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DEVELOPMENT OF A HIGH-FREQUENCY-RESPONSE PRESSURE-SENSING RAKE FOR TURBOFAN ENGINE TESTS

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16. Abstract

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DEVELOPMENT OF A HIGH-FREQUENCY-RESPONSE PRESSURE-SENSING RAKE FOR TURBOFAN ENGINE TESTS

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SUMMARY

The application of miniature pressure transducers for dynamic pressure measurements within the air passages of jet engines is a relatively new but practical approach. This report describes the development of a measuring rake having a removable transducer sensor within the rake and a flat amplitude response to 500 Hz. Calibration and development was done through the use of a piston-in-cylinder calibrator using a shaker as the driver. A recommended design is described for pressure-sensing rakes to be used in future jet engine tests.

INTRODUCTION

Improvement in compressor performance for advanced aircraft turbine engines has been accomplished with higher stage loadings. Concomitantly, the operation of the compressor has become more sensitive to inlet air profiles, inlet airflow perturbations, and stage matching. Lewis Research Center has undertaken to systematically investigate the effects of these variables. Special high-frequency-response pressure instrumentation has been developed to better define the cause and initiation of the stall phenomenon and its progression through the compressor.

Pressure- and temperature-sensing rakes were designed for insertion into the different stages of the engine compressors. Any blockage of the compressor air passages by the rakes had to be minimized lest the rake itself become the initiator of compressor stall. The dynamic pressure measurements extended over a frequency range that required the transducer to be mounted close to the sensing point. This necessitated the use of miniature pressure transducers. Small cooling jackets were designed for the transducers to provide thermal stability. For the frequency range of interest, a calibration method was devised to determine frequency response.

This report describes the design factors for a miniature semiconductor pressure transducer installed in several configurations of sensing line tube assemblies. To know the frequency response of a system is to know the amplitude ratio and phase shift as a function of frequency. This response was determined with the use of a shaker-driven piston-in-cylinder calibrating device. The effect on frequency response of combinations of sensing tube length and diameter was determined. The effect of porous plugs to increase the damping ratio was also measured. Damping ratio ξ is defined as the ratio of the degree of actual damping to the degree of damping required for critical damping.

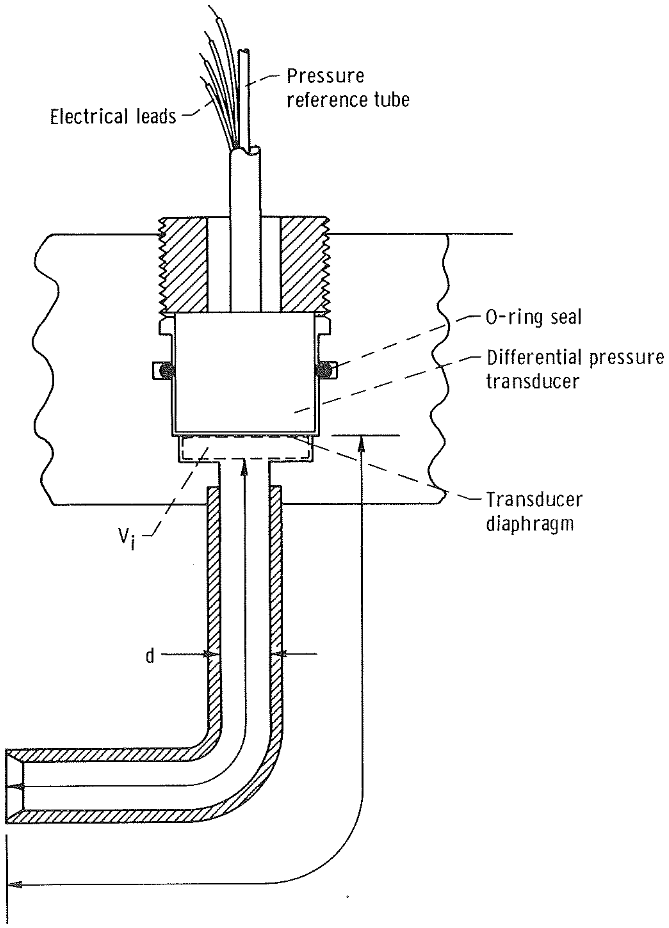


Figure 1. - Typical transducer mounting.

Critical damping provides the most rapid transient response to a step change without overshoot. The inside diameter of the sensing tubes varied from 0.020 to 0.089 inch (0.0508 to 0.2261 cm) and the coupling length from 0.625 to 4.0 inches (1.587 to 10.16 cm). Coupling length is defined as the distance from the face or diaphragm of the transducer to the tip of the sensing port in the gas stream, where the measurements are desired. In figure 1, the coupling length is indicated by l'. This differs from the connecting tube length L by the height of the transducer cavity, which is one dimension of the instrument volume V_i in the same figure.

BACKGROUND AND THEORY

Pressure measurements in jet engine studies generally require that the transducers be connected to the sensing points with tubes. While it reduces the optimum frequency response, tubing is sometimes necessary to provide thermal isolation from the hot gas stream, or to avoid physical limitations both on the size of the transducer or on the engine air passage. Even when a connecting tube is used, care must be exercised to minimize blockage of the air passage. The effects of the length of tubing can be pronounced. If more than a few inches are used, the reduction in accoustical frequency response will far outweigh any possible gains derived from transducers with higher mechanical natural frequencies. A flush-mounted transducer, though not always practical because of physical mounting limitations, is the ultimate approach. In this case, the mechanical natural frequency of the transducer becomes all important.

If only steady-state measurements are required, the transducer can be mounted at some remote location where temperature and mounting area are not as restrictive. A long length of tubing and a large instrument volume V_i may be used to deliberately average out any pressure fluctuations.

