

R761328

AD732 402

Report 3707

MIT LIBRARIES



3 9080 02753 7379

NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20034

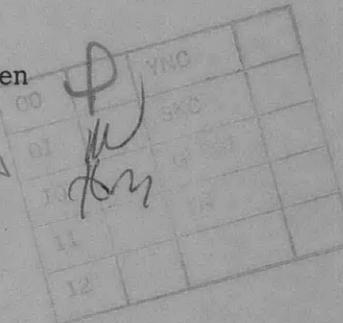


V393
.R46

MEASUREMENT OF THE BOUNDARY-LAYER PRESSURE FLUCTUATIONS ASSOCIATED WITH TURBULENT AIR FLOW IN A RIGID PIPE

by

F. C. DeMetz and D. W. Jorgensen



APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED



SHIP ACOUSTICS DEPARTMENT
RESEARCH AND DEVELOPMENT REPORT

MEASUREMENT OF THE BOUNDARY-LAYER PRESSURE FLUCTUATIONS ASSOCIATED
WITH TURBULENT AIR FLOW IN A RIGID PIPE

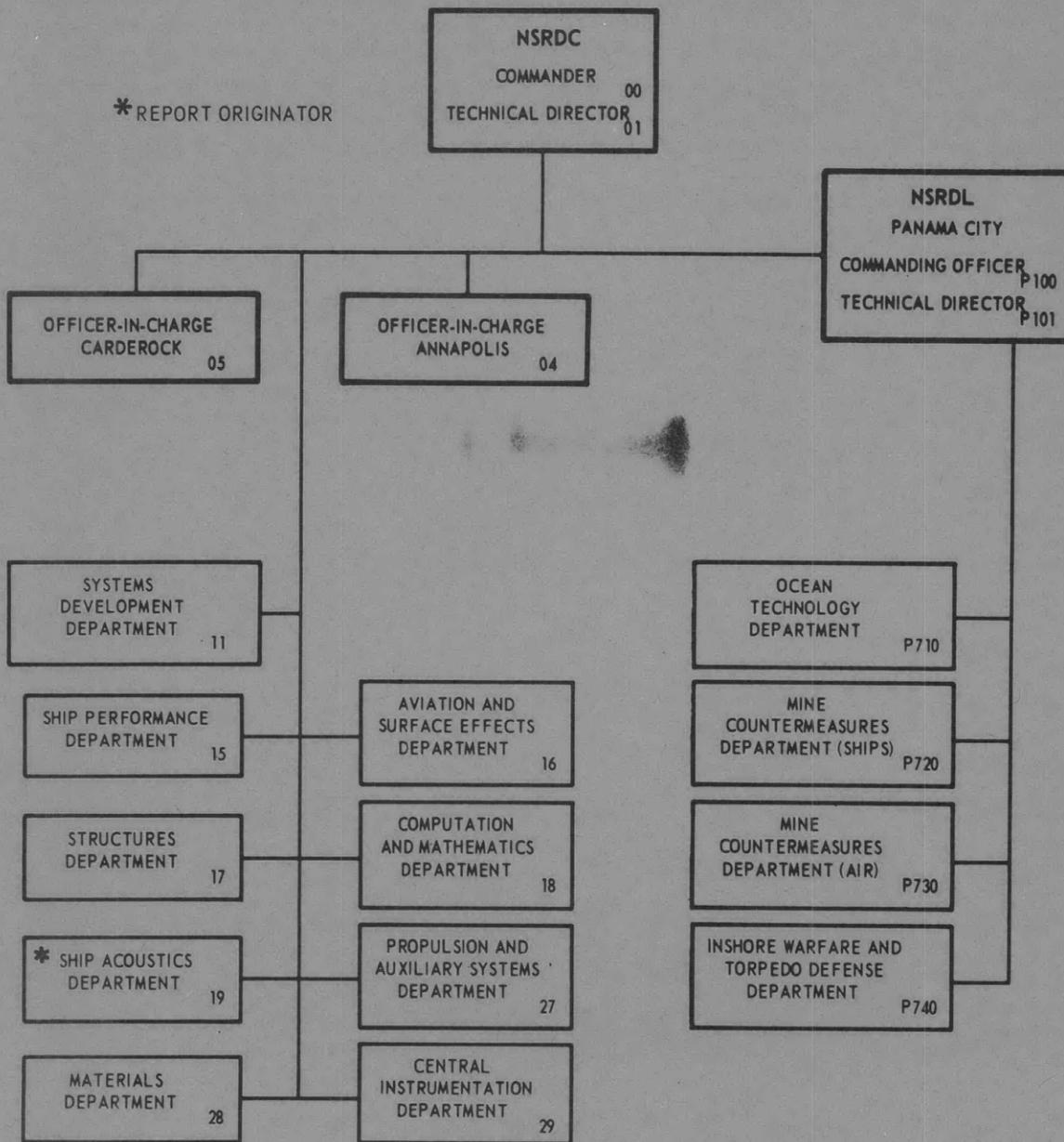
October 1971

Report 3707

The Naval Ship Research and Development Center is a U.S. Navy center for laboratory effort directed at achieving improved sea and air vehicles. It was formed in March 1967 by merging the David Taylor Model Basin at Carderock, Maryland and the Marine Engineering Laboratory (now Naval Ship R & D Laboratory) at Annapolis, Maryland. The Mine Defense Laboratory (now Naval Ship R & D Laboratory) Panama City, Florida became part of the Center in November 1967.

Naval Ship Research and Development Center
Bethesda, Md. 20034

MAJOR NSRDC ORGANIZATIONAL COMPONENTS



DEPARTMENT OF THE NAVY
NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER
BETHESDA, MD. 20034

MEASUREMENT OF THE BOUNDARY-LAYER PRESSURE
FLUCTUATIONS ASSOCIATED WITH TURBULENT
AIR FLOW IN A RIGID PIPE



by

F. C. DeMetz and D. W. Jorgensen

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

October 1971

Report 3707

TABLE OF CONTENTS

	Page
ABSTRACT	1
ADMINISTRATIVE INFORMATION	1
INTRODUCTION	1
STATEMENT OF THE PROBLEM	1
BACKGROUND	1
ASPECTS OF THE MODELING	2
PRESENT MODEL AND ITS APPLICATION	3
EXPERIMENTAL APPARATUS AND PROCEDURE	4
TEST FACILITY	4
PRESSURE TRANSDUCERS AND CALIBRATION	5
CONTROL OF AIR VELOCITY	6
BACKGROUND NOISE IN THE FACILITY	7
DATA ANALYSIS EQUIPMENT	7
EXPERIMENTAL RESULTS AND DISCUSSION	9
ACKNOWLEDGMENTS	12
REFERENCES	22

