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TURBULENT PRESSURE SPECTRUM MEASUREMENTS ON A COMPLIANT SURFACE

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ABSTRACT

Experimental results obtained by measuring the drag, wall pressure fluctuations, and radiated sound from a compliantly coated cylinder, 21 inches in diameter, and rotating in water are described. The compliant layer was a ¼-inch thick closed cell, air-filled neoprene which was mounted on the 3/8-inch thick aluminum cylinder walls. Results are presented for four speed conditions; one condition is below the speed where a sudden increase in drag is obtained, and the other speed conditions are at and above this critical speed. In general, the results indicate a surface which becomes increasingly more roughened as the critical speed is exceeded.

INTRODUCTION

Compliant coatings are being considered for application in underwater acoustics problems at an ever increasing rate. These coatings, which are termed compliant because of their low moduli of elasticity, are usually some form of elastomer, and are generally quite effective acoustically; the major hindrance to their application has been attachment problems, and the lack of knowledge of their effect on drag coefficients and flow noise. This paper reports the results of an experimental investigation which studies these latter two effects as produced by a very acoustically effective compliant coat.

Experimental measurements of the flow noise characteristics are extremely sparse, the work of Von Winkle and Barger (Von Winkle and Barger, 1961) being the only one known to the author. Much more plentiful are experiments measuring the drag reductions or increases which are possible with compliant coatings of various constructions. Presumably, a reduction in wall pressure fluctuations would be inherent with reduced skin friction. Unfortunately, as pointed out in a recent extensive survey of this area (Blick, 1974), the design of a drag reducing coating is still in the "hit-or-miss" stage. With little knowledge of the effect of the elasticity or other properties of the coating on drag, experimenters report uneven results. In fact, a drag <u>increasing</u> coating appears as likely to be the outcome of a given design as a drag reducing coating would be. When the more modest approach of attempting to design a coating which, at least, does not increase drag is taken, the results of Hansen and Hunston (Hansen and Hunston, 1974) are pertinent. They found that above a certain critical speed, which is a simple function of the coating modulus only, a hydroelastic instability occurs which produces standing waves on the coating surface. The deformations associated with these waves drastically increase drag similarly to the effect of surface roughness.

In this work, the flow noise characteristics of an elastomer coating subjected to operation above, at, and below the above mentioned critical speed are studied. The wall pressure fluctuations and radiated sound, when compared to similar measurements on a smooth and a roughened surface, indicate the manner of generation of flow noise, and provide corroborative evidence for the compliant coating behavior suggested by the experiments of Hansen and Hunston.

APPARATUS AND PROCEDURES

The Compliant Coating

The compliant coating material used was an air-filled, closed cell rubber (Rubatex G-207-N), commonly referred to as "bubble rubber." It is often used as a pressure-release material for shallow underwater acoustical applications, and it was chosen for experiment here as an extreme example of a compliant coating for use as a radiated sound mitigator. The material is ¼-inch thick. The elastic properties of the material are variable, so that it was necessary to measure them for the sample used in this experiment. Both the modulus of rigidity and the Young's Modulus of the material were measured using the simple scale and dial gage arrangement shown in figure 1. For measurement of the shear modulus, the coating was bonded between two 4 inch by 4 inch, ¼-inch thick plywood faces, and the extensions resulting from an applied force as measured by the spring scale were recorded. The force was cycled slowly at small and at large amplitudes so that any hysteretic effects would be noticed. Since it was suspected that the material properties would be different under water pressure (due to the squeezing of interior air cells), the modulus of rigidity was measured with a pressure load applied by means of a weight of the appropriate magnitude. The Young's modulus was measured by simply stretching a sample of material and recording the extensions. Again, any hysteresis effects were noted; however, this modulus was measured without a pressure load, since Young's modulus was assumed to scale with pressure similar to modulus of rigidity. It was felt that these simple measurements would provide material properties of sufficient accuracy for the experiment. No attempt was made to measure any dynamic modulii of the material.

The Rotating Cylinder

The experiments were performed using the rotating cylinder apparatus which is schematically illustrated in figure 2. The aluminum cylinder is 21 inches in diameter, 18 inches long, and has 3/8-inch thick walls. It is suspended by a 2-inch diameter shaft at mid-depth in semi-anechoid acoustic tank, 6 feet by 9 feet by 8 feet deep. This shaft is driven, via a vibration isolation mount and rubber belt-pully drive, by a 40 horsepower, 240 volt shunt wound DC electric motor equipped with tachometer feedback so that a precisely controlled speed is available from 75 to over 1000 rpm. This corresponds to cylinder surface speeds of 9 to over 100 feet per second. The maximum torque load is about 300 ft-lbs, and the entire motor and support frame system is isolated from the floor to minimize machinery-induced noise in the tank.

The cylinder rpm was measured by a magnetic pick-up on the cylinder shaft and displayed on a HP2535 Universal Counter. The torque required to drive the cylinder was obtained by measuring the motor armature and field currents; the torque is proportional to the product of these currents minus any loss torques due to friction. The torque measurement system had been previously calibrated (Brady, 1973) using calibrated disks and torque meters. Torque differences of less than 4% could easily be measured. Flow noise related quantities were obtained using transducers and preamplifiers mounted inside the cylinder and brought out to topside using two sets of 10 channel slip rings. Noise from the slip rings limited the sensitivity of the instrumentation; however, adequate data was obtained above 200 rpm. The transducer used in this study was a flush-mounted ¼-inch diameter piezoelectric pressure transducer (Kistler Model 202AS). This transducer has internal acceleration compensation and its frequency response is flat up to and above the 20 kHz upper limit used in this experiment. The radiated sound was measured by a Wilcoxon model 50 hydrophone suspended four feet from the barrel. Signals from these transducers were frequency-analyzed using a General Radio Model 1921 Real Time 1/3-Octave Analyzer. A simplified block instrumentation is shown in figure 3.

A problem which arises when using a compliant coating is the arrangement of the flush mounted pressure transducer relative to the wall-to-coating and the coating-to-water interfaces. Three possible arrangements, shown in figure 4, were considered:

(1) The transducer face at the wall-to-coating interface with the coating intact above the transducer (figure 4(a)). The disadvantage of this arrangement is that the elastic and inertial properties of the coating will modify the coating-to-water pressure field characteristics. This arrangement has the advantage, however, of not introducing any interference with the flow.

(2) The pressure transducer face is mounted flush with the coating-water interface figure 4(b). If the coating is not bonded adequately to the pressure transducer, deformation of the coating will produce flow interference with the transducer possibly protruding or recessed. If the bonding is adequate, the coating properties will be altered near the transducer.