The instrument volume V_i is the volume between the transducer diaphragm and the sensing tube, as shown in figure 1. This volume must be kept as small as possible for good frequency response. When the tubing diameter is small enough so that viscosity effects predominate, the response is approximately that of a first-order system having a time constant

$$\mathcal{T} = \frac{128 \mu_o L V_i}{\pi d^4 P_o} \text{ seconds}$$

where

μ_o fluid viscosity, (lb)(sec)/in.^{2}; (N)(sec)/cm^2 (for air at room temperature, 2.75×10^{-9} (lb)(sec)/in.^{2}; 0.019 cp or 19×10^{-6} N-sec/m^2

L tubing length, in.; cm

V_i instrument volume, in.^{3}; cm^3

d tubing inside diameter, in.; cm

P_o pressure sensed, psi; N/cm^2

With a very small transducer instrument volume and a smooth constant-area sensing tube of fairly large diameter (so that damping is low), the system will exhibit a resonant frequency closely approximated by

$$f_r = \frac{3a}{L} \text{ hertz}$$

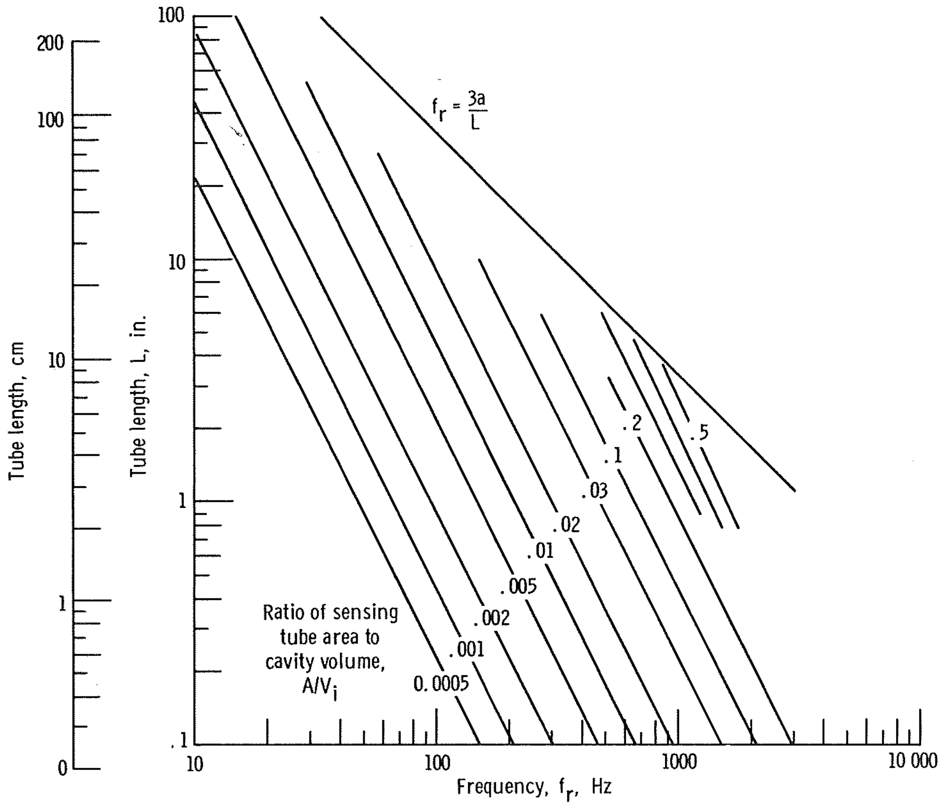


Figure 2. - Resonant frequency obtainable for different tube area to cavity volume ratios as function of tubing length. For air at 75° F and atmospheric pressure; a is speed of sound.

where

a speed of sound in gas media at test temperature, ft/sec; m/sec

Peaks will also occur at odd harmonics of this frequency. This equation represents the typical organ pipe resonance.

If the transducer instrument volume V_i is not small, the resonant frequency is reduced according to the Helmholtz resonator equation

