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DEVELOPMENT OF A DYNAMIC PRESSURE CALIBRATION TECHNIQUE

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Sinusoidally varying pressures of 34 kPa zero-to-peak have been produced, to date, between 40 Hz and 750 Hz by vibrating a 10-cm column of a dimethyl siloxane liquid at 36 g_n zero-to-peak. Damping of the liquid column was accomplished by packing the fixture tube with a number of smaller diameter tubes.

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; liquid column; pressure; sinusoidal pressure; transducer.

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DEVELOPMENT OF A DYNAMIC PRESSURE CALIBRATION TECHNIQUE A PROGRESS REPORT

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Institute for Applied Technology
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Progress Report Covering Period 2-15-74 to 8-15-74

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Hampton, Virginia 23365

U.S. DEPARTMENT OF COMMERCE, Rogers C.B. Morton, Secretary
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

Development of a Dynamic Pressure Calibration Technique

A Progress Report

by: C. F. Vezzetti, J. S. Hilten, and P. S. Lederer

Work continues on the development of a method of producing sinusoidally varying pressures of at least 34 kPa zero-to-peak with amplitude variations within ±5% up to 2 kHz for the dynamic calibration of pressure transducers.

Sinusoidally varying pressures of 34 kPa zero-to-peak have been produced, to date, between 40 Hz and 750 Hz by vibrating a 10-cm column of a dimethyl siloxane liquid at 36 g_n zero-to-peak. Damping of the liquid column was accomplished by packing the fixture tube with a number of smaller diameter tubes.

Key Words: Calibration; dynamic; liquid column; pressure; sinusoidal pressure; transducer.

DEVELOPMENT OF A DYNAMIC PRESSURE CALIBRATION TECHNIQUE

Progress Report for the Period
February 15, 1974 to August 15, 1974

to the

NASA Langley Research Center
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NBS Project 4253456

Prepared by

C. F. Vezzetti, J. S. Hilten, and P. S. Lederer

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1. INTRODUCTION

This is the third progress report [1,2]* of an experimental investigation to develop a source of dynamic sinusoidal pressures of at least 34 kPa zero-to-peak, at frequencies of up to 2 kHz or greater, for calibrating pressure transducers. Pressure amplitude variations over this frequency range are not to exceed ±5%.

The method selected is based on an extension of a method (previously developed by the NBS Instrumentation Applications Section [3]) which is capable of generating sinusoidally varying pressures of 10 kPa zero-to-peak over the frequency range 15 Hz to about 1 kHz with a pressure amplitude variation of less than ±5%, and pressures of 67 kPa zero-to-peak between 100 Hz and 300 Hz.

1.1 Basic Method

The transducer to be calibrated is mounted near the base of a liquid-filled tube; the tube is mounted on the armature of an electrodynamic vibration exciter and vibrated so as to produce a sinusoidally varying pressure at the transducer diaphragm. The amplitude of this pressure

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*Figures in brackets indicate references, section 5.

is proportional to the product of the liquid head (above the center of the transducer diaphragm) and the acceleration of the tube. Various parameters limit the frequency range over which the method is effective and the maximum pressure levels attainable.

Both the natural frequency and the degree of damping of the combined liquid-column and transducer structure determine the useful upper frequency limit. The natural frequency of a liquid column is directly proportional to the speed of sound in the liquid and inversely proportional to the height of the column. An undamped system is usable (i.e., capable of generating pressures with a variability in peak amplitude of less than ±5%) over a range of frequencies up to about 20% of the natural frequency; an optimally damped system is usable over a frequency range with an upper limit of about 80% of the natural frequency [3].

The factors that in combination determine the pressure levels attainable over the frequency range of interest are (1) the force and displacement capabilities of the vibration exciter, (2) the density of available working fluids, and (3) the height of the liquid column. The range of exciter capabilities is determined by the specific instrument available and is therefore fixed; for a selected fluid density, the column height required to generate a given pressure (at a given acceleration) is first determined by calculation and then verified experimentally.

1.2 Summary of Progress in Previous Reporting Period

In the previous reporting period, a test fixture was fabricated for preliminary testing of various liquids as working fluids and of various means of damping the liquid column [2]. The fixture was designed to accommodate different experimental tubes and transducers of different sizes.

Liquids tested in the period were water, a fluorcarbon liquid of specific gravity 1.88, tetrabromoethane, and a light petroleum oil. The effect on damping of increasing the wetted surface through the use of tubes with various special internal configurations was evaluated. Tube designs tested include tubes with smooth inside walls, with spiral fins on the inside walls, with interlacing diagonal fins, and with multiple separate channels. The use of a sintered-metal filter in the tube was also tested.

Test results were given in the previous report.

2. EXPERIMENTAL DEVELOPMENT

2.1 Completion of Preliminary Experiments

At the start of the reporting period, the schedule of preliminary work included several elements not then completed.