(3) The transducer face is at the coating-wall interface, and a hole is cut in the coating above the transducer. In this arrangement, the water filled cavity acts as a pressure transmitting column. The first acoustic resonance of the cavity is estimated at about 60 kHz, thus, as long as the correlated area of the pressure field is greater than the face area, the coating-to-water interface pressure should be transmitted. The obvious disadvantage of this arrangement is the introduction of flows within the cavity which will produce additional pressure levels.

For this experiment, the last arrangement was chosen. Each arrangement has disadvantages but it was felt this arrangement would yield more interpretable results because any additional flows internal to the cavity would produce higher pressure fluctuation levels. Thus, when compared to an uncoated cylinder, any data lower in level could definitely be attributed to coating effects.

<u>Procedures</u>

All results were compared to a baseline - an uncoated cylinder. Thus, the torque vs. rpm, wall pressure fluctuations, and radiated noise levels of the uncoated cylinder were first determined. Each measurement was repeated at least three times to check repeatability. Next, torque vs. rpm curves were taken for the coated cylinder, and the critical speed noted. Wall pressure and radiated noise 1/3-octave band levels were then taken at the critical speed, below it, and above it.

The method of attaching the coating to the cylinder consisted of stretching and gluing. By using the measured modulus of elasticity and assuming a coating-to-wall coefficient of friction of 0.5, the circumferential length of the coating was determined so that, when stretched onto the cylinder, there was adequate friction to prevent the coating from slipping. The end seam of the coating was then glued and the coating stretched over the cylinder. All edges were then trimmed and glued to form as smooth boundaries as possible. Despite these precautions, the coating would detach at high rpms; fortunately, this speed was well above any required for measurement.

RESULTS

<u>Coating Properties</u>

The measured properties of "bubble" rubber showed that it was a compressible material with high internal losses, whose characteristics were a function of external pressure. The "small" deformation (less than 30% longitudinal strain and less than 10% shear strain) properties are listed in table I. These values were derived by using force-deflection hysteresis curves measured during the tests. A typical curve is shown in figure 5. The shear storage modulus, G' , was calculated by measuring the small deflection slope of the "backbone" curve (the curve connecting points of maximum amplitude), and then applying the formula,

$$G' = hS^{-1}(\Delta F/\Delta\delta)_{\delta=0} \quad (1)$$

where h is the material thickness, S is the sectional shearing area of the sample and $(\Delta F/\Delta\delta)_{\delta=0}$ is the small deflection slope of the force versus deflection "backbone" curve. Similarly, Young's storage modulus, E', was computed from the experimental results using the relation

$$E' = l A^{-1} (\Delta F/\Delta\delta)_{\delta=0} \quad (2)$$

where l is the tensile sample length, A is the cross-sectional area exposed to tension, and $(\Delta F/\Delta\delta)_{\delta=0}$ is the small deflection slope of the backbone curve, as before. From these two moduli, Poisson's ratio could be calculated using the equation

$$G' = 0.5\, E'\, (1+V)^{-1} \quad (3)$$

where V is Poisson's ratio. The above equations are basic relations of elasticity theory (Love, 1927). The shear loss modulus, G", was computed by calculating the area under the hysteresis loop, which is the energy dissipated per cycle, and plotting this energy versus cycle amplitude. The resulting curve is also shown in figure 5. At small amplitudes, and when pressurized, the energy dissipated per cycle is proportional to the square of the cycle amplitude. Thus the storage modulus is independent of cycle amplitude under these conditions and it is given by

$$G'' = hS^{-1}\pi^{-1}D_o\delta^{-2} \quad (4)$$

where D_o is the energy dissipated per cycle and δ is the cycle deflection amplitude. This method for deriving the storage modulus is similar to those described by Kolsky (Kolsky, 1953). When there was no pressure load, the energy dissipation was proportional to the cycle amplitude; thus, the storage modulus is a function of amplitude. The loss moduli in tension were not calculated.

<u>Torque</u>

The results of the torque vs. rpm tests are plotted in figure 6. Each data point for the uncoated configuration is the average of five measurements; for the coated configuration, three measurements were averaged. Data for the uncoated configuration were repeatable to ±5 ft-lbs; for the coated cylinder, the scatter was slightly larger, being about ±7 ft-lbs. At low rpm, the two curves coincide with no discernable difference. At about 360 rpm (33 ft/sec), the drag on the coated cylinder begins a sharp increase relative to the uncoated cylinder. This increase becomes more pronounced as the cylinder speed is increased.

Wall Pressure Fluctuations

The results of the wall pressure fluctuation spectrum measurements are shown in figures 7 and 8. These curves represent the mean square pressure levels in 1/3-octave filter bands from 20 Hz to 8.0 kHz center frequencies. For the high speed data, the upper frequency limit was due to background noise and the lower frequency was limited by the range of the analyzer. At lower speeds, these frequency ranges were reduced further by the deteriorating signal-to-noise levels. Each curve represents the average of two runs at a given rpm. The uncoated data had a ±2 dB range; the coated data had a larger spread (±3 dB). The data for the uncoated cylinder showed a typical shape and a smooth variation in speed. The uncoated data, however, show a more humped spectrum and a more drastic rise in level as the speed is increased.

Radiated Noise

The radiated noise measurements are shown in figure 9. These curves represent the mean square pressure levels, in 1/3-octave bands from 50 Hz to 20 kHz center frequencies. The units are decibels referenced to one micropascal. The predominant features of the curves are: (1) the similar levels between the coated and uncoated configurations at each rpm for frequencies below 2 kHz, (2) the lower level of the coated data relative to the uncoated data at 360 rpm; and, (3) the higher level of the coated data relative to the uncoated data at the higher rpm.