$$f_r = \frac{3ad}{\pi \sqrt{l_e V_i}}$$

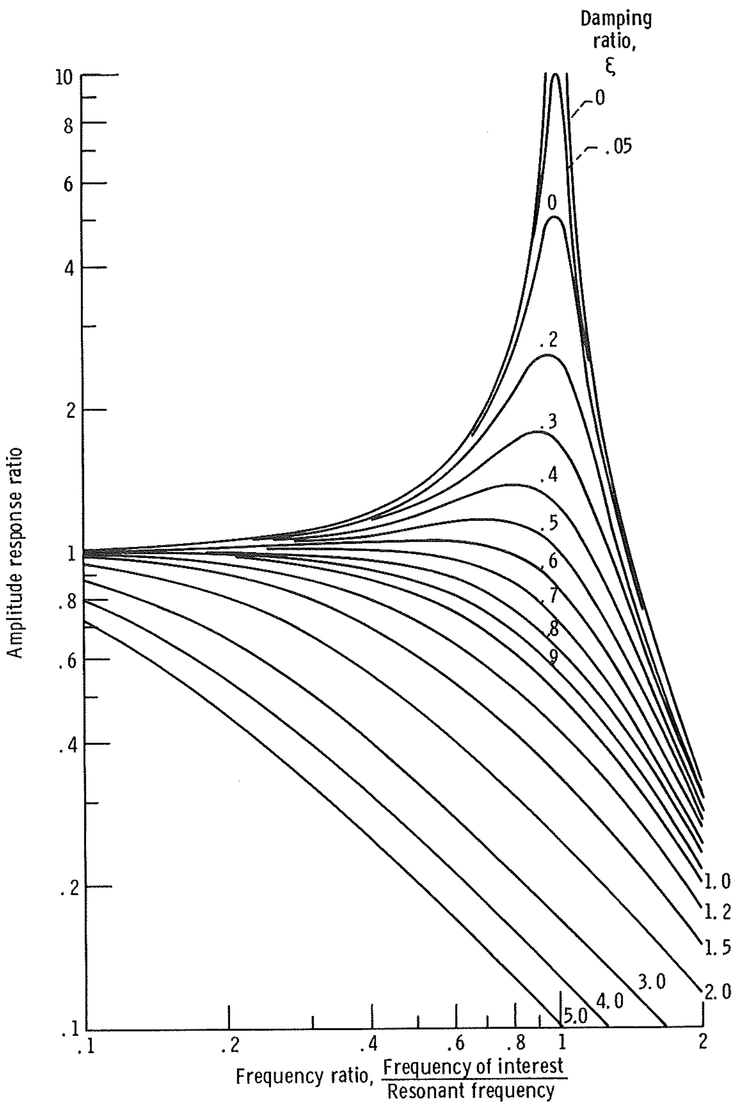


Figure 3. - Response of linear second-order system with various damping ratios to sine wave inputs.

where $l_e = L + 0.85\ d$. The Helmholtz resonator equation yields good results for short tubing lengths. The addition of instrument volume lowers the frequency response, as shown in figure 2. And as expected, for any fixed V_i, increasing the tube diameter shifts the curve toward the organ pipe curve, since the tube diameter then approaches the diameter of the instrument volume. This does not hold true if there is a restriction in the line, however.

The miniature transducers used, as explained in the next section, were underdamped, with damping ratios of the order of 0.005 to 0.03. This low damping ratio, as shown in figure 3, produces a narrow frequency range for flat amplitude response for such a transducer. Attempts were made to increase the damping ratio, and hence increase the range for flat amplitude response, through the use of different tubing sizes and porous plugs.

The amount of damping plays an important role in the accuracy of a transducer pressure measurement. If too much damping is added, the signal will be attenuated over all frequencies. It is therefore important to know the effect of any damping added to the system. Unlike some calibrators which can determine only the resonant frequency and the damping ratio, the calibrator employed generated the complete frequency-response curve. The numerical value of the damping ratio for any test configuration was not considered necessary and not determined.

PRESSURE TRANSDUCER ASSEMBLIES

Initial research requirements specified an amplitude response ratio for dynamic instrumentation that was flat to within ±5 percent over a range of 0 to 200 hertz. Characteristics of the engine system and the inlet distortion hardware used, as indicated by the initial data, required the range to be extended to 500 hertz and the number of measurement stations on each rake to be increased. The new measurement locations and the increased number of measurements severely limit the size of the individual transducer probes. The smaller probes and the increased usable frequency range are opposing factors leading to the need for a reduced coupling length and an improved damping ratio.

Description of Semiconductor Transducers

The miniature transducers used in the dynamic airflow studies of the turbofan engine have been of the semiconductor strain-gage type. This type is very similar to the bonded strain-gage transducers with the foil gages replaced by semiconductors. For the same stress, the semiconductor provides a signal significantly greater than that obtainable with metal foil or unbonded wire gages. In the early transducers, temperature changes produced large errors; the transducers had high hysteresis, poor repeatability, and were large and bulky. Experience and improved mounting techniques have now greatly reduced most of these faults. The present semiconductor transducer is nearly equivalent in overall accuracy to the much-larger-diameter, bonded and unbonded, foil- and wire-type transducers.

The 0.250-inch- (0.635-cm-) diameter-type transducers used for the intitial tests are being replaced by an 0.082-inch- (0.208-cm-) diameter transducer. This transducer has a silicon diaphragm with the strain gages diffused into the diaphragm itself. The stress sensors then become an integral and inseparable part of the diaphragm and do not depend upon some elastic material to transmit the strain.

The hysteresis and linearity of the most recent transducers has been improved by moving the electrical lead attachment to the strain sensors to the edge of the diaphragm. This eliminates the inelastic soldering mass from the center and sensitive area of the diaphragm.

Both types, the bonded semiconductor and the diffused diaphragm, can be considered as simple spring-mass systems. The diaphragm constitutes most of the mass, and, as the force member, represents the principal spring element. It is made as light as possible and the full-range deflection is extremely small. Typical diaphragm deflections are of the order of 3×10^{-4} inch (0.00076 cm); thickness ranges from 1 to 3 mils (0.0254 to 0.0762 mm). This combination of low diaphragm mass and high spring rate gives a high mechanical natural frequency to the transducer. The 0.082-inch- (0.208-cm-) diameter transducer has a resonant frequency greater than 200 kilocycles.

The extremely small deflection of the diaphragm prohibits any form of damper, so the transducer must remain essentially undamped. Typical damping ratios are of the order of 0.005 to 0.03 for both the 0.082- and 0.250-inch-diameter (0.208- and 0.635-cm-diam) transducers.

Description of Mounting and Coupling

To circumvent possible variation in the transducer output due to temperature gradients and the high temperature environment each transducer was enclosed in a cooling jacket. For the 0.250-inch- (0.635-cm-) diameter transducers, two concentric tubes were used with the outer tube pressed into an elliptical shape so that the two tubes touched at the sides, forming two separate water paths. This jacket is shown in figure 4. The major diameter of the elliptical water jacket for the 0.250-inch- (0.635-cm-) diameter transducer was 0.406 inch (1.0312 cm).