2.1.1 Experiments with Transducer Recessed. Measurements with the same transducer mounted first in an earlier one-piece fixture and then in the test fixture [2] showed a reduction in the resonance frequency of about 40 Hz for a water column 35-cm high. The suggestion was made that this reduction resulted from the geometry of the test fixture, in which the transducer sensing head is recessed from the chamber. Several tests were run at the 35-cm water-column height with spacer rings inserted between the transducer mounting surface and the test fixture. With various rings in place, the transducer sensing head was recessed by an additional distance of either 1.0 cm or 2.2 cm. The results did not show a significant variation in resonance frequency.

2.1.2 Magnetic Damping Experiment. The possibility of using magnetic damping was investigated with a hydrocarbon-base magnetic fluid. Because only a small amount of the magnetic fluid was available, a special fixture was fabricated for this experiment. A 34-cm-long glass tube, 0.5-cm i.d., was epoxy bonded into a bore through a 2.5-cm-diameter by 3.8-cm-long aluminum base block. The opposite end of the bore was threaded to receive a pressure transducer, as shown in figure 1.

The tube was vacuum filled with magnetic fluid to a height of 35 cm. The fixture was then mounted on the vibration exciter armature, and the frequency characteristics measured. The resonance frequency of this system was determined to be 737 Hz with an amplitude ratio of 18. For purposes of this report, amplitude ratio is defined as the ratio of the measured maximum amplitude (at resonance) to the measured amplitude at frequencies below the natural frequency over which the frequency-response plot exhibits no significant departure from a straight line parallel to the frequency axis. A magnet was first placed along the side of the glass tube near the top surface of the liquid column, then at the center, and finally near the bottom. No changes in resonance frequency or in amplitude ratio were observed for any of the magnet positions. Next, a strip of magnetic material was placed along the entire length of the column; again, no changes in resonance frequency or in amplitude ratio were detected. Finally, a solenoid was formed with approximately 800 turns of 0.058-cm-diameter (23 AWG) wire wound around the glass tube and energized with 10 V dc (current of 4 A). This attempt also resulted in no observable changes in resonance frequency or in amplitude ratio.

2.1.3 Vacuum Chamber Modification. The presence of gas bubbles and dissolved gases in the working fluid tends to lower the natural frequency of the column. The liquid-filled test fixture was placed in a vacuum chamber held at reduced pressure for at least 15 min. The pressure in the chamber was intended to be above that at which the fluid boils and low enough to degas the liquid in an open cylindrical tube. However, bubbles remained in the liquid in a rectangular-cross-section tube with interlacing diagonal fins even after 30 min in the chamber. Bubbles also were observed remaining in tubes in which the less porous of the filter types tested were installed. Accordingly, the vacuum chamber was modified to provide a means for vacuum filling the test fixture.

A short length of copper tubing was inserted through a hole drilled in the removable cover of the vacuum chamber and an air-tight seal made between tubing and cover. A vacuum valve and a stainless-steel beaker with a hole drilled in the bottom were mounted on top of the tubing with a liquid- and air-tight seal between tubing and beaker, and a short length of rubber hose was attached to the vacuum side of the tubing.

For vacuum filling, the fixture is placed in the chamber. As the cover of the chamber is being replaced, the free end of the rubber hose is guided into the open end of the fixture. The vacuum valve is then closed, and the chamber evacuated for about 15 min. Enough liquid to fill the test fixture is poured into the beaker, and the valve opened slowly to allow the liquid to flow into the fixture. When the beaker is almost empty, the valve is closed. The fixture is left in the chamber at the reduced pressure for an additional 15 min to complete the procedure.

2.1.4 Liquid-Tube Combination Experiments. Tests were conducted to evaluate the various liquid-tube combinations not yet studied, including tests with a heavy petroleum oil (of viscosity about 15 St). Table 1 is a summary of the combinations tested, with resonant frequency and amplitude ratio of each combination as experimentally determined.

Difficulty was again encountered in filling the rectangular cross-section tube and tubes equipped with low-porosity filters with either water or tetrabromoethane as the working fluid. An explanation is that at the lowered pressure of the chamber, irregularities and sharp corners serve as bubble formation sites in an early stage of boiling.

The problems associated with filling, coupled with more promising indications from other experiments, resulted in a decision to discontinue tests of low-viscosity working fluids with the rectangular-cross-section tube (with internal diagonal fins) and with tubes equipped with filters.

2.2 Experiments Using High-Viscosity Liquid Columns

A decision was made to concentrate on tests using high-viscosity working fluids. The upper frequency capability specification of 2 kHz requires either: (1) the use of an undamped column with a natural frequency of at least 10 kHz, or (2) the use of a damped column with a natural frequency between 2.5 and 10 kHz, the specific natural frequency depending on the degree of damping achieved. For all situations, the liquid head must be large enough to produce 34 kPa zero-to-peak pressures at an acceleration level within the capability of the vibration exciter. Low-viscosity fluids have experimentally not been found to provide the amount of damping required by a practical method.