DISCUSSION OF RESULTS

The Critical Speed

The primary reason for measuring the viscoelastic properties of the coating was to calculate the critical speed, observed by Hansen and Hunston on a rotating disk, at which the hydroelastic instability which causes roughness appears (Hansen and Hunston, 1974). These investigators give the following equation for the critical speed;

$$V_c/\sqrt{G'/\rho_e} = 1.4 \rightarrow 3.5 \quad (5)$$

where V_c is the critical velocity, G' is the storage shear modulus, and ρ_e is the density of the medium flowing adjacent to the coating. The lower value in equation (5) is determined by theoretical considerations for an incompressible material; the upper value is experimentally determined. The "bubble" rubber used on the cylinder experiments was not incompressible; however, the theoretical arguments of Hansen and Hunston can be easily extended using simple considerations from the theory of elasticity for the case of compressible materials. Instability will occur when the pressure created by the potential flow over a sinusoidally corrugated surface equals the pressure required to maintain the corrugations on an elastic half-space. For a corrugated surface which has a wave number given by k, and an amplitude given by W, the pressure, p, created by the potential flow is

$$p = -\rho_e W V^2 k \cos kx \quad (6)$$

where x is the position coordinate. The pressure required to maintain the corrugation, when the half space is compressible, (LOVE, 1927) is given by

$$p = k G' W (1-\nu)^{-1} \cos kx. \quad (7)$$

Thus, instability will theoretically occur when

$$V_c/\sqrt{G'/(1-\nu)\rho_e} = 1 . \quad (8)$$

Using this equation, and the measured values of shear modulus and Poisson's ratio for the "bubble" rubber coat used in the cylinder experiments, a critical velocity of 33.2 feet per second, corresponding to 370 rpm, is obtained. This value agrees very well with the critical rpm which was measured. Thus it is assumed that an instability similar in form to that observed by Hansen and Hunston is occurring. The loss modulus seems to have little effect in determining the critical speed. Further evidence that this phenomenon is due to the onset of an instability is the torque vs. rpm curve for a roughened cylinder shown by the dashed curve in figure 6. This curve was obtained in another experiment. For this curve, the excess torque required increases smoothly and is apparent at all speeds. It is interesting to note that the coated cylinder torque curve intersects the roughened cylinder curve at about 650 rpm. At this point, one might expect similar magnitudes of roughness on the coated and "roughened" cylinder. The roughness of the coating was about 300 μ inches.

Flow Noise

The comparison of the wall pressure fluctuations for the two cases is shown in figure 10. In this figure, the wall pressure fluctuations have been scaled to a speed of 660 rpm in order to facilitate comparison. The technique for scaling is based upon well known, non-dimensionalization techniques employed in the study of turbulent boundary layer pressure fluctuations (Foxwell, 1966). According to these techniques, the wall pressure spectrum magnitude is proportional to the term, $T_W^2 \delta^* U_\infty^{-1}$, where T_W is the wall shear stress δ^* is the boundary layer displacement thickness, and U_∞ is the free stream velocity. The frequency dependendence scales with a Strouhal number based on the displacement thickness, i.e., $f \delta^* U^{-1}$, where f is the frequency. For the rotating cylinder, there is no accurate information regarding the boundary layer thickness; however, some information (Cham and Head, 1970) indicates that the layer thickness remains approximately constant over the speed ranges used in this experiment. Thus, the δ^* term is neglected, and the experimentally measured wall pressure spectrums are scaled using the speed, U_∞, and the wall shear stress, T_W, which is proportional to the torque required to drive the cylinder. The scaling equations that result are

$$\langle p^2 \rangle' = (T660/T)^2 (660/RPM) \langle p^2 \rangle \quad (9)$$

and

$$f' = (660/RPM) f \quad (10)$$

where $\langle p^2 \rangle'$ is the scaled mean square pressure in any filter band corresponding to the measured pressure $\langle p^2 \rangle$, $T660/T$ is the ratio of the drive torques at 660 rpm to the measured torque (after frictional torques are subtracted), 660/RPM is the speed ratio relative to 660 rpm, and f' is the scaled frequency corresponding to f. The data for the uncoated cylinder collapsed well as shown in figure 10. The coated data did not collapse as well. In the figure, the data for 360, 460, and 660 rpm were included, the 280 rpm data did not scale.

Despite the lack of knowledge of the boundary layer thickness, it is apparent that the flow was turbulent. First, because the uncoated data collapsed well, and also, the Reynold's number based on "reasonable estimates of boundary layer thickness and this lowest speed (100 rpm equal to about 10 fps) is on the order of 10,000 - much greater than critical for flow conditions of this sort.

The behavior of the scaled wall pressure levels is similar to behavior measured between roughened and smooth flat plates (Burton, 1971). The most similar features are the higher mid-frequency levels and the closer levels at high frequencies. Also shown in figure 10 is the wall pressure spectrum measured on a roughened cylinder at 660 rpm; this curve further elucidates the similarity to flow over a roughened surface. Some caution must be urged in this interpretation of the data, because the exact shape of the mid-frequency levels may be influenced by the pressure transducer mounting arrangement.

The radiated noise data also indicated that surface roughness is present above the critical speed, since the levels are higher relative to the uncoated data at the greater speeds. Unfortunately, no radiated noise from a roughened cylinder is available for comparison.

CONCLUSIONS

The results of this experiment indicate that a critical speed, where drag suddenly increases, occurs for compliant coatings. This behavior has been observed on a rotating cylinder with a compressible, compliant coat, thus extending and corroborating rotating disk results made with an incompressible layer. The critical speed matches very well with the theoretically predicted speed.

Furthermore, the results indicate that the added drag comes about because of an increase in surface roughness. The wall pressure spectrums behave similarly to those observed on roughened surfaces. Radiated noise levels are higher as expected from a rough surface.

ACKNOWLEDGEMENTS

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PRESSURE LOAD (PSI)	0	1.6
SHEAR STORAGE MODULUS (PSI)	12.1	12.1
SHEAR LOSS MODULUS (PSI)	*	137
YOUNG'S STORAGE MODULUS (PSI)	28.4	28.4
POISSON'S RATIO	0.18	0.18

*NOT APPLICABLE BECAUSE OF HYSTERETIC FORM OF ENERGY DISSIPATION

TABLE I. MEASURED MATERIAL PROPERTIES FOR ¼-INCH THICK "BUBBLE" RUBBER COMPLIANT COAT.