LIST OF FIGURES

Figure 1 - Turbulent Flow Facility	13
Figure 2 - Schematic Diagram of Power Spectra Transducer Assembly	13
Figure 3 - Schematic Diagram of Cross Spectra Transducer Assembly (Transverse Alignment Shown)	14
Figure 4 - Frequency Response of Pinhole Microphone	14
Figure 5 - Frequency Response of 1/2-Inch Transducer	15
Figure 6 - Frequency Response of Cross Spectra Transducer Element	15
Figure 7 - Power-Spectral Density of the Pressure at the Pipe Wall	16
Figure 8 - Exhaust Muffler Schematic	16
Figure 9 - Dimensionless Spectral Density of the Pressure	17
Figure 10 - Real Part of Normalized Cross-Spectral Density (Longitudinal)	17

	Page
Figure 11 - Imaginary Part of Normalized Cross-Spectral Density (Longitudinal)	18
Figure 12 - Normalized Modulus	18
Figure 13 - Normalized Cross-Spectral Density (Transverse)	19
Figure 14 - Average Ratios of Convection and Centerline Velocity for Longitudinal Transducer Separations of 0.132 In., 0.267 In., and 0.402 In. for $U_{CL} = 100$ and 200 Feet/Sec	19
Figure 15 - Dimensionless Spectral Density of the Pressure Corrected for Transducer Size Effects	20
Figure 16 - Comparison of Dimensionless Spectra with Results of Other Investigators	20
Figure 17 - RMS Pressure versus Reynolds Number	21

ABSTRACT

This report gives the results of an experimental investigation of the pressure fluctuations associated with turbulent flow in a rigid pipe. Measurements were made of the power-spectral and cross-spectral densities of the pressure fluctuations on the pipe wall for fully developed turbulent air flow over a Reynolds number range of approximately 20 to 1. The variation in Reynolds number was achieved by variation in flow velocity; in this experiment the centerline velocity U_{CL} was varied from 16 ft/sec to 316 ft/sec. The spectral content of the pressure field was investigated for frequency components from 10 to 10,000 Hz. Special attention was given to obtaining spectral levels for the low-frequency components of the pressure field because the nature of the power spectral density in the low wave-number region for turbulent pipe flow is still uncertain.

ADMINISTRATIVE INFORMATION

The work described in this report was funded by Naval Ship Systems Command under Project SF 35 452 007, Task 01356.

INTRODUCTION

STATEMENT OF THE PROBLEM

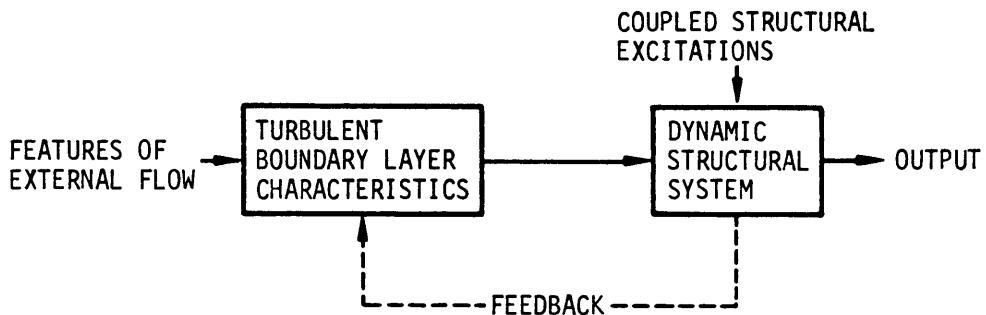
The purpose of this study is to measure the power-spectral and cross-spectral densities of the fluctuating pressure field on the smooth inner wall of a rigid pipe containing fully developed turbulent air flow.

BACKGROUND

Some qualitative features of the viscous boundary layer near a translating rigid body depend, to a marked extent, on surface geometry, roughness of the structure, turbulence intensity of the external flow, and Reynolds number of the external flow.¹ The interaction of this viscous flow field with a moving flexible structure is a complex problem with few successful analytical methods of solution. In most of the attempts at

¹References are listed on page 22.

modeling the problem, the fluctuating pressure field generated by the turbulent boundary layer is assumed to act as a prescribed excitation or forcing function upon the structural surface which most generally constitutes a dynamic system. However, the response of the dynamic system to the excitation may in turn cause feedback altering the structure of the turbulent boundary layer as illustrated in the following way:



ASPECTS OF THE MODELING

The difficulties which arise in modeling such a system result from the unpredictability of the details of the turbulent excitation and from the complexity of the features usually encountered in the structure of a realistic dynamic system. A successful resolution of the problem of modeling must rely on a statistical treatment of an idealized system. Some specialized treatments of boundary-layer excitation of a dynamic system are given by McCormick,² White,^{3,4} Maidanik,⁵ Heckl,⁶ and Strawderman and Brand,⁷ to name a few. All of these treatments incorporate an experimentally determined statistical model for the boundary-layer pressure fluctuations with a specialized model of the dynamic structure. It is assumed in this study that no feedback mechanism exists between the pressure field and the dynamic structure. The more complex situations when the motion of the boundaries results in an appreciable back reaction on the flow are discussed by Powell⁸ and Maidanik.*

Most experimental determinations of the turbulent pressure field which are readily available in the literature are made for flow situations

*NSRDC Tech Note AVL-237-902 of Jan 1969.

which ostensibly are ideally controlled although it is known that spurious effects which invariably enter into turbulence experiments prevent, to a greater or lesser extent, the ideal control which is desired. Furthermore, these experimental determinations are limited in the detailing of the spatial and temporal dependence of the forcing function by various inherent properties of the measuring instruments, e.g., the finite size and nonuniform response of the sensitive faces of the pressure transducers⁹⁻¹² and, indeed, are also limited by procedures employed to determine the statistical properties of the data, e.g., assumption of stationarity of the data, use of finite bandwidth filters, etc.