2.2.1 Properties of Liquids. Table 2 lists pertinent properties of liquids which were considered as working fluids for this method, and figure 2 is a plot of the calculated acceleration levels required to produce a sinusoidally varying pressure of 34 kPa zero-to-peak as a function of the liquid column height, for each liquid.

On the basis of its properties, glycerine appeared to be the most suitable high-viscosity liquid. Dimethyl siloxane liquids also showed promise. These liquids may be obtained in a large range of viscosities (up to 1000 St) which are relatively constant over a wide temperature range. Petroleum oils also showed promise but exhibit highly temperature-dependent viscosities.

Figure 2 also shows that a 2.5-cm column of mercury vibrated at 10 g_n zero-to-peak should produce the desired pressure levels and flat frequency response without any damping other than that of the mercury itself; however, because of health hazards and other problems related to the use of mercury, only a limited amount of experimentation is planned with mercury as a working fluid.

2.2.2 Experiments Using Glycerine. Several attempts were made to use glycerine as the working liquid. The glycerine contained many small bubbles which could not be removed by heating, or even by maintaining the glycerine-filled tube at reduced pressure for several days. The presence of bubbles reduced the natural frequency below the minimum required frequency of 2.5 kHz.

2.2.3 Experiments Using Dimethyl Siloxane Liquids. Samples of dimethyl siloxane liquids of 10-, 12.5-, 30-, and 60-St viscosities were available. Experiments were conducted to determine which of these liquids would be most useful, that is, which would be viscous enough to provide sufficient internal damping but not so viscous as to cause problems with the filling operation or the degassing process.

2.2.3.1 For the initial experiments with dimethyl siloxane liquids, a test fixture of about 11-cm overall length was fabricated from 2.4-cm-i.d. brass tubing as shown in figure 3. To fill the fixture, the test liquid was poured into the fixture; then the fixture was placed in a vacuum desiccator, and the pressure lowered. The fixture was maintained at reduced pressure until the liquid ceased to bubble. This process required as long as four hours for some configurations.

After filling, the fixture was mounted on the vibration exciter armature. Liquid was added or removed to bring the column height to 10 cm, and the frequency characteristics were measured. The natural frequency of a 10-cm column of dimethyl siloxane liquid is computed to be very close to the target frequency of 2.5 kHz, and the acceleration necessary to produce the 34 kPa zero-to-peak pressure level is computed to be 36 g_n.

Measured amplitude ratios of these liquid-and-tube combinations ranged from 33 for the 10-St liquid to 13 for the 30-St and 60-St liquids. Results of measurements with dimethyl siloxane liquids are given in table 3.

2.2.3.2 A series of experiments using both 10-St and 60-St liquids was performed to determine tube diameter for optimum damping. Tubes with diameters of 2.4, 1.1, 0.50, 0.28, 0.23, and 0.15 cm were tested.

The fixture used for the tests with the 2.4-cm column was that illustrated in figure 3. The 1.1-cm column fixture was of similar construction. The fixtures for the smaller-diameter columns were of similar construction to that of the fixture used for the magnetic damping experiments and illustrated in figure 1.

The two larger diameter fixtures were filled as described in 2.2.3.1. The four smaller-diameter fixtures were filled by submerging them base-up in a beaker of the test liquid. The transducer was suspended inside of the beaker with the liquid covering the mounting threads. The beaker was placed in the vacuum desiccator, and the pressure lowered as before. After the beaker was removed from the desiccator, the transducer was screwed into the fixture base while still immersed in the liquid. This procedure was intended to prevent air bubbles from contaminating the system.

The fixture was mounted on the vibration exciter armature and the amplitude ratio measured. With 60-St liquid, amplitude ratios of 13, 8, and 3.3 were obtained with tubes of 2.4-, 1.0-, and 0.5-cm-i.d., respectively. Tubes of smaller diameter could not be filled successfully with 60-St liquid. With 10-St liquid, the measured amplitude ratios were 33 for a 2.4-cm tube, 26 for a 1.1-cm tube, 7.4 for a 0.50-cm tube, 2.7 for a 0.28-cm tube, and 1.4 for a 0.23-cm tube. With 10-St liquid the 0.15-cm tube was slightly overdamped, and no measurement was taken. Examination of the results of these experiments suggests that the tube diameter for optimum damping (defined as amplitude ratio = 1.04) with 10-St liquid should lie between 0.15 and 0.23 cm.