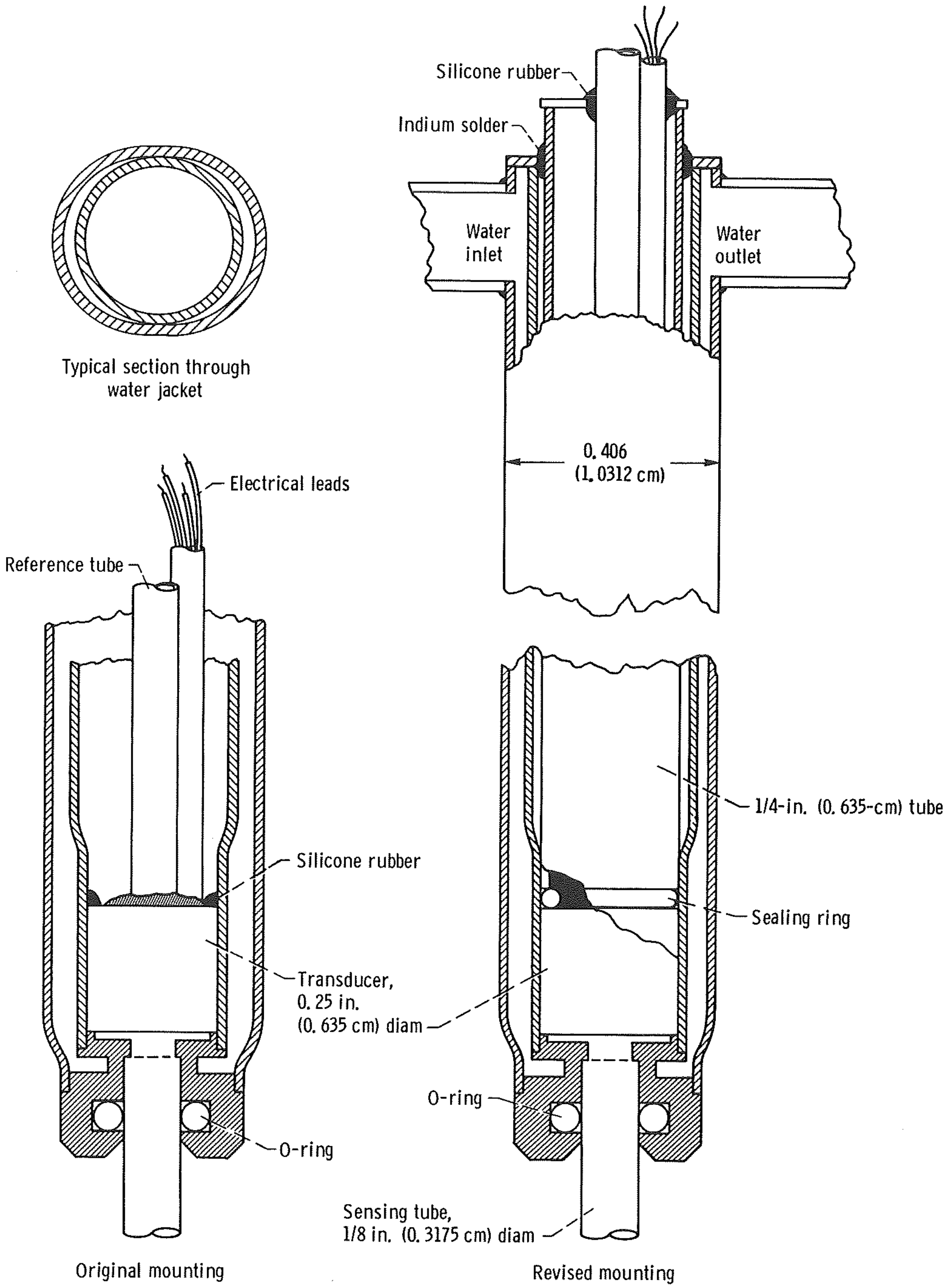


Figure 4. - Cooling jacket mounting for 0.25-inch- (0.635-cm-) diameter transducer.

Mounting the transducer, whether it be in a cooling jacket, special housing, or a rake body requires considerable care. A small force on the transducer shell can cause a change in the response characteristics detectable only through careful recalibration. Because of the cooling jacket design and the requirement that the transducers be removable, a flexible cement mounting technique was developed. Initially, the transducer was cemented in place in the cooling jacket with ordinary rubber cement. This was later replaced with silicon rubber, which improved the transducer performance and produced less leak paths around the transducer. Certain manufacturers have suggested the use of sealing wax or epoxy-type cement. To minimize leakage, an additional tube, approx-