Some improvement concerning the difficulties of measurement derives from a recent approach which employs the finite dimensions of the pressure transducers (in the form of an acoustic diffraction grating) to some advantage in the measurements of the turbulent pressure fields of spatially homogeneous boundary layers.^{13,14}

PRESENT MODEL AND ITS APPLICATION

In the present experimental study of turbulent boundary-layer fluctuating pressures, efforts were made to minimize the effects of complicated surface geometry, roughness, adverse pressure gradient, and coupling between the boundary layer and the structural surface. It is desired to determine the statistical properties of the pressure field on a smooth, highly rigid surface of simple geometry for the fully developed turbulent flow field. Measurements were made of the fluctuating pressure field on the inner wall of a rigid pipe for fully developed turbulent air flow. The air-pipe system was designed to minimize effects due to pipe wall vibrations and far-field acoustic wave sources. The measured fluctuating pressures are assumed to be the nonpropagating, or near field, components generated in close proximity to the pressure transducers by the turbulent eddies of the flow. The spatial and temporal characterization of the pressure field is determined by using two small pressure transducers and "mapping" the forcing function of the turbulent pressure fluctuations by measuring the cross-correlation between the outputs of the transducers at varying spatial separations in various frequency bands, or equivalently, by measuring the cross-frequency spectral density between the two transducers at the various

spatial separations. Recently Chandiramani¹¹ and Maidanik* have defined the significant differences in the basic experimental methods employed in the various investigations. The statistical properties of the fluctuating pressures were determined so as to minimize, as much as possible, any effects due to finite bandwidth of the analyzing processes and non-stationarity of the data in time. These results augment understanding of the very low- and high-frequency components of the pressure field on a smooth, symmetrically curved, rigid surface in a constant pressure gradient and supplement the results of many previous investigations. While this study avoids the still more complicated problem of the flexible boundary, which probably has more practical importance, these and other similar results should nevertheless be useful as a reference for future work that will hopefully be conducted on the effects of additives, coatings, roughness, and shapes on the boundary-layer fluctuating pressure fields adjacent to translating surfaces. Only after evaluating these as well as the structural properties of vehicles will the best means be found for minimizing adverse effects on the intended function of the vehicles by the boundary-layer excitation.

EXPERIMENTAL APPARATUS AND PROCEDURE

TEST FACILITY

Figure 1 illustrates the pipe facility. Air passes from the compressed air tanks through a regulating system and into a large settling tank. A rubber hose is used to isolate the settling tank from structure-borne vibration. The settling tank is baffled and lined with fiberglass to further attenuate any noise coming from upstream. From the settling tank, the air flows into the 3 1/16-inch diameter smooth pipe. Any roughness or protuberances are less than 0.001 inch and are contained within the laminar sublayer over the range of flow velocities. The air is expelled through a diffuser after passing through a 15-foot fiberglass-lined muffler to reduce any sound waves that are reflected upstream at the

*NSRDC Tech Note AVL-237-902 of Jan 1969.

exit. The pipe is rigidly fixed and mechanically damped with sandbags along its length. The microphones for measuring the pressure fluctuations are located 110 pipe diameters downstream from the entrance. Air speeds are determined by measuring the static pressure drop along a length of the pipe with two pressure taps flush with the inner pipe wall. These are connected to a differential pressure gage to give a continuous reading of the air speed.

PRESSURE TRANSDUCERS AND CALIBRATION

The transducer for measuring the power spectral densities is shown in Figure 2. Figure 3 shows the transducer used for the cross-spectral density determinations. The fluctuating pressure on the pipe wall is sensed through 3/64-inch diameter holes drilled in the brass plugs machined flush with the inner pipe wall. Each "pinhole" leads to a small cavity in which a nominal 1/4-inch diameter condenser microphone of BrueI and Kjaer Type 4136 is mounted. This microphone system has a resonance at about 16 kHz due to the fact that the combined pinhole and cavity behave like a simple Helmholtz resonator.¹⁵ Figures 4 and 5 show the pressure response of the power spectra transducers. Figure 6 illustrates the pressure response of a typical element of the transducer used for measuring the cross spectra. The sensitivity is determined at the output of the cathode-follower preamplifier. The pressure calibration was made by a comparison method using a sound source in a very small coupling chamber.

The use of a single tubular piezoelectric cylinder^{16*} as both a coupling chamber and sound source has proven effective in providing a sufficiently small cavity for use in obtaining pressure calibrations of transducers up to frequencies as high as 8 kHz, using air as an acoustic medium.

A very small coupling chamber** employing this principle has been developed which permits the calibration of transducers with small sensing areas to frequencies up to 16 kHz in air.

*A similar device is employed in the General Radio Company microphone reciprocity calibrator, Type 1559-A.

**This method was suggested by Dr. M. Strasberg.

A commercially available piezoelectric cylindrical tube of 1/4-inch diameter and 1/8-inch length is mounted between rubber insulating washers in a brass holder. An airtight chamber is achieved by pressing a standard transducer against one open cylinder end, and the transducer to be calibrated against the other. The cylinder is made to oscillate by exciting it radially with AC voltage. The oscillations of the cylinder walls produce a uniform sound pressure in the cavity between the transducers as long as the cavity dimensions are smaller than approximately one-fourth the acoustic wavelength. The output signals of the two transducers are compared to determine the unknown sensitivity.

This device was used to calibrate a 1/4-inch condenser microphone which has been adapted to have 3/64-inch diameter sensing area as shown in Figure 2. The frequency response of the transducer is shown in Figure 4. The peak shown at 16 kHz was due to the Helmholtz resonance of the small cavity between the microphone diaphragm and the 3/64-inch diameter hole. At approximately 16-kHz wave effects in the cylindrical coupler became evident and thus this frequency was considered the upper limit for the calibrator when air is used. The accuracy of the calibration is within 1 dB.

At frequencies near the resonance of the pinhole microphone, the wave motion in the chamber limited the accuracy of calibration. Although the resonance peak could be clearly identified, its magnitude was sensitive to a slight change in the volume of the calibration chamber. Therefore, measurements could yield only approximate values for the pressure fluctuations at frequencies above 10 kHz. Below 100 Hz, the sensitivity decreased gradually. The lower limit of our measuring range with the 1/4-inch microphones was 20 Hz. For the low-frequency power spectra measurements below 100 Hz, a 1/2-inch diameter Brue1 and Kjaer Type 4134 was substituted for the 1/4-inch microphone. This resulted in an improved frequency response at the frequencies below 100 Hz; with this modification, the resonance peak occurred at about 4 kHz (see Figure 5).

CONTROL OF AIR VELOCITY

The air velocity could be regulated and maintained constant within 1 ft/sec through use of a pressure feedback system which maintained a

constant pressure in the settling tank regardless of the diminishing pressure in the air supply tank, during any run.

BACKGROUND NOISE IN THE FACILITY

Due to very effective isolation of structural and airborne noise paths between the air source and the test section, background noise in the facility was at least 20 dB below the flow noise for the frequency range from 100 to 10,000 Hz over the range of air velocities.