2.2.4 Multi-Tube Fixture Experiments. A new fixture was constructed based upon the results of the experiments described in 2.2.3. This fixture was designed to be used with 10-St liquid and was of multi-tube design; that is, a single large tube was packed with a number of smaller tubes, and the voids between tubes filled so that the cross-sectional area of any liquid column would be no greater than that of a small tube. As shown in figure 4, a number of 8-cm lengths of 0.16-cm-i.d. brass tubing were soldered together and into a 2.4-cm-i.d. brass tube about 11-cm long, so that the bundle was 1 cm away from the intended top end of the large tube. Solid copper rods were used to fill large spaces between tubes. A plug was soldered into the other end of the large tube, with a small space between the top of the plug and the bottom of the bundle. A hole was drilled through the plug at its center, and threaded to accept a transducer for test. This multi-tube design permitted the use of small-diameter tubes for damping in a fixture large enough to accept a pressure transducer for test. The clear space at the top of the bundle permitted a more precise measurement of liquid level than would have been possible if the level had to be determined inside a 0.16-cm tube.

Filling this fixture with 10-St liquid required modification of the vacuum-filling procedure previously described in 2.2.3.1. With a liquid of this viscosity and with the given tube size, it proved necessary to pour the liquid in a little at a time and to reduce the pressure around the fixture after each addition of liquid.

Sinusoidally varying pressures of 34 kPa zero-to-peak, of constant amplitude to within ±5%, were produced in this fixture at an acceleration of 36 g_n zero-to-peak at frequencies between 40 Hz and 750 Hz. Displacement capability of the vibration exciter limited the maximum acceleration to less than the 36-g_n level below 40 Hz. At the lower acceleration level of 10 g_n*, a sinusoidally varying pressure of 9.7 kPa zero-to-peak was produced between 20 Hz and 1250 Hz, of constant amplitude to within ±5%, except for an anomaly in the region of 500 Hz observed in a number of measurements. Detailed results for the multi-tube fixture are given for measurements with transducer A-5 in table 4, with the measured response expressed as a root-mean-square value in millivolts.

To provide an indication of the temperature stability of this liquid-and-tube combination, the effect on the frequency characteristics of temperatures 10°C above and below room temperature (25°C) was investigated. The fixture was mounted on the vibration exciter armature, and an environmental chamber placed around it. The frequency characteristics were measured at 15°C and at 35°C after a soak time of 30 min to allow the liquid and fixture temperatures to stabilize. The results of this experiment are given in table 5 with the measured transducer response, corresponding to various test frequencies, expressed as a root-mean-square value in millivolts for the three temperatures; measurements of pressure amplitude at a given frequency agree to within ±6%. Transducer A-4 was used for these measurements, as A-5 was not available. Both A-4 and A-5 have temperature coefficients of about 0.05% · $°C^{-1}$.

2.2.5 Proposal for Balls as Tube Packing. At an early stage of the work, the use of a material such as sea sand had been proposed as a means of increasing the column wetted surface, and hence the degree of damping, by a very large factor. However, the results of a preliminary experiment discouraged further work along these lines. The comparative success of the multi-tube fixture design suggests that further investigations of the use of small particles is now warranted. The suggestion has been made that small spheres, such as balls used in instrument-grade ball bearings, be packed into a fixture tube. Because balls can be added incrementally, problems of filling the column with the 10-St fluid may not be as great as with the multi-tube fixture. Using balls of different sizes for different packings of the tube should provide a wide range of wetted surface areas. Accordingly, work with columns packed with balls will be included in the next reporting period.

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*As 36 g_n was close to the upper capabilities of the vibration exciter at low frequencies and operation at that level resulted in severe shaking of the transducer leads, a majority of the tests were conducted at 10 g_n. Reducing the acceleration level also reduced the risk of of exciter thermal overload.

3. PLANS FOR THE REPORTING PERIOD AUGUST 15, 1974 TO DECEMBER 15, 1974

Work on this task is scheduled for completion in the next reporting period.

3.1 Check-Out of Controller for Vibration Exciter

A programmable controller system for the vibration exciter, capable of automatic frequency sweeping at constant armature acceleration, amplitude, or velocity over the frequency range 5 Hz to 5000 Hz, has been delivered to the laboratory but not yet tested. Advantages provided by this system include the capability of measuring and recording transducer response over a continuous frequency sweep instead of at a necessarily limited number of discrete frequencies. This controller system will be checked out and put into operation before further tests are conducted.

3.2 Damping with Small Spheres

As discussed in 2.2.5, an evaluation of the use of balls as a packing for the fixture tube will be carried out.

3.3 Tests Using Mercury

A brief series of experiments using mercury as the working fluid may be conducted to determine if the advantages of the high density of this material compensate for the hazards and difficulties associated with its use. These experiments will be dropped from the program if other approaches are successful.

3.4 Transducer Calibration

Transducers supplied by NASA Langley will be calibrated using the method selected on the basis of the work of this project.