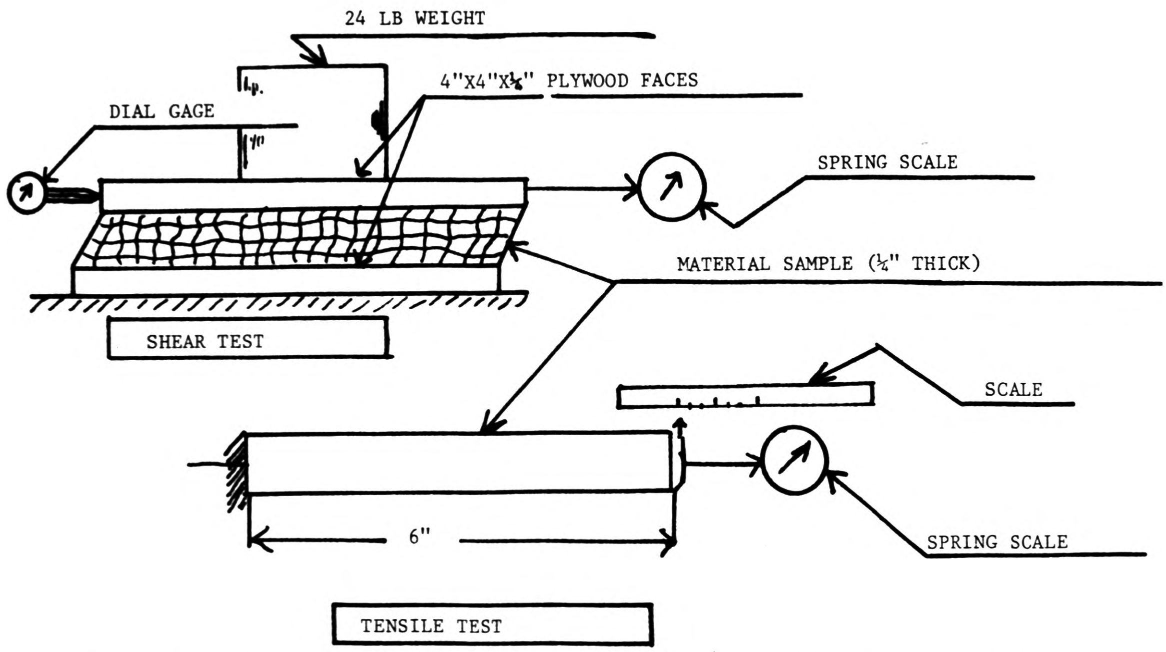

FIGURE 1. SCHEMATIC ILLUSTRATION OF SIMPLE TESTING ARRANGEMENTS USED TO MEASURE THE SHEAR AND TENSILE MODULI OF THE COMPLIANT COATING.

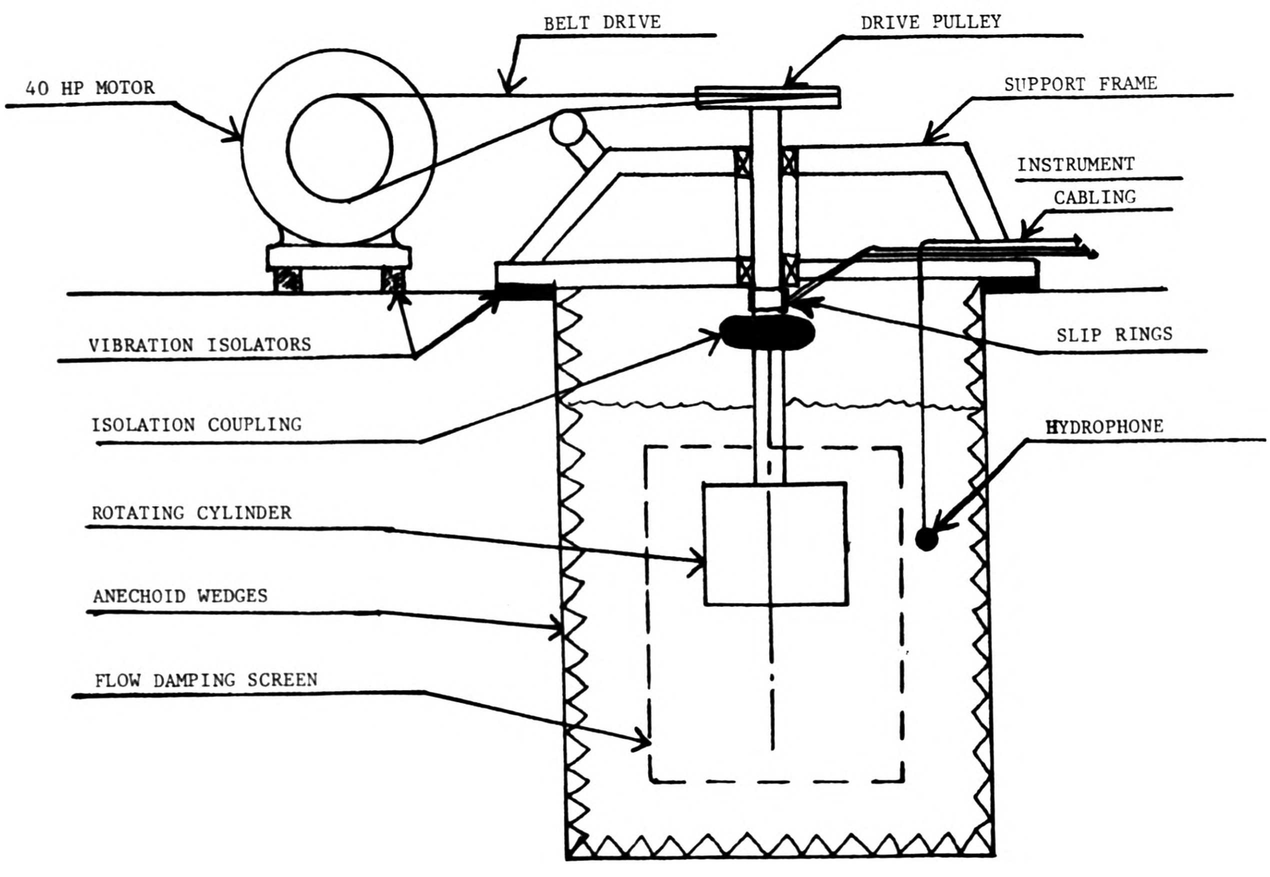

FIGURE 2. SCHEMATIC DIAGRAM OF ROTATING CYLINDER TEST APPARATUS.