However, over the range of frequencies below 100 Hz, a series of harmonically related maxima and minima were found in the power spectra of the original measurements. Subsequent investigation has led to abundant evidence that this result was associated with standing acoustic waves in the pipe, and, therefore, in the graph of the results in Figure 7, the peaks have been ignored and only the envelope of the successive minima is shown for each curve, as representing the level of the pressure spectrum on the wall. In support of this interpretation, it is noted that the frequencies at which the maxima occurred were independent of flow velocity and corresponded closely to the value calculated for longitudinal pipe modes, while the amplitudes of the maxima were reduced considerably and the amplitudes of the minima were virtually unchanged when a dissipative termination (Figure 8) was installed on the pipe. Furthermore, a 1964 report by CONCESCO, Inc.¹⁷ which investigated similar phenomena gives strong support for the conclusion that the envelope of the minima in the spectrum probably represents the contribution due to turbulence. Although the precise generating mechanism of the low-frequency acoustic waves was not determined in this experiment, probable mechanisms are within the turbulent boundary layer itself and the discontinuities at the entrance and exhaust of the pipe and/or the interaction of the turbulent flow with these discontinuities.

DATA ANALYSIS EQUIPMENT

The power spectral densities were determined by analyzing the output of the microphone by a variable frequency filter of constant narrow bandwidth. The filter used was a Radiometer wave analyzer, Type FRA 2cAT3a, with continuously variable center frequency in readily selected

optional bandwidths of 4, 11, and 31 Hz constant width. The narrowest bandwidth (4 Hz) was employed below 100 Hz, while the wider bandwidths were used for the higher frequency measurements. The analyzed signal is approximately squared, averaged, and recorded graphically by a General Radio graphic level recorder, Type 1521-A.

The cross-spectral densities were determined from recordings of the microphone signals on continuous tape loops by two independent methods. The primary method employs a dual-channel analyzer system developed at the Naval Ship Research and Development Center (NSRDC),* which uses two matched variable frequency filters of constant 10-Hz bandwidth to analyze the two analog signals recorded on the tape loop. The filter outputs were connected to a polarity-coincidence correlator, and the normalized cross-spectral density is displayed on a meter.

The cross-spectral densities were also determined by digital computer. The digital analysis was made with a computer program developed in the Computation and Mathematics Department at NSRDC.** This method calculated the cross spectrum by converting the analog signals on the tape loop to digital form*** and using an IBM 7090 digital computer which first calculated the cross correlation of the two signals and the autocorrelation of each. Then, the Fourier transforms of these results were calculated to obtain the cross-spectral density and the power spectra of the two signals.[†] Finally, the cross spectra were normalized with respect to the power spectra (reported informally by DeMetz^{††}).

*"Dual Channel Analyzer System," unpublished report by L. Gordon, Ship Acoustics Department.

**"Identification of Cross-Spectrum Executive Program," unpublished report by R. Mejia, Computation and Mathematics Department.

***A half second analog data was digitized, both signals simultaneously, at a 32,000 sample/second rate.

[†]The cross-spectral determination was made using 3200, 1600, and 160 lags and both exponential lag windows and Hanning spectral windows for smoothing.

^{††}NSRDC Tech Note AVL-168-942 of Feb 1967.

In the graphs of the results, the analog method was used to determine the power and the lateral and longitudinal cross-spectral densities, whereas the convection velocities as defined by Reference 18 were determined from the computer calculations. There was excellent agreement between the two independent methods of calculation.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 7 presents the spectral densities of the fluctuating pressure on the pipe wall as a function of frequency. The curves correspond to velocities which cover a Reynolds number range of 23,000-460,000. The Reynolds number is defined in terms of the mean flow velocity, the pipe diameter, and the kinematic viscosity. The curves are seen to be fairly flat at the intermediate frequencies and falling off at high frequencies. At frequencies above 10,000 Hz, curves are shown as dashed lines to signify that some inaccuracy may be present near transducer resonance.

The results shown for the range of frequencies below 100 Hz indicate that the spectrum of the boundary-layer pressure fluctuations increases gradually with decreasing frequency. It is noted that some previous experimental data for flow noise over a flat plate^{19,20} has shown a decreasing power spectra with decreasing frequency at low frequencies. No evidence of this was found in the pipe data of this experiment even though efforts were made to eliminate possible sources of background noise. The results of other investigations¹⁸ of pipe flow noise seem to indicate that the nature of the fully developed turbulence noise in pipe facilities, or some inherent property in piping systems in general, results in a slowly increasing or nearly constant spectrum for flow noise at low frequency.

Figure 9 indicates the dimensionless spectral density. The power spectral density $P(f)$, is expressed nondimensionally in terms of air density ρ , the centerline velocity U_{CL} , and the pipe diameter d . This dimensionless quantity is plotted as a function of a Strouhal number. The Strouhal number is defined in terms of the frequency f , the diameter of the pipe, and the centerline velocity. We can see in the intermediate Strouhal number region a slight but systematic dependence on the Reynolds number. At high Strouhal numbers, an effect due to finite microphone size becomes

important and a correction is necessary to predict the spectral levels that would be measured by a transducer of infinitesimal area.

Figures 10 and 11 show the normalized, real, and imaginary parts of the longitudinal cross-spectral density. Figure 12 shows the modulus of the normalized longitudinal cross-spectral density, for a range of transducer separations, as a function of Strouhal number, based on centerline velocity. The longitudinal transducer separation ξ ranged from 0.132 inch to 0.402 inch.

Figure 13 gives the normalized real part of the cross-spectral density as a function of Strouhal number, for a range of lateral transducer separations from 0.132 inch to 0.402 inch and for the extreme separation of 3.062 inches (the pipe diameter). Here η is the magnitude of the vector separation of the transducers. The imaginary part of the cross spectra for the lateral separations was essentially zero for all frequencies, as expected, for the lateral cross-spectral densities when all net flows normal to the pipe wall and transverse to the axial direction are zero.

One can assume, for computational purposes, that the normalized cross-spectral density can be written in the form

$$\frac{U_{12}(f, \Delta f, S', S'') + i V_{12}(f, \Delta f, S', S'')}{[P_1(f, \Delta f) P_2(f, \Delta f)]^{1/2}} = e^{-B'|S'| - B''|S''|} e^{iAS'} \quad (1)$$

where U_{12} and V_{12} are the real and imaginary parts of the cross-spectral density, and P_1 and P_2 are the power spectral densities of the member functions. The centerband frequency is f and Δf is the bandwidth in which the experimental measurements were made; $S' = f\xi/U_c$ and $S'' = f\eta/U_c$ where ξ and η are the longitudinal and transverse transducer separations, respectively, and U_c is the convection velocity.²¹ The approximately constant quantities B' , B'' , and A determined from the experimental data and the empirical formula resulting from Equation (1) are shown in Figures 10-13.