4. REFERENCES

[1] Lederer, P.S., Development of a Dynamic Pressure Calibration Technique - Progress Report for the Period June 15, 1973 to September 15, 1973, NBSIR 73-290 (October 1973).

[2] Vezzetti, C.F., Lederer, P.S., and Hilten, J.S., Development of a Dynamic Pressure Calibration Technique - Progress Report for the Period September 15, 1973 to February 15, 1974, NBSIR 74-503(R) (June 1974).

[3] Hilten, J.S., Lederer, P.S., and Sethian, J.D., A Simple Hydraulic Sinusoidal Pressure Generator, NBS Tech Note 720 (April 1972).

Table 1

Resonance Frequency and Amplitude Ratio of Liquid-and-Tube Combinations

Liquid	Tube	Resonance Frequency (Hz)	Amplitude Ratio
Water	2.2-cm Inside Diameter Smooth Walls	944	14
	1.3-cm Inside Diameter Smooth Walls	732	12
	1.3-cm Inside Diameter Spiral Fins	639	9.5
	1.3-cm Inside Diameter Smooth Walls with Filter "C"	702	8.0
	1.3-cm Inside Diameter Smooth Walls with Filter "HX"	*	*
	51-Channel Tube	713	9.0
	Rectangular Cross Section with Interlacing Fins	*	*
Tetrabromoethane	2.2-cm Inside Diameter Smooth Walls	642	5.0
	1.3-cm Inside Diameter Smooth Walls with Filter "C"	*	*
	1.3-cm Inside Diameter Smooth Walls with Filter "HX"	*	*
	51-Channel Tube	466	3.7
"Light" Petroleum Oil	2.2-cm Inside Diameter Smooth Walls	918	16
	1.3-cm Inside Diameter Smooth Walls with Filter "C"	918	3.8
	51-Channel Tube	706	4.5
"Heavy" Petroleum Oil	2.2-cm Inside Diameter Smooth Walls	926	12
	51-Channel Tube	∿500	1.1
Fluorocarbon Liquid	2.2-cm Inside Diameter Smooth Walls	425	9.0

*No data obtainable

Table 2

Characteristics of Working Liquids

Liquid	Viscosity @25°C (St)	Density (kg/m^3)	Velocity of Sound (m/s)	Comments
Mercury	0.001	13.6×10^3	1410	Health hazard; dissolves most metals; low vapor pressure
Tetrabromo-ethane	0.080	2.95×10^3	1007	Corrosive to steel, aluminum, and other metals, and rubber; unpleasant odor; non-toxic; high vapor pressure
Fluorocarbon	0.026	1.88×10^3	730	Non-toxic; non-flammable
Glycerine	7.500	1.26×10^3	1904	Non-toxic; water soluble
Water	0.009	1.00×10^3	1460	High vapor pressure
Dimethyl Siloxanes	*	0.97×10^3	987	Low vapor pressure; non-toxic; little dependence of viscosity on temperature
Petroleum Oils	*	0.86×10^3	1340	Viscosity highly dependent on temperature

*Available in large range of viscosities.

Table 3

System Resonance Frequency and Amplitude Ratio for 10-cm Columns of Dimethyl Siloxane Liquids

Viscosity (St)	Resonance Frequency (Hz)	Amplitude Ratio
10	2000	33
12.5	2000	20
30	2100	13
60	1900	13

Tube diameter = 2.4 cm; acceleration = 10 g_n zero-to-peak.

Table 4

Multi-Tube Fixture Frequency Response Characteristics

10-St Dimethyl Siloxane
Transducer A-5

Frequency (Hz)	Transducer Response (mV rms)			Normalized Transducer Response*		
	run 1	run 2	run 3	run 1	run 2	run 3
40	94.0	95.2	94.5	0.98	1.00	0.99
50	94.4	95.7	95.3	0.99	1.00	1.00
75	95.1	95.7	96.0	1.00	1.00	1.01
100	96.1	96.7	96.9	1.01	1.01	1.01
150	96.4	97.4	97.7	1.01	1.02	1.02
200	97.1	97.7	98.0	1.02	1.02	1.03
300	98.3	98.4	99.3	1.03	1.03	1.04
400	101.3	100.8	92.9	1.06	1.06	0.97
500	96.2	95.8	96.9	1.01	1.00	1.01
750	104.1	102.9	104.2	1.09	1.08	1.09
1000	112.9	110.6	113.1	1.18	1.16	1.18
1250	106.1	106.4	- -	1.11	1.11	--
3000	- -	47.7	- -	--	0.50	--

Acceleration = 36 g_n zero-to-peak.

*Average of transducer responses from 40 Hz to 100 Hz set equal to 1.00.