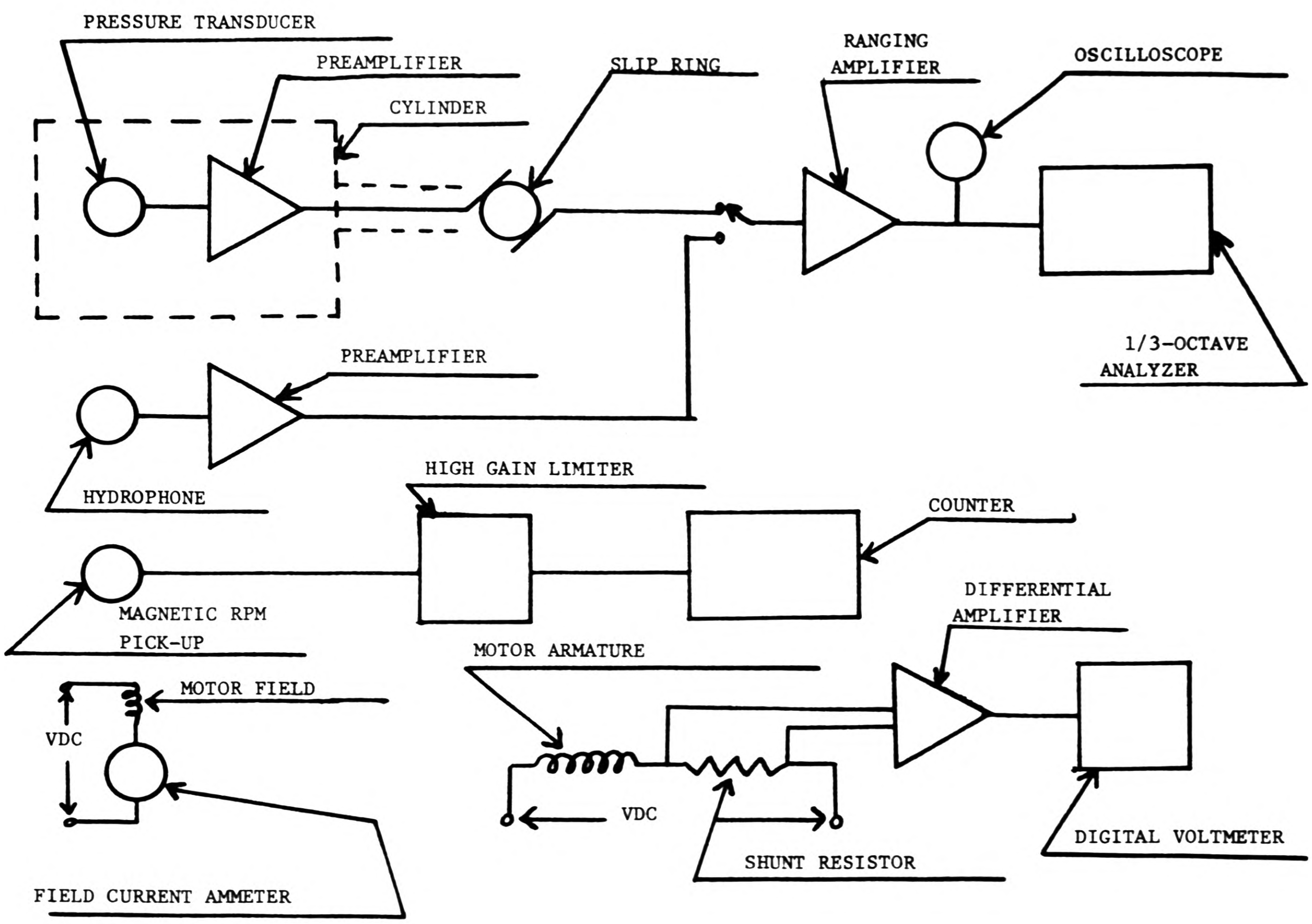

FIGURE 3. BLOCK DIAGRAM OF INSTRUMENTATION

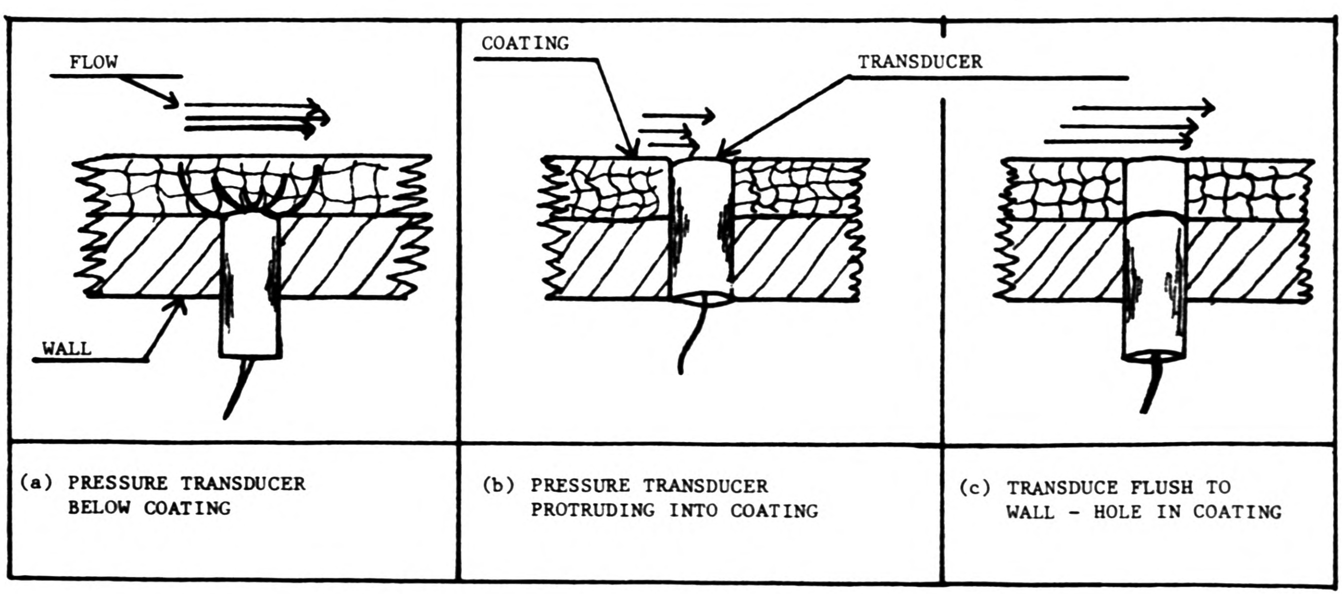

FIGURE 4. DIFFERENT POSSIBLE ARRANGEMENTS OF PRESSURE TRANSDUCER RELATIVE TO COATING