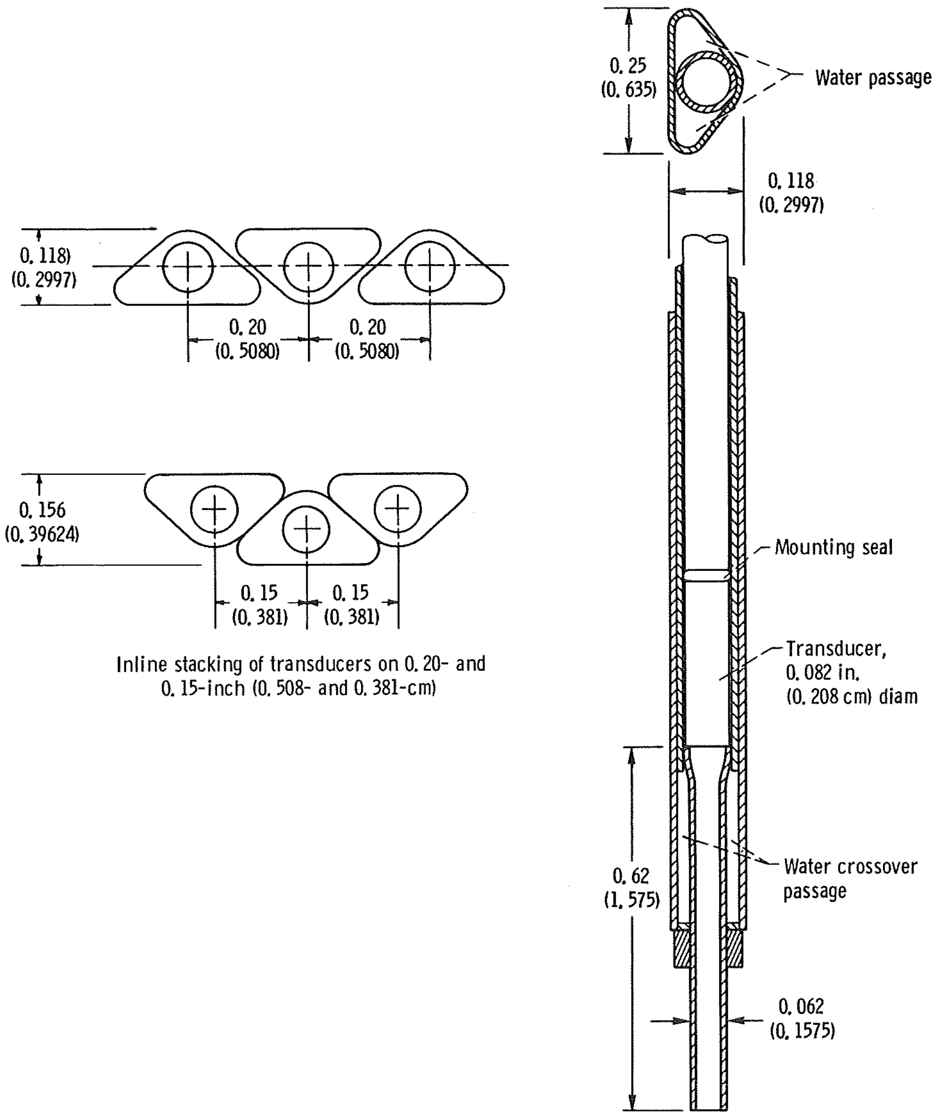


Figure 5. - 0. 082-Inch- (0. 208-cm-) diameter transducer and cooling jacket with stacking detail. Dimensions are in inches (cm).

imately the same diameter as the transducer, was attached to the rear of the transducer body. A sealing ring was molded in place on this attached tube to provide a seal near the sensing end when the transducer was inserted into the cooling jacket. The tube at the opposite end of the cooling jacket was sealed with indium solder to provide a positive seal, but at the same time, be easily removable.

The cooling jacket was mounted to the pressure-sensing 1/8-inch- (0.3175-cm-) diameter tube by means of an O-ring within the cooling jacket. This O-ring also served as a thermal barrier and reduced the heat load on the transducer.

The cooling jacket for the 0.082-inch- (0.208-cm-) diameter transducer, as shown in figure 5, was wedge-shaped so that several transducers could be mounted in a minimum of space. The overall length of a wedge was 0.254 inch (0.6452 cm); and when stacked one behind the other on 0.20-inch (0.508-cm) centers with the centers in line, the overall width was 0.118 inch (0.2997 cm). When stacked on 0.15-inch (0.381-cm) centers, the overall width was 0.156 inch (0.3962 cm). This means of stacking is illustrated in figure 5. A typical instrumentation rake with a transducer and cooling jacket assembly in place is shown in figure 9 (p. 15).

CALIBRATOR DESCRIPTION

General

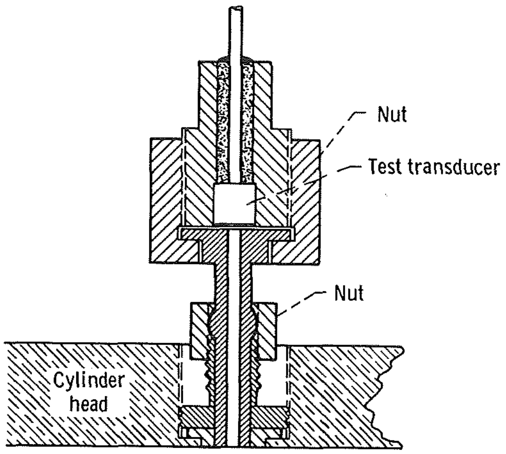
Any method of transducer calibration requires that a known input be applied and that the output be measured precisely. In the dynamic calibration of transducers, the time phase between the two must also be determined.

The testing and evaluation of the pressure transducer systems was done mainly on a piston-in-cylinder calibrator but good correlation was also obtained on the other calibrators available, such as the rotating disk, shock tube, and resonant tube pressure generators.

Calibrators in the periodic function generator class, such as the rotating disk and piston-in-cylinder, are restrictive in both amplitude and frequency but can generate a complete frequency response curve. The range of these two calibrators is good to approximately 3000 hertz, however, which was sufficient for these tests.