Table 5

Multi-Tube Fixture Frequency Response Characteristics at 15°C, 25°C, and 35°C

10-St Dimethyl Siloxane Liquid
Transducer A-4

Frequency (Hz)	Transducer Response (mV rms)			Normalized Transducer Response*		
	15°C	25°C	35°C	15°C	25°C	35°C
20	24.8**	25.1	24.5**	0.96**	0.97	0.95**
25	25.3**	25.2	24.9**	0.98**	0.98	0.97**
30	25.5	25.4	25.1	0.99	0.98	0.97
40	25.7	25.6	25.3	1.00	0.99	0.98
50	25.8	25.8	25.4	1.00	1.00	0.98
75	26.0	25.9	25.7	1.01	1.00	1.00
100	26.2	26.1	25.9	1.02	1.01	1.00
150	26.4	26.3	26.2	1.02	1.02	1.02
200	26.5	26.5	26.3	1.03	1.03	1.02
300	26.6	26.7	26.8	1.03	1.03	1.04
400	26.6	27.0	27.3	1.03	1.05	1.06
500	22.7	24.4	24.2	0.88	0.95	0.94
750	26.6	27.7	28.7	1.03	1.07	1.11
1000	26.7	28.2	29.7	1.03	1.09	1.15
1250	25.4	27.1	28.0	0.98	1.05	1.09
1500	23.3	23.8	24.3	0.90	0.92	0.94
1750	23.3	22.8	22.3	0.90	0.88	0.86
2000	25.2	25.4	23.4	0.98	0.98	0.91
2250	41.2	29.7	28.7	1.60	1.15	1.11
2500	61.2	55.0	53.2	2.37	2.13	2.06
2750	38.5	--	--	1.47	--	--
3000	22.6	--	--	0.88	--	--

Acceleration = 10 g_n zero-to-peak.

*Average of transducer responses from 40 Hz to 100 Hz set equal to 1.00.

**Taken at less than 10 g_n because environmental chamber limited the displacement of the vibrating column.

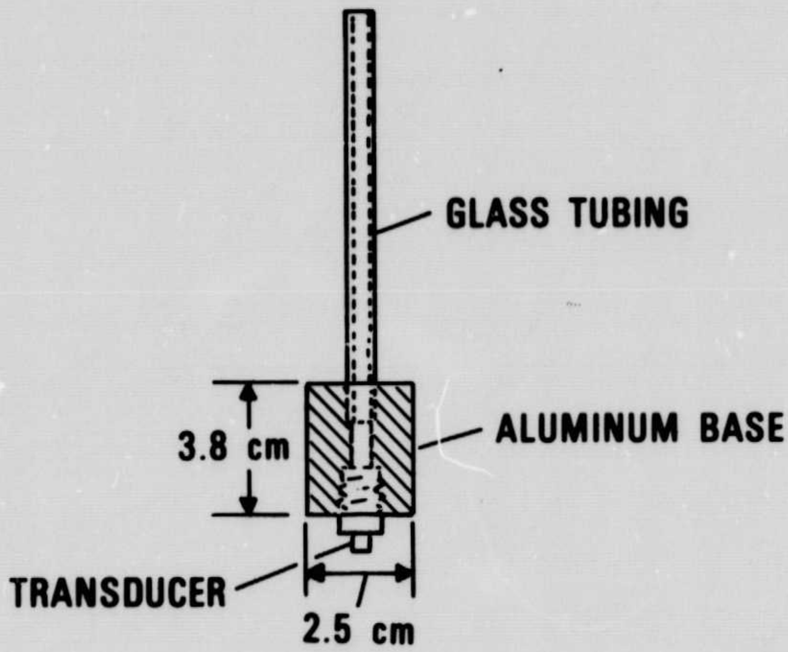

FIGURE 1. FIXTURE FOR MAGNETIC-DAMPING EXPERIMENTS. THE GLASS TUBING HAD A BORE OF 0.5 CM. FIXTURES OF SIMILAR CONSTRUCTION WERE EMPLOYED FOR SOME OF THE EXPERIMENTS USING DIMETHYL SILOXANE LIQUIDS. FOR THIS WORK, GLASS TUBING WITH BORES OF 0.15, 0.2, 0.3, OR 0.5 CM WAS USED.