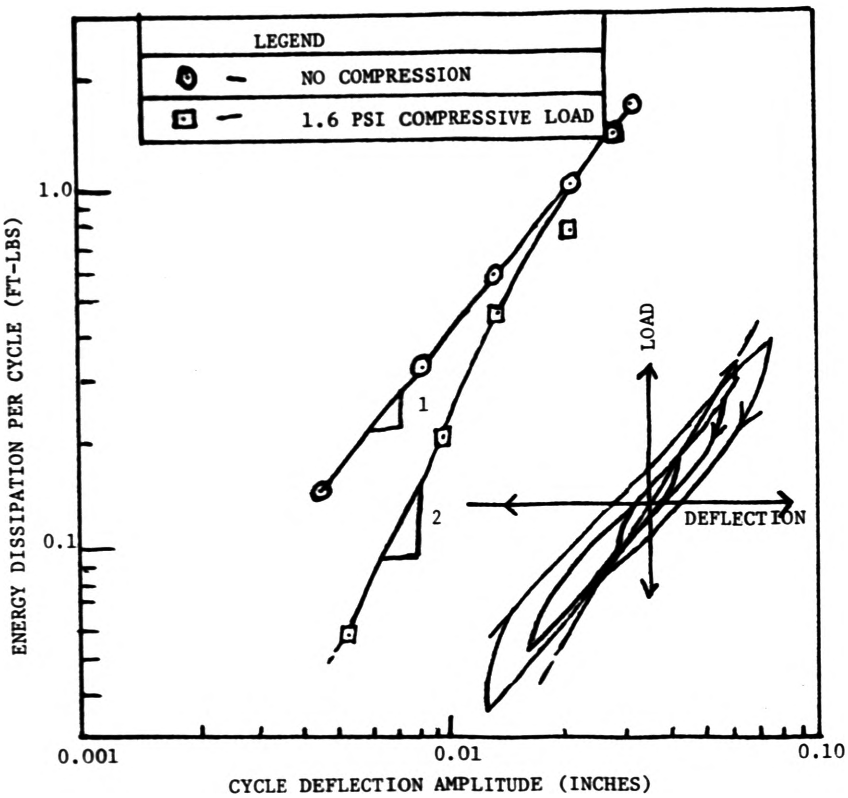

FIGURE 5. COATING MATERIAL PROPERTIES

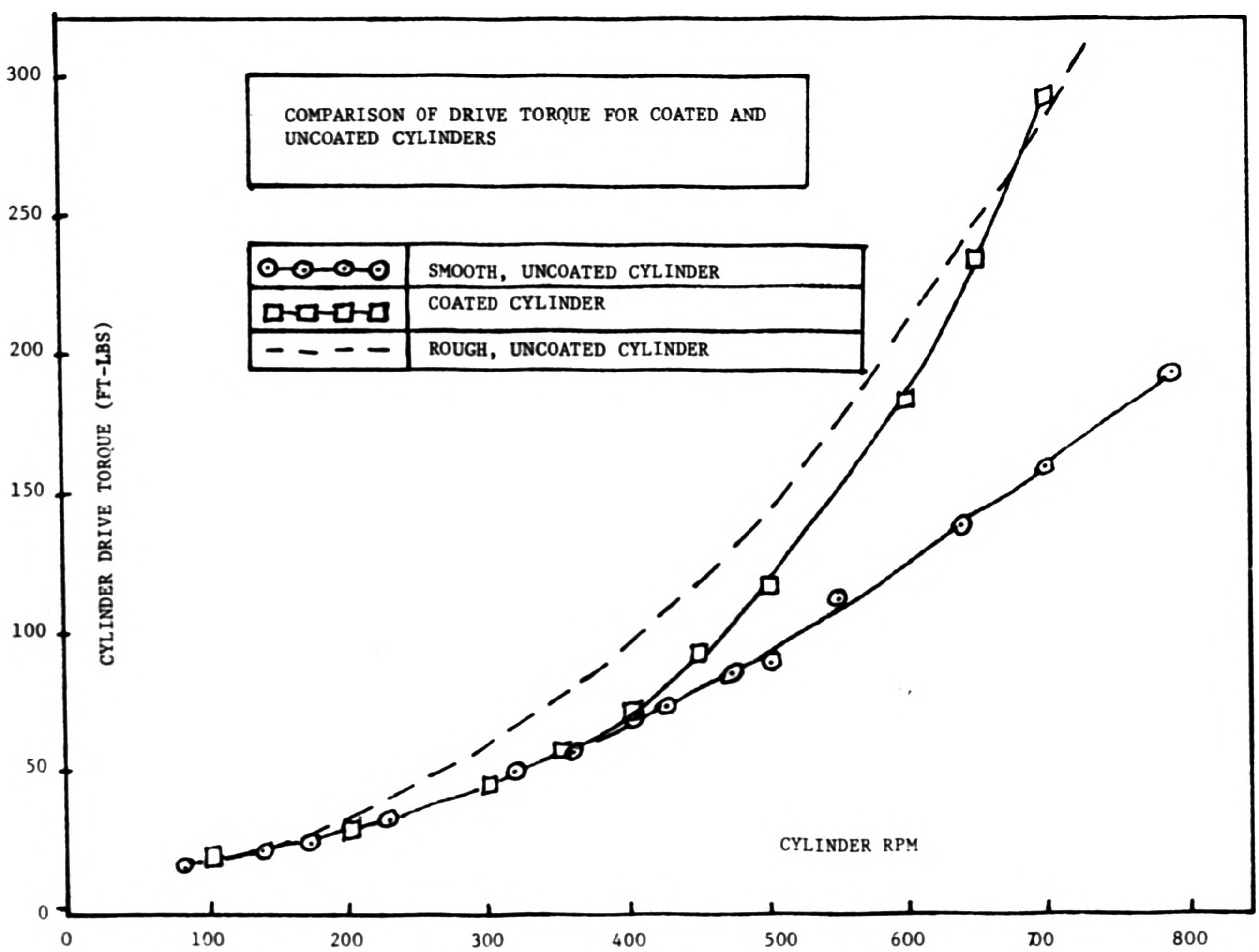

FIGURE 6. RESULTS OF TORQUE VS RPM EXPERIMENT

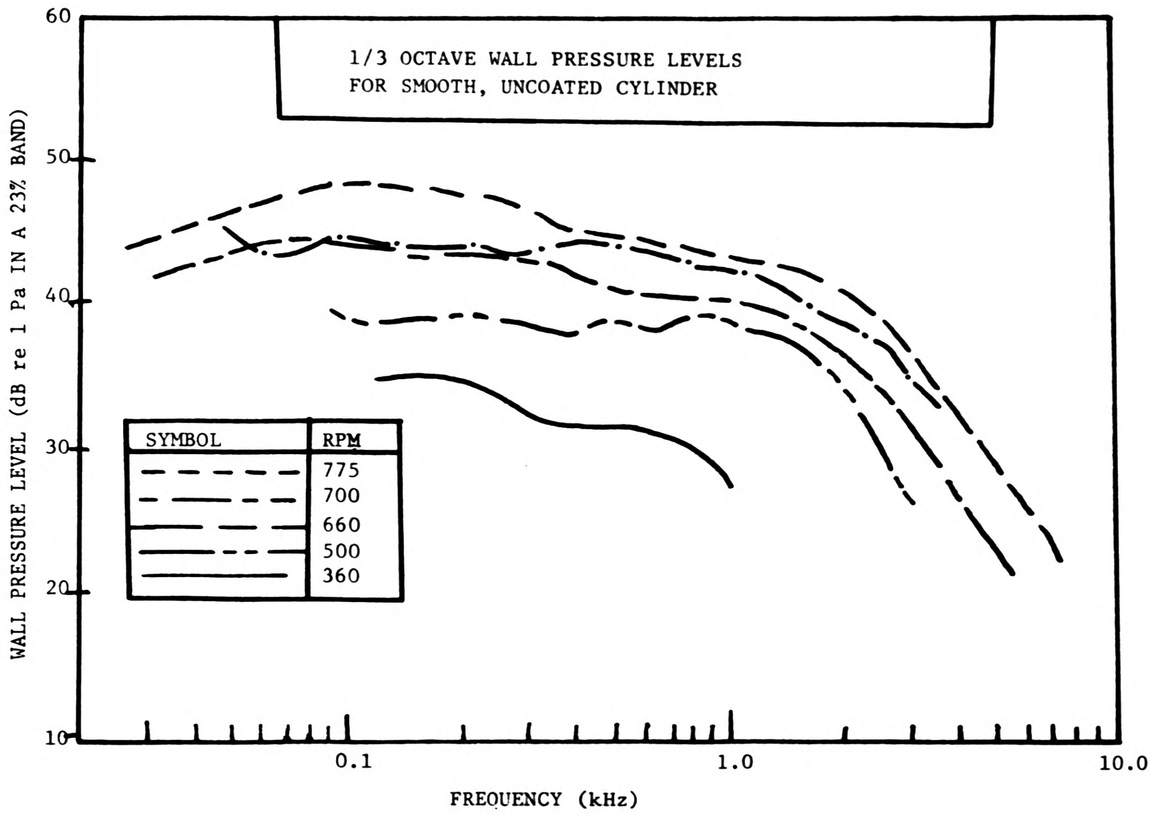