Description of Piston-in-Cylinder Calibrator

The piston-in-cylinder calibrator (fig. 6) was patterned after a device used at the NASA Flight Research Center. A piston which was actuated by a frequency and ampli-



Enlarged view of test transducer mounting

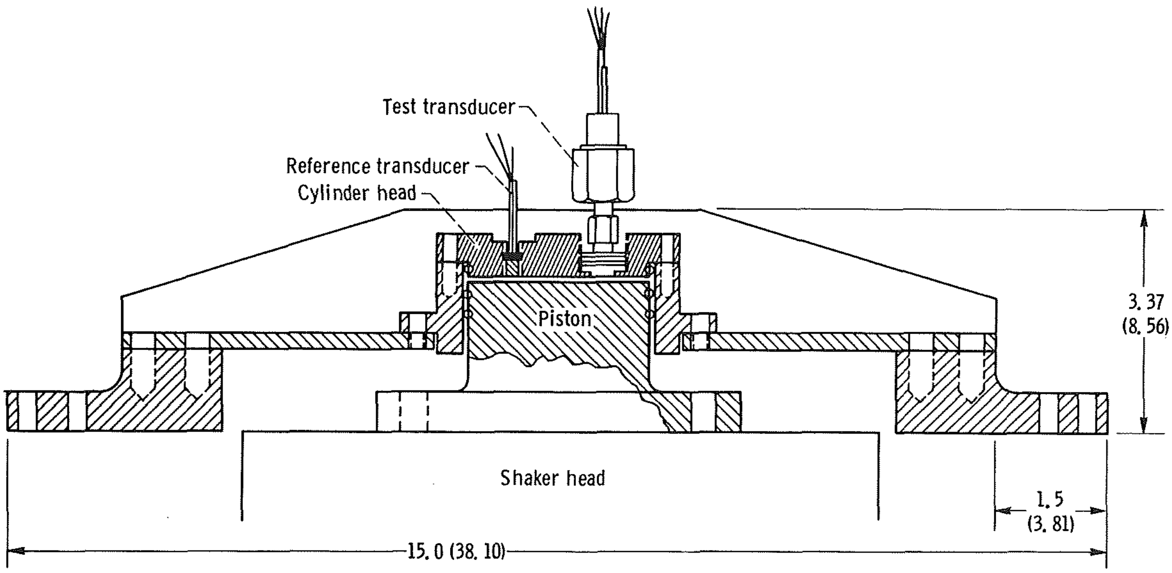


Figure 6. - Piston-in-cylinder calibrator. Dimensions are in inches (cm).

tude controlled shaker was positioned in a fixed cylinder. Two openings were provided in the cylinder head for mounting a reference transducer and the test transducer.

A charging port was also provided to change the static-pressure level. The assembly was placed on a shaker with the cylinder and head mounted to the unmovable part of the shaker and the piston mounted to the shaker head. This type of piston mounting eliminated the need of any piston rod and its associated problems of sealing and bending. The motion of the piston was limited by the maximum stroke of the shaker. The length of the air column above the piston was made as small as possible to eliminate cavity resonances in the range of frequency interest.

The output of the transducer system on test was compared to that of a reference which was flush mounted in the cylinder head. Therefore, if the shape of the pressure wave differed for any reason, both systems, the reference and the transducer being tested, saw the same input.

The shaker, as the excitor, provided true vertical motion without side effects. It was capable of providing (1) a stepless frequency output with easily adjustable amplitude and control and (2) distortion-free sinusoidal forces.

Tests on the shaker could be run in either a constant displacement or a constant acceleration level mode over the desired frequency range. At constant displacement, the double amplitude or total vertical motion of the piston was limited by the rating of the shaker at the high end of the frequency range. This resulted in a constant dynamic pressure level over the entire frequency range but it was also limited to a very small dynamic pressure level. In the constant acceleration mode, the dynamic pressure changed over the frequency range but it was always as high as possible at any given frequency.

Results were then compared for the test transducer and the flush-mounted reference transducer which had been tested on many different calibrators and had a flat response greater than 3000 hertz.

TEST RESULTS

Five different tube sizes were selected as representative of those used in the majority of pressure-sensing rakes:

Tube	Outside diameter		Wall thickness		Area	
	in.	cm	in.	cm	in.^{2}	cm^2
1	0.032	0.08128	0.006	0.01524	0.000314	0.002026
2	.062	.15748	.008	.02032	.001665	.010743
3	.062	.15748	.012	.03048	.001131	.007297
4	.093	.23622	.012	.03048	.003632	.023434
5	.125	.3175	.018	.04572	.006362	.041048

The results of the frequency-response tests with these five tube diameters, each at lengths of 4, 3, 2, and approximately 1 inch, are shown in figure 7. In all cases, the instrument volume was the same and the same 0.250-inch- (0.635-cm-) diameter test pressure transducer was used. The data indicate that for a constant instrument volume a greater resonant frequency is obtained with a tube of greater inside diameter. To re-

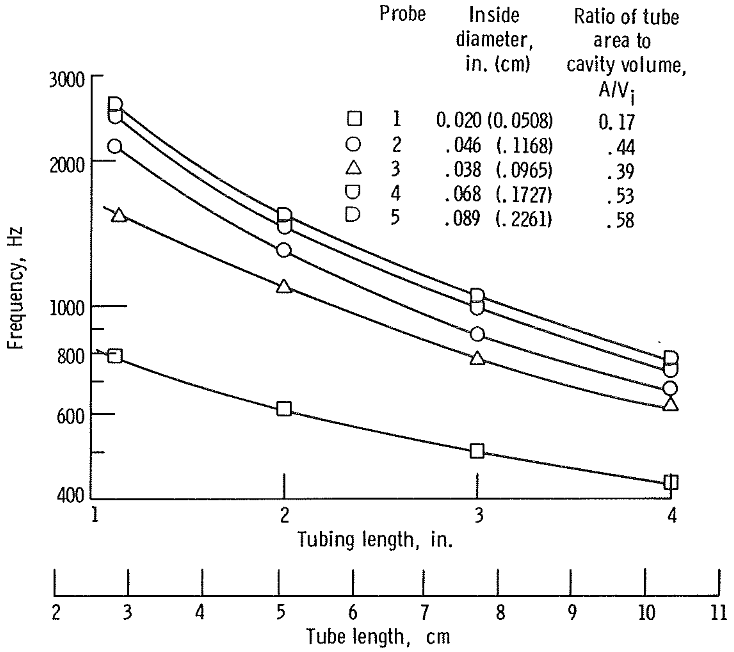


Figure 7. - Effect of tube length on resonant frequency of different-sized sensing tubes; instrument volume remaining constant. For air at 75° F and at atmospheric pressure.