Figure 14 gives the results of the convection velocity determination as a ratio of convection velocity to centerline velocity shown as a function of frequency.

Using Figure 14 and the theory of Corcos,⁹ we can correct Figure 9 for the effect of the finite size of the pressure transducer. The corrected results are shown in Figure 15. The correlation factor proposed by Corcos has been found in numerous independent investigations to be approximately correct for cases when the size of the transducer is small compared to the boundary layer thickness.¹² However, it should be noted that contrary to the results of investigators who have used truly flush-mounted transducers (see References 18, 22, and 23), the power spectral densities measured in this experiment with *pinhole* microphones do not collapse at high Strouhal numbers when plotted in dimensionless form (even after a size correction is applied). This is in agreement with the results of Geib,¹² who also employed pinhole transducers. This noncollapse of the power spectra may be due to an interaction effect of the small cavity (*pinhole*) with the flow.²⁴

A comparison of dimensionless spectra with results of other laboratories,^{18,23,25} all corrected for the size effect by the method of Corcos, is shown in Figure 16. Each of the independent investigations presents a single faired curve drawn through data obtained for a specified range of Reynolds numbers. For the comparison, we have similarly taken a faired curve through our data for the appropriate Reynolds number range. In the region of low and intermediate Strouhal numbers, our results tend to generally confirm those of other investigators of pipe flow noise who used the corresponding Reynolds number range. In the region above a Strouhal number of 10 the effects of finite transducer size, still not completely understood, may contribute to the scatter in the data between different investigations.

Figure 17 presents the rms pressures as a function of Reynolds number obtained by determining the areas under the nondimensional power-spectral density results shown in Figure 15. The data point at a Reynolds number of 150,000 is somewhat higher than adjoining values and could be due to the aforementioned possible pinhole-flow interaction effect. The ratio of rms pressure to centerline dynamic pressure decreases with increasing Reynolds number, approaching a value of approximately 0.006 at high Reynolds number. This is a higher value than the previous, narrow band, pipe flow measurements of Corcos¹⁸ which report a value closer to 0.005. Other previous pipe measurements^{22,23} employing bandwidths in the power spectra

measurements which were not truly narrow band in the sense that the spectra levels could have possibly varied over the bandwidths employed, reported values ranging from 0.005 to 0.008.

ACKNOWLEDGMENTS

The authors wish to thank Mr. R. William Brown who so successfully designed and oversaw the construction of the turbulent air flow facility in which the reported measurements were made. The help of Messrs. Robert Briggs and Burton Rieley in the actual operations of the air facility was greatly appreciated. Thanks are also due to Dr. Charles Devin for his helpful criticism and suggestions and to Dr. Murray Strasberg who suggested the unique method for calibrating the pressure transducers. Finally, appreciation is expressed to Dr. Mario Casarella for his suggestions in the preparation of this report.