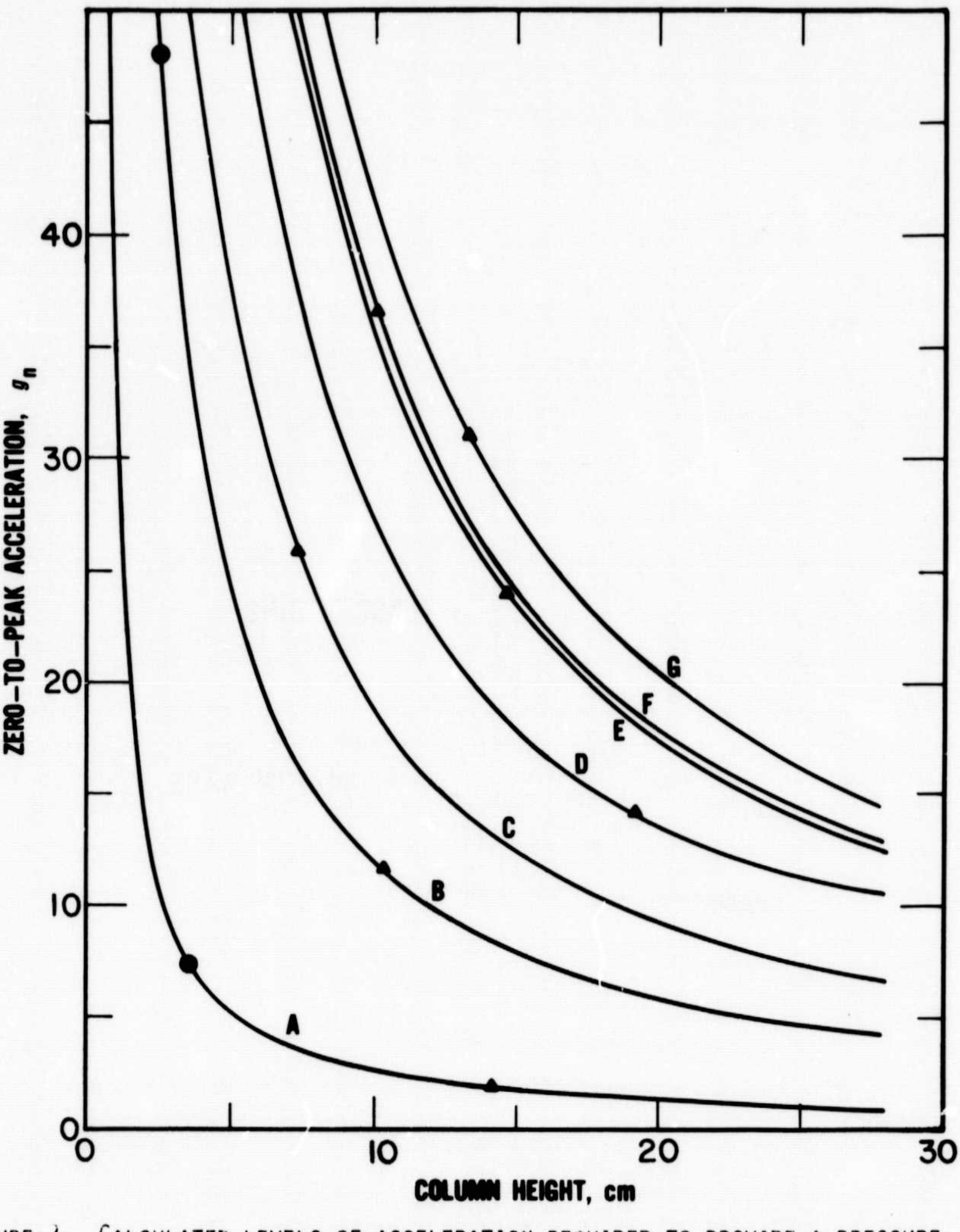

FIGURE 2. CALCULATED LEVELS OF ACCELERATION REQUIRED TO PROVIDE A PRESSURE AMPLITUDE OF 34 kPA AS A FUNCTION OF COLUMN HEIGHT FOR VARIOUS LIQUIDS: A, MERCURY; B, TETRABROMOETHANE; C, FLUOROCARBON; D, GLYCERINE; E, WATER; F, DIMETHYL SILOXANE; AND G, PETROLEUM OILS. THE SYMBOL ▲ IDENTIFIES THE POINT ON EACH CURVE CORRESPONDING TO A CALCULATED NATURAL FREQUENCY OF 2.5 kHZ, AND THE SYMBOL ● IDENTIFIES POINTS CORRESPONDING TO A CALCULATED NATURAL FREQUENCY OF 10 kHz.