alize the same resonant frequency for a smaller-diameter tube, the instrument volume must be decreased. However, the availability of suitable smaller-diameter transducers limits the reduction of instrument volume. The amplitude response curve of a transducer system is very similar to that shown in figure 3 for near-zero values of damping ratio. The usable ±5 percent flat portion is approximately 20 percent of the resonant frequency. One way to increase the frequency range corresponding to the flat portion of the curve in figure 3 would be to increase the resonant frequency. Since increases in resonant frequency are limited by available transducer sizes and by the limited size of the tubes which can be used in many locations in the engine, another means of obtaining a flat response to a higher frequency is required. This can be accomplished by increasing the damping ratio.

The use of porous bronze, molded into slugs, afforded a damping device which was subject to quality control. This material is available commercially in various porosities with controlled limits on mean pore diameter. The curves shown in figure 8 illustrate the response changes obtainable by using different slug densities. The damping slugs used for curves 1 and 2 were made from a coarser powder than those for curves 3 and 4. With the test configuration used, it was possible to vary the usable portion from 240 to 440 hertz, an increase of approximately 83 percent. To accomplish the same thing, a sensing system having a coupling length of 2.03 inches (5.1562 cm) and a resonant frequency of 1700 hertz would require an increase in its resonant frequency to 3120 hertz

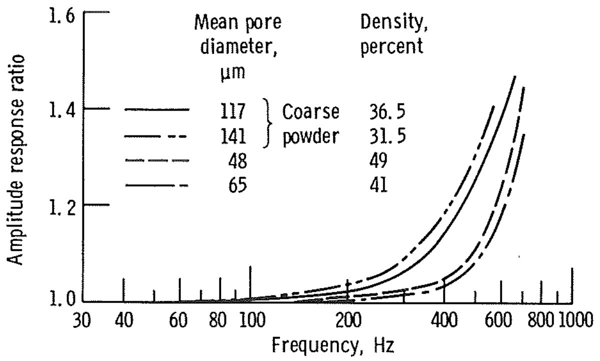


Figure 8. - Variation in frequency of a pressure transducer system using sintered bronze molded slugs of different porosities to change the damping ratio. Tube inside diameter, 0.042 inch (0.1067 cm); tube length, 2.03 inches (5.156 cm); transducer diameter, 0.082 inch (0.208 cm); air at atmospheric pressure and 75° F.

by reducing its coupling length to 1.0 inch (2.540 cm).

The transducer and cooling jacket used for these tests were identical to that shown in figure 5. To avoid disturbing the transducer before all tests were completed, the damping slug was placed in the end of the sensing tube, approximately 0.50 inch (1.270 cm) from the transducer diaphragm. Consequently, the porous slug could not be positioned close to the diaphragm, as shown in figure 9, so the curves should not be interpreted as optimum, but only representative of the possibilities. Figure 10 affords the response comparison for the damping slug mounted close to the diaphragm, as shown in figure 9, against the case of no added damping slug.

Using the same 0.250-inch- (0.635-cm-) diameter transducer and coupling length as that of probe 3 in figure 7, the porous slug was positioned at the sensing end and at the diaphragm end. The results are shown in figure 11. With a damping slug at the transducer diaphragm end, an amplitude response ratio below 1.05 is maintained up to 480 hertz, as contrasted to a limit of 240 hertz for an undamped (no porous slug) probe. Moving the damping slug to the sensing end attenuates the signal to the extent that it is down 5 percent at 100 hertz and down 19 percent at 240 hertz. Measured values of phase shift are also shown in figure 11. Phase shift is a function of frequency and damping. With zero damping, phase shift is theoretically nonexistent until resonance is reached. For any increase in damping ratio, the phase shift is correspondingly higher.