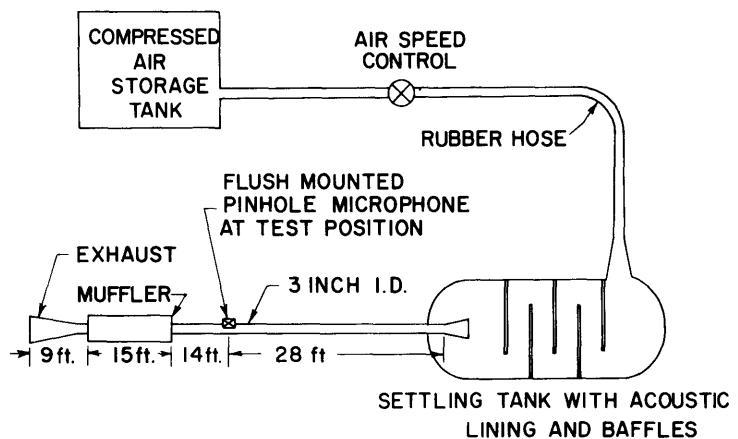


Figure 1 - Turbulent Flow Facility

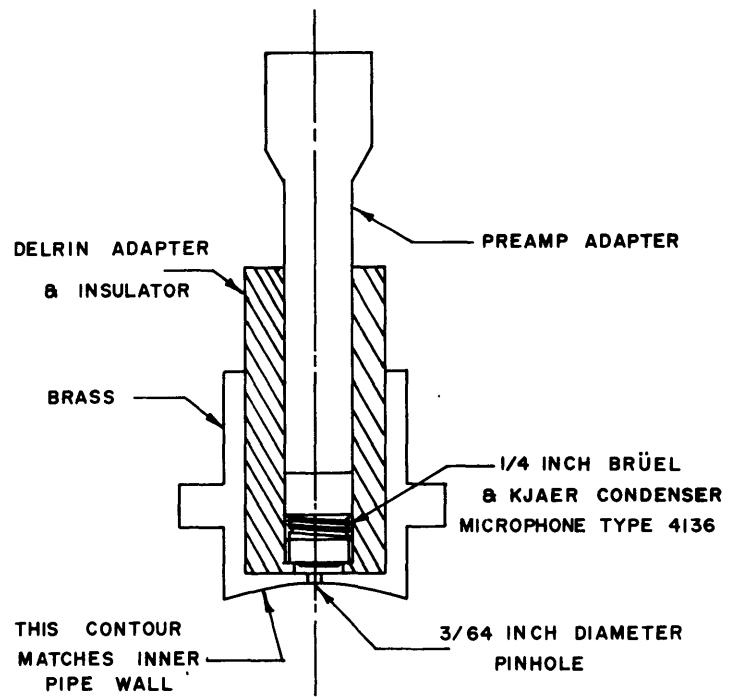


Figure 2 - Schematic Diagram of Power Spectra Transducer Assembly

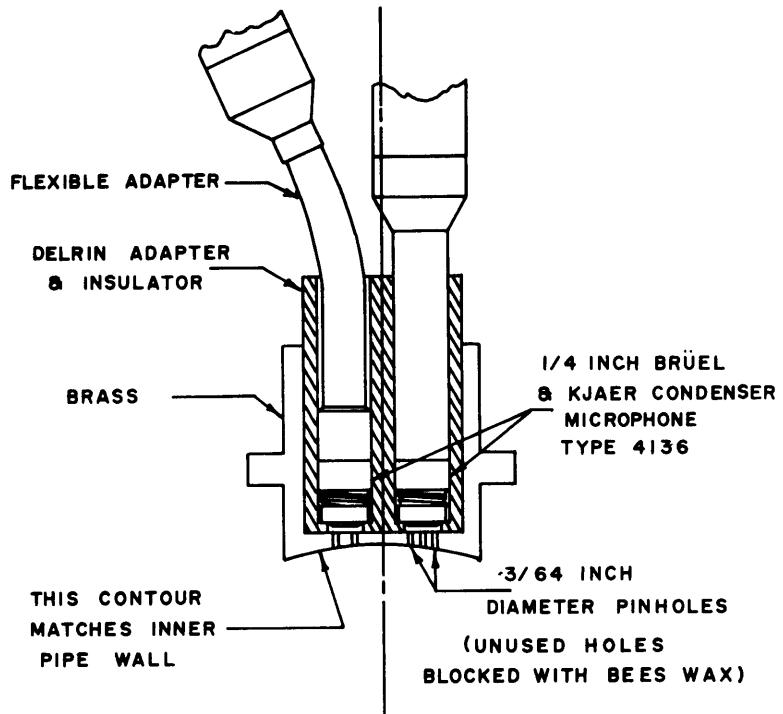


Figure 3 - Schematic Diagram of Cross Spectra Transducer Assembly (Transverse Alignment Shown)

