTION OF CALIBRATOR DIAMETER
FIGURE 7
9.0 IN. COLUMN OF WATER
0.625 IN. ID
1.0 IN. ID
1.5 IN. ID
RESPONSE RATIO
FREQUENCY, Hz
300
600
900
1200
1500
1800
2100
TRANSDUCER B
10 g PEAK-TO-PEAK
3.2 PSI PEAK-TO-PEAK
(90 IN. WATER PEAK-TO-PEAK)
1 PSI = 6.89 kN/m2
KEUFFEL & ESSER CO.


EFFECTS OF DAMPING ON SYSTEM RESPONSE
FIGURE 8
9.0 IN. COLUMN OF LIQUID, 1.0 IN. ID
WATER, NO TUBES
WATER, TWELVE 0.25 IN. OD TUBES
WATER, FORTY-EIGHT 0.125 IN. OD TUBES
140 WT. OIL, TWELVE 0.25 IN. OD TUBES
140 WT. OIL, FORTY-EIGHT 0.125 IN. OD TUBES
TRANSDUCER B
10g PEAK-TO-PEAK
3.2 PSI PEAK-TO-PEAK (90 IN. WATER PEAK-TO-PEAK) FOR WATER
3.0 PSI PEAK-TO-PEAK (81 IN. WATER PEAK-TO-PEAK) FOR OIL
1 PSI = 6.89 kN/m2
RESPONSE RATIO
FREQUENCY, Hz
300
600
900
1200
1500
1800
2100
KEUFFEL & ESSER CO.


SYSTEM FREQUENCY RESPONSE AS A FUNCTION OF TEMPERATURE FIGURE 9
9.0 IN. COLUMN OF P29 OIL, 1.0 IN. ID
34.5°C
29.0°C
26.7°C
TRANSDUCER B
THREE 0.5 IN. OD TUBES
10 g PEAK-TO-PEAK (81 IN. WATER PEAK-TO-PEAK)
1 PSI = 6.89 kN/m²
FREQUENCY, Hz
10
50
100
200
500
1000
2000
RESPONSE RATIO
1.0
.8
.6
.4
.2
0

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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 paper describes a simple, accurate device for the sinusoidal calibration of pressure transducers. Calibration is achieved by vibrating a liquid tube on an electrodynamic shaker (vibration generator); the pressure transducer mounted at the base of the tube senses the sinusoidally varying pressure in the tube. The frequency range is 15 Hz to 2000 Hz with a maximum obtainable amplitude of 19.5 psi (134 kN/m^2) peak to peak. The transducer can easily be calibrated statically in the same device, thus permitting precise correlation between static and dynamic calibrations. Agreement between static and dynamic calibrations to within 0.1% has been achieved.

17. KEY WORDS (Alphabetical order, separated by semicolons)

Calibrator; dynamic; hydraulic; InterAgency Transducer Project; pressure transducer; sinusoidal pressure.

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