FIGURE 7. WALL PRESSURE FLUCTUATION 1/3-OCTAVE BAND LEVELS FOR UNCOATED CYLINDER AT VARIOUS RPM.

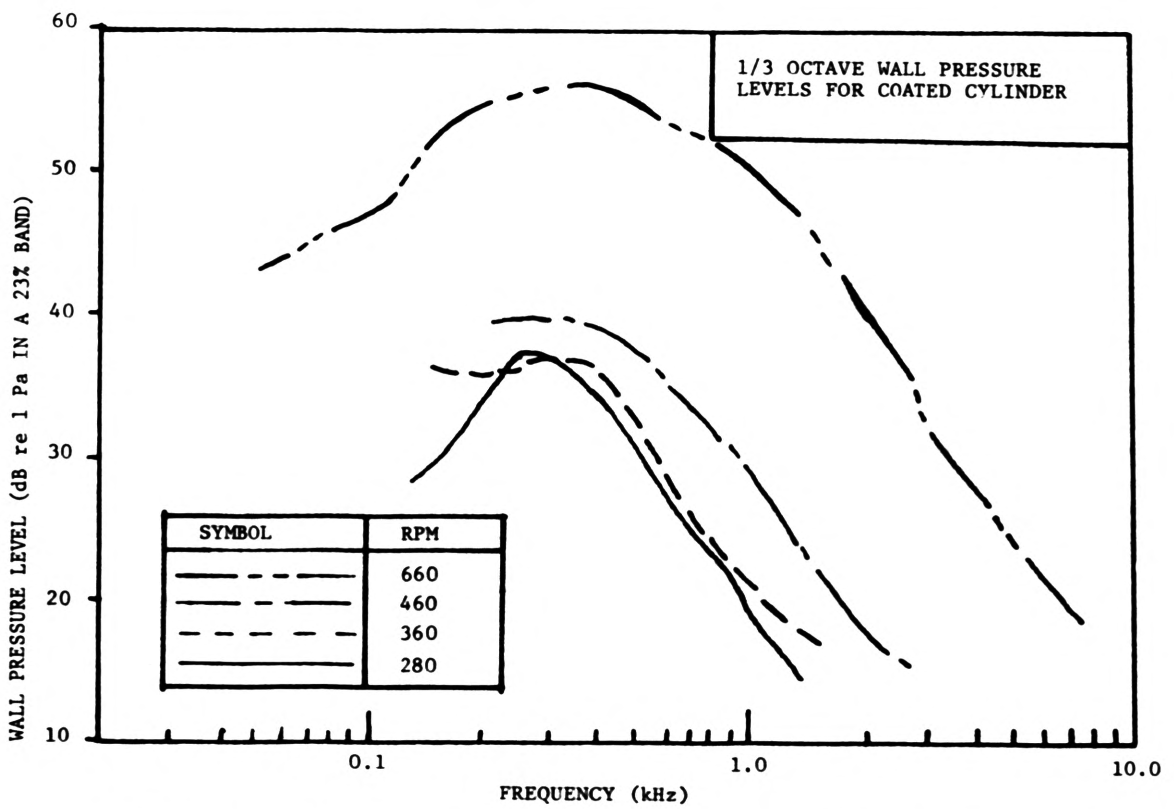

FIGURE 8. WALL PRESSURE FLUCTUATION 1/3-OCTAVE BAND LEVELS FOR COATED CYLINDER AT VARIOUS RPM.