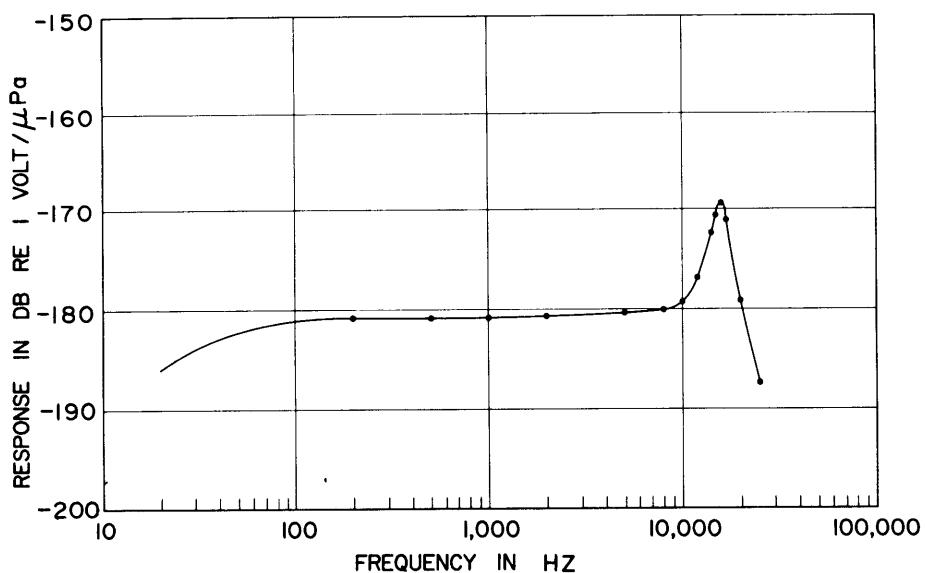


Figure 4 - Frequency Response of Pinhole Microphone

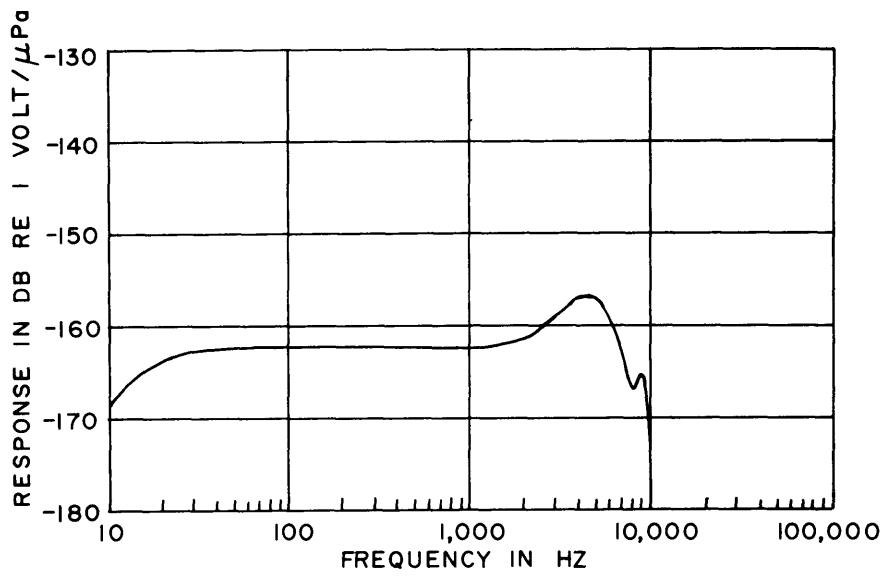


Figure 5 - Frequency Response of 1/2-Inch Transducer

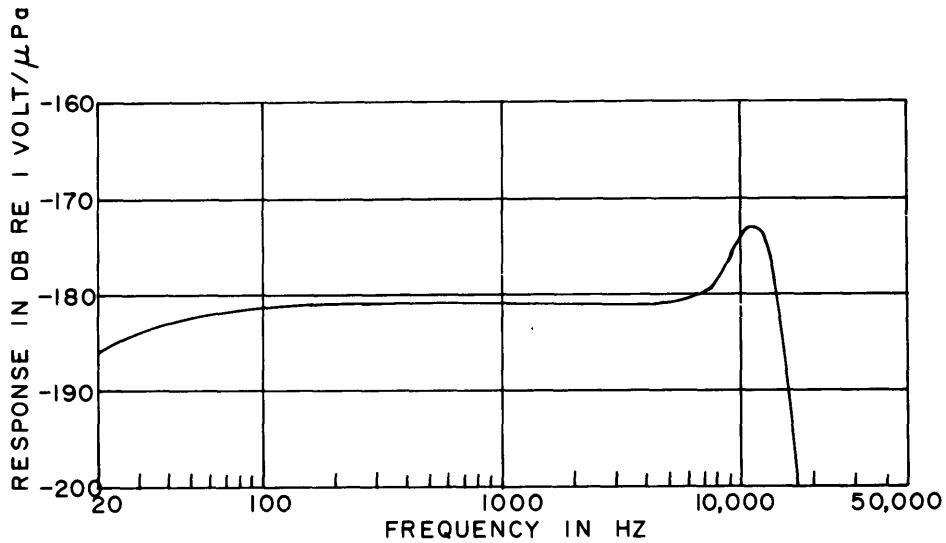


Figure 6 - Frequency Response of Cross Spectra Transducer Element

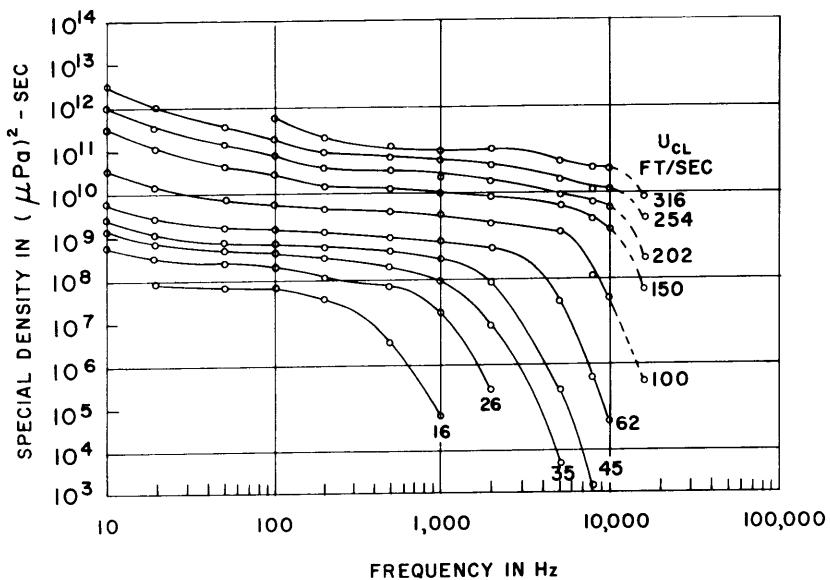


Figure 7 - Power-Spectral Density of the Pressure
at the Pipe Wall

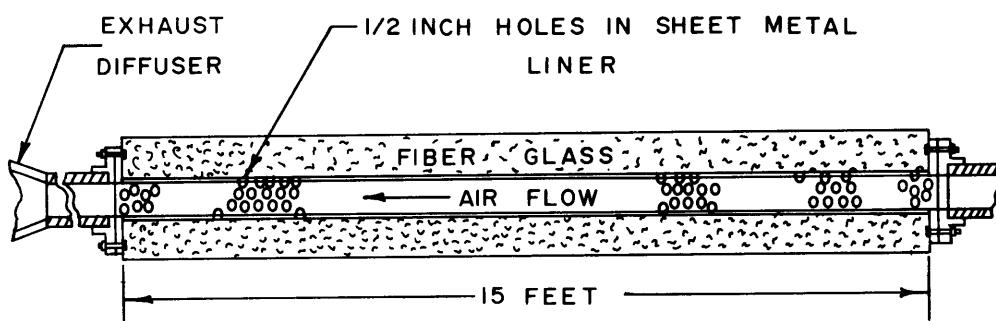


Figure 8 - Exhaust Muffler Schematic

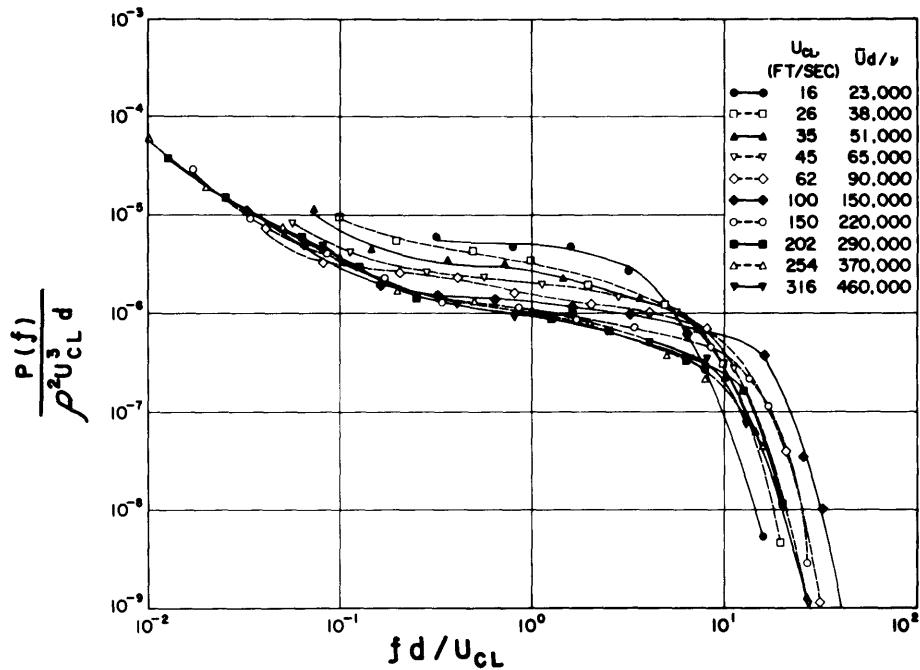


Figure 9 - Dimensionless Spectral Density of the Pressure

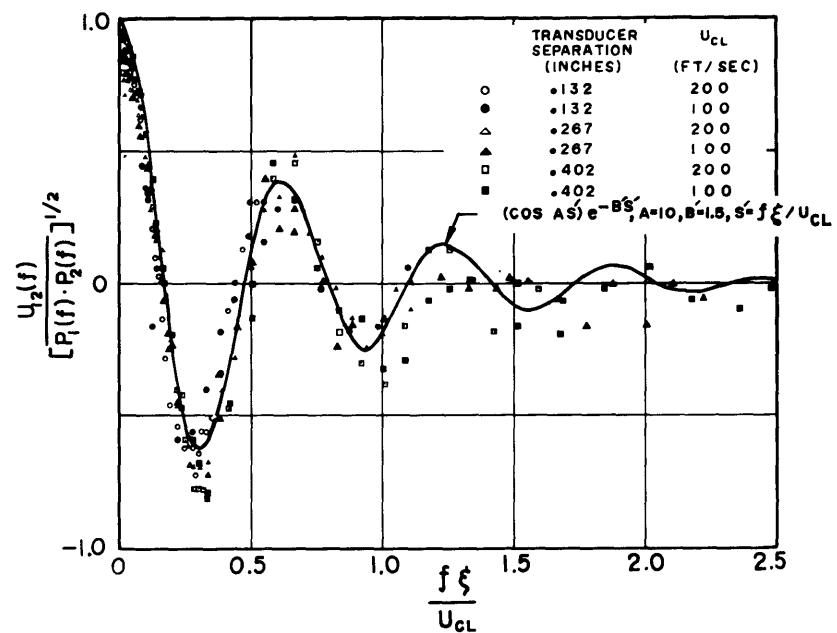


Figure 10 - Real Part of Normalized Cross-Spectral Density (Longitudinal)