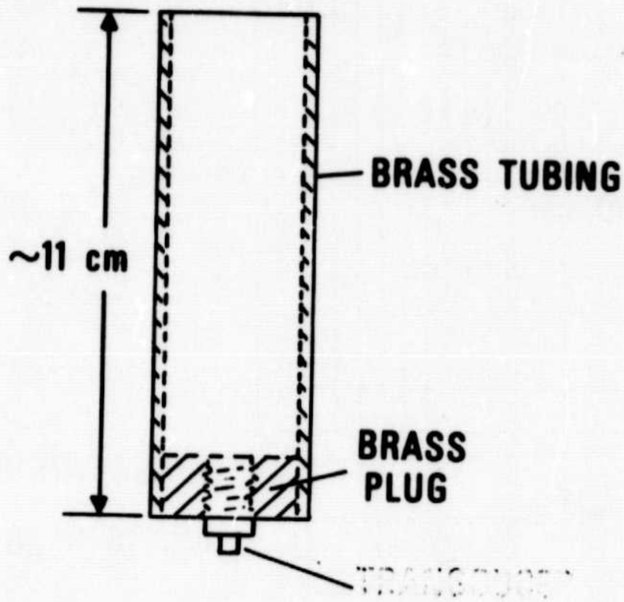

FIGURE 3. FIXTURE FOR EXPERIMENTS USING DIMETHYL SILOXANE LIQUIDS. THIS DESIGN OF FIXTURE WAS USED WHEN THE DESIGN OF FIGURE 1 WAS NOT SUITABLE. THE BRASS TUBING HAD BORES OF 1.1 OR 2.4 CM.

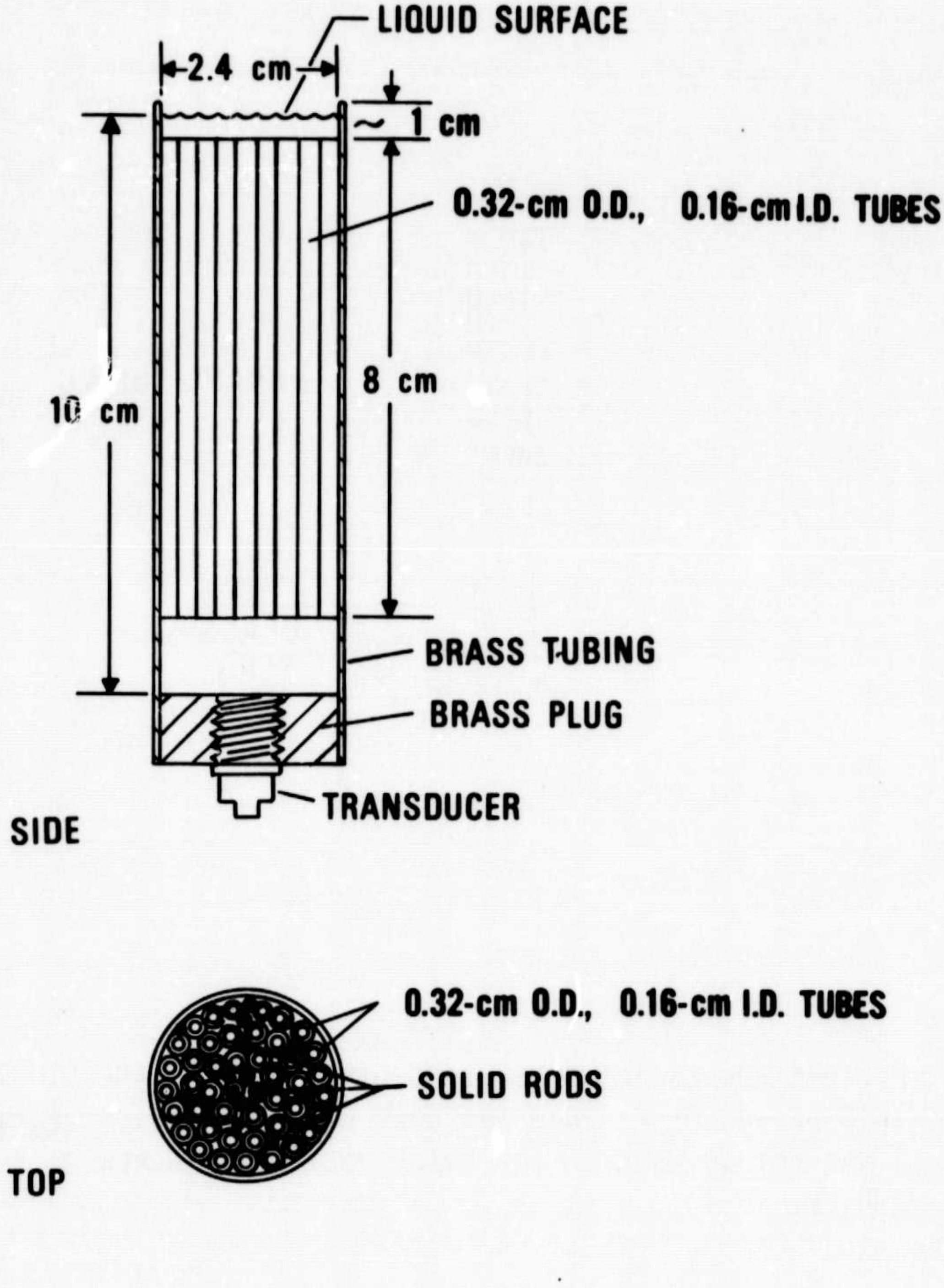

FIGURE 4. MULTI-TUBE FIXTURE.