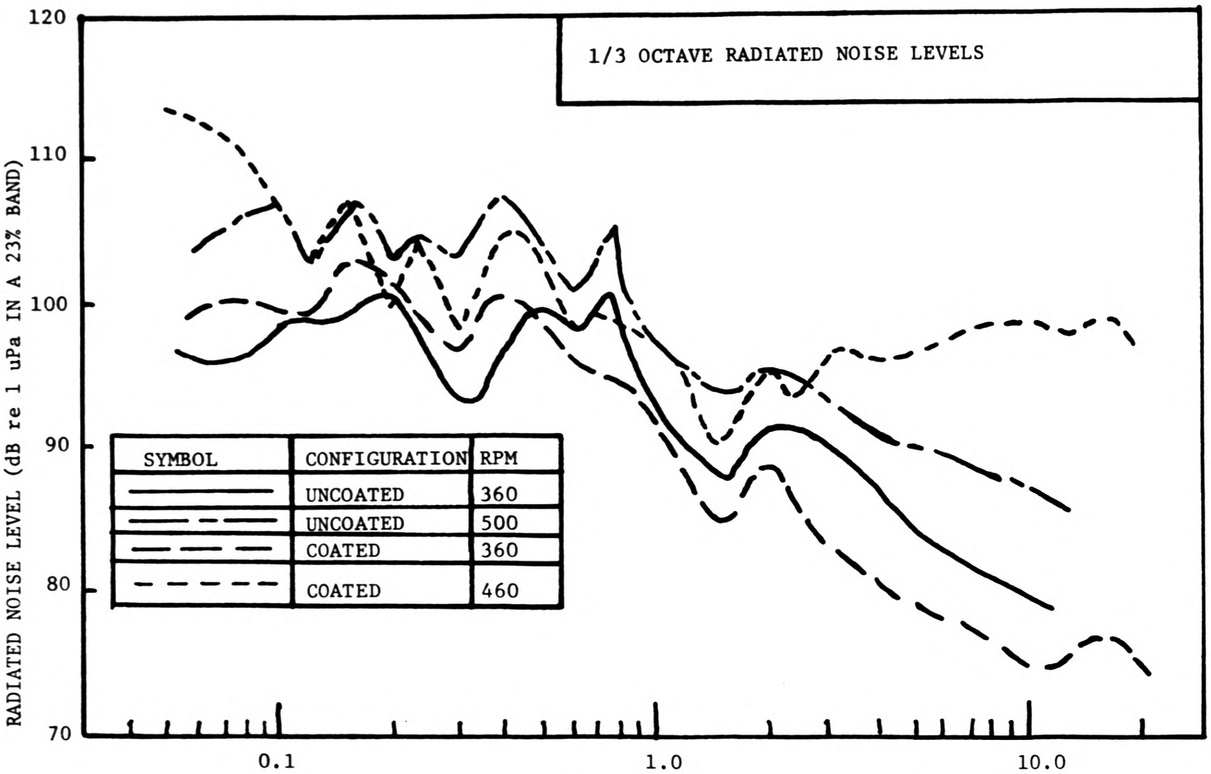

FIGURE 9. RADIATED NOISE LEVELS FOR COATED AND UNCOATED CYLINDERS AT VARIOUS RPM.

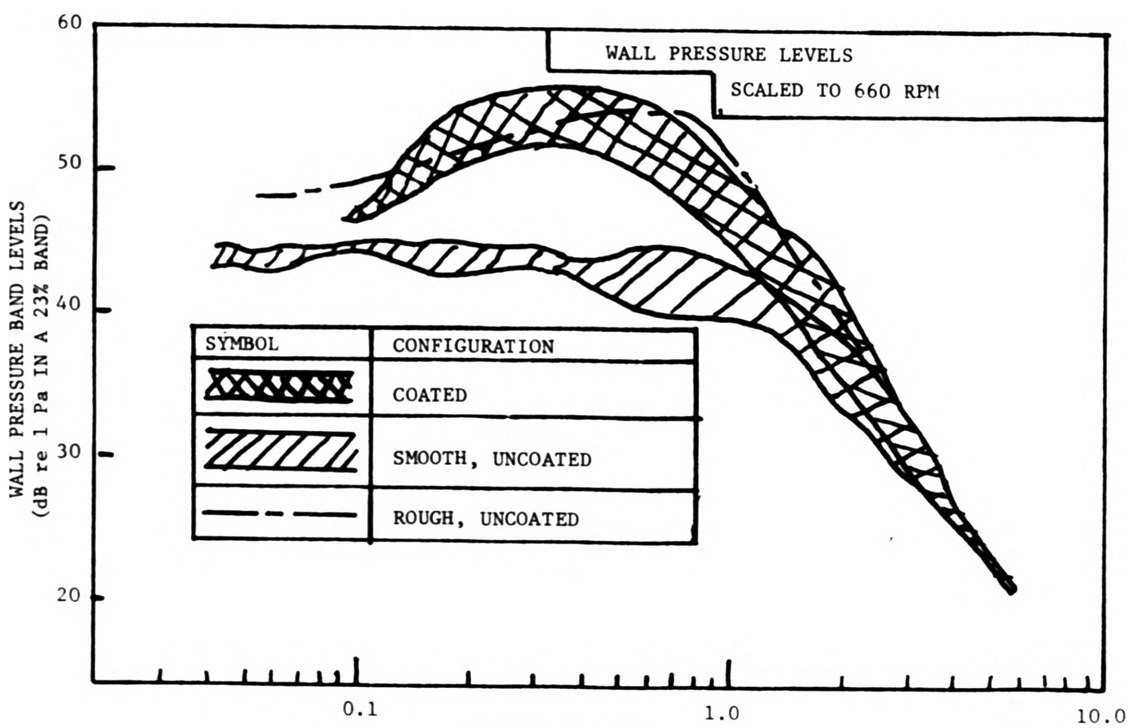

FIGURE 10. 1/3-OCTAVE WALL PRESSURE LEVELS FOR VARIOUS CONFIGURATIONS SCALED IN MAGNITUDE AND FREQUENCY BASED ON RPM AND WALL SHEAR. COATED RESULTS ARE SIMILAR TO ROUGHENED WALL RESULTS.

DISCUSSION

P. McConachie, University of Queensland: I understand your concern regarding the location of the wall pressure transducer. One thing that does worry me about this effect is that you actually have circulation down into or out of the pressure sensing cavity thus implying that the flow streamlines will be bent down into the cavity. Therefore, how can you really claim that you are measuring the pressure at the surface plane of the compliant medium?

Brown: As I indicated this pressure transducer arrangement was not ideal. Our basic assumption is that water column above the transducer acts as a pressure transmitting column and that circulation effects are negligible.

McConachie: To overcome the surface moved, you must have a flow in and out of that cavity which therefore means that you're not measuring the pressure at the surface of that, you must be measuring some combination of dynamic pressure and some static pressure.

Brown: This is very probable. That is one of the disadvantages of this treatment.

E. Blick, Univ. of Oklahoma: We also measured this instability of the compliant surface on flat surfaces. We had our compliant coating maybe 10 or 12 inches long and 6 or 7 inches wide in a wind tunnel and we got up to 120 or so miles per hour. A standing wave developed on our compliant coating. It was a sine wave and was sort of quasi-steady.