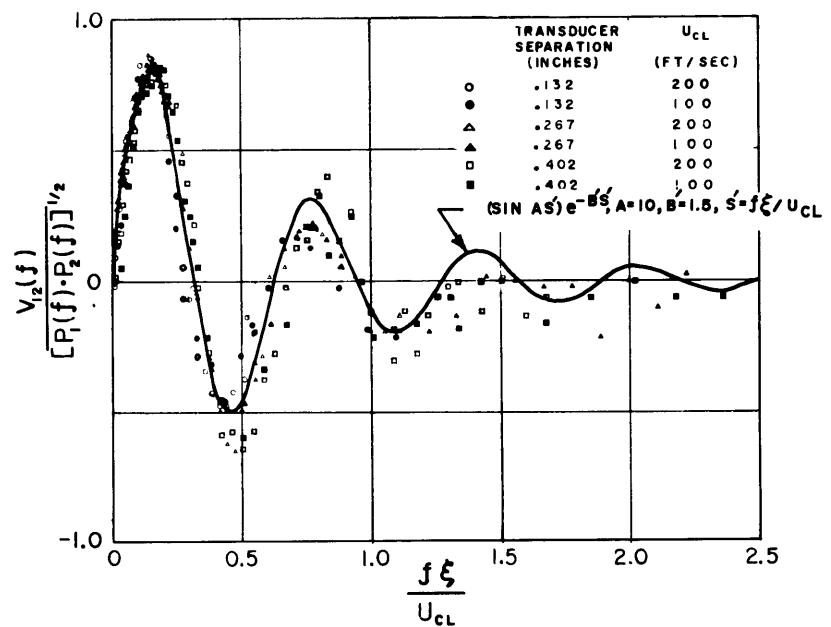


Figure 11 - Imaginary Part of Normalized Cross-Spectral Density (Longitudinal)

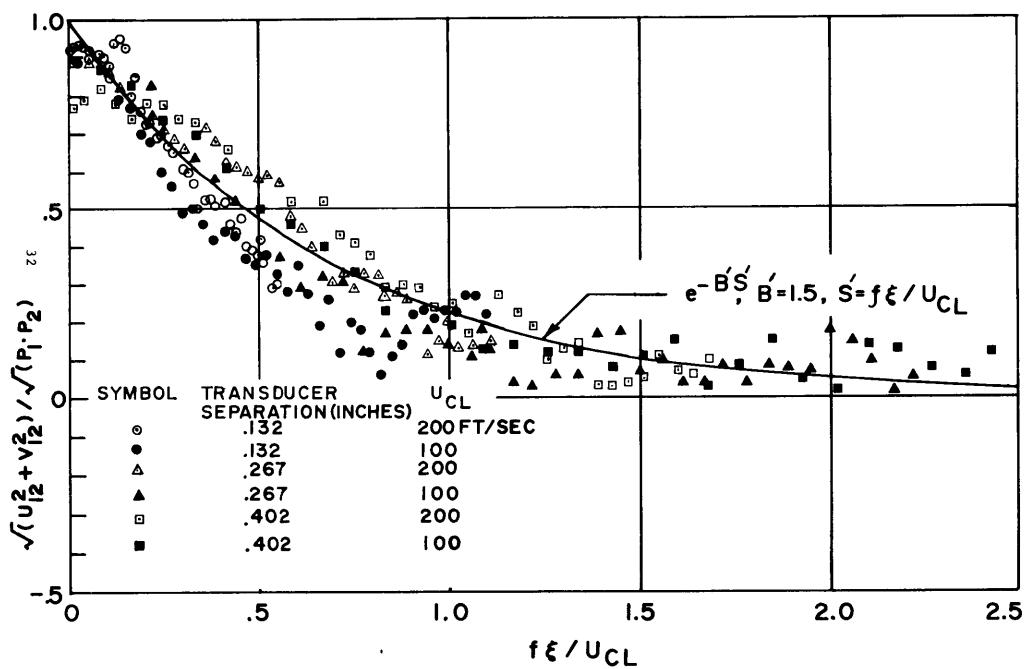


Figure 12 - Normalized Modulus

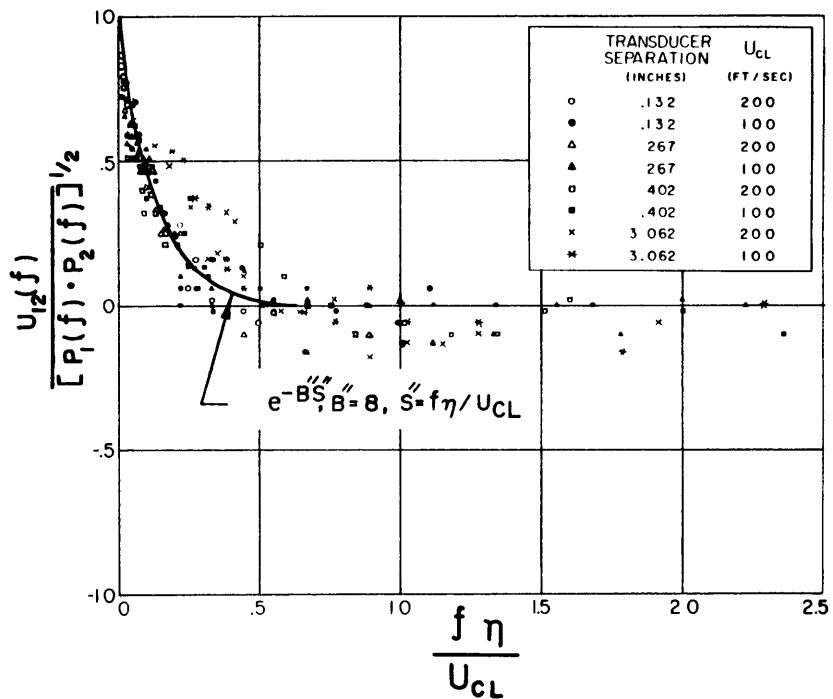


Figure 13 - Normalized Cross-Spectral Density
(Transverse)