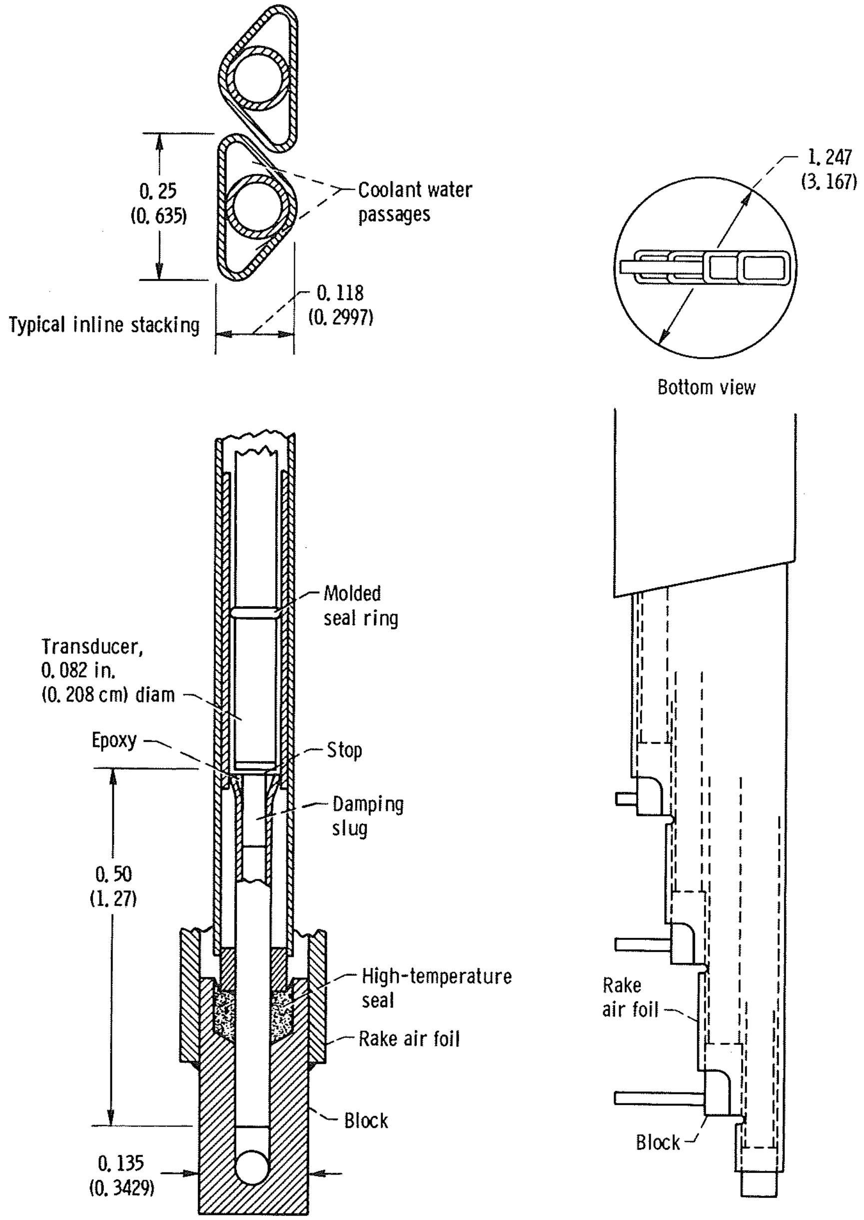


Figure 9. - Multipoint sensing rake showing transducer mounting. Dimensions are in inches (cm).

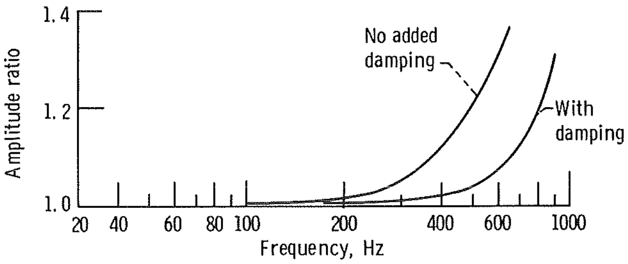


Figure 10. - Improved response obtainable with increased damping. Transducer diameter, 0.082 inch (0.208 cm); coupling length, 2.03 inches (5.156 cm); air at 75° F.

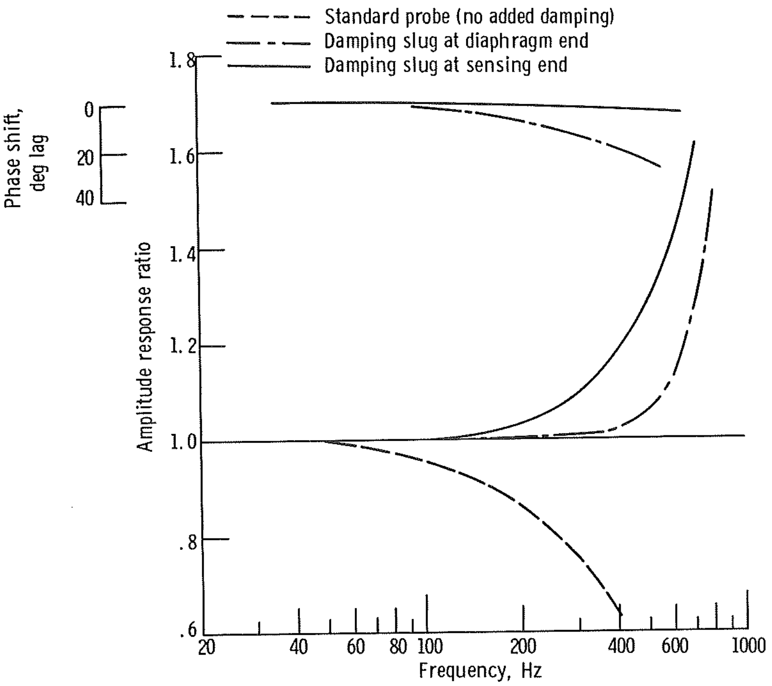


Figure 11. - Variation in frequency response caused by positioning damping slug at sensing end and diaphragm end of probe. Probe inside diameter, 0.038 inch (0.0965 cm); probe length, 1.25 inches (3.175 cm); air at atmospheric pressure and 75° F.

RECOMMENDED DESIGN

As a result of these tests, the transducer mounting, size, damping ratio, and coupling length were changed from the figure 4 configuration to that shown in figure 9. The transducer size was reduced to 0.082 inch (0.208 cm) diameter since test results indicated performance as good as that obtained on the 0.125-inch- (0.318-cm-) diameter transducers and better than that of the 0.250-inch- (0.635-cm-) diameter transducers being used. The smaller size also permitted a reduction in rake thickness and allowed the installation of more sensing points in each rake.

The molded seal ring near the transducer sensing end not only provided a better pressure seal but also easier removal of the transducer from the cooling jacket. Installation of a damping slug at the transducer diaphragm provides controlled increases in the flat amplitude response but at the expense of increased phase shift. A screen was also added to the transducer face to prevent contact of the damping slug with the diaphragm. Hysteresis, linearity, and zero stability were improved through the use of the sealing ring mounting technique and the new diaphragm layout. Leakage of the sensing pressure past the transducer was minimized by the use of a backup indium solder seal at the top of the cooling jacket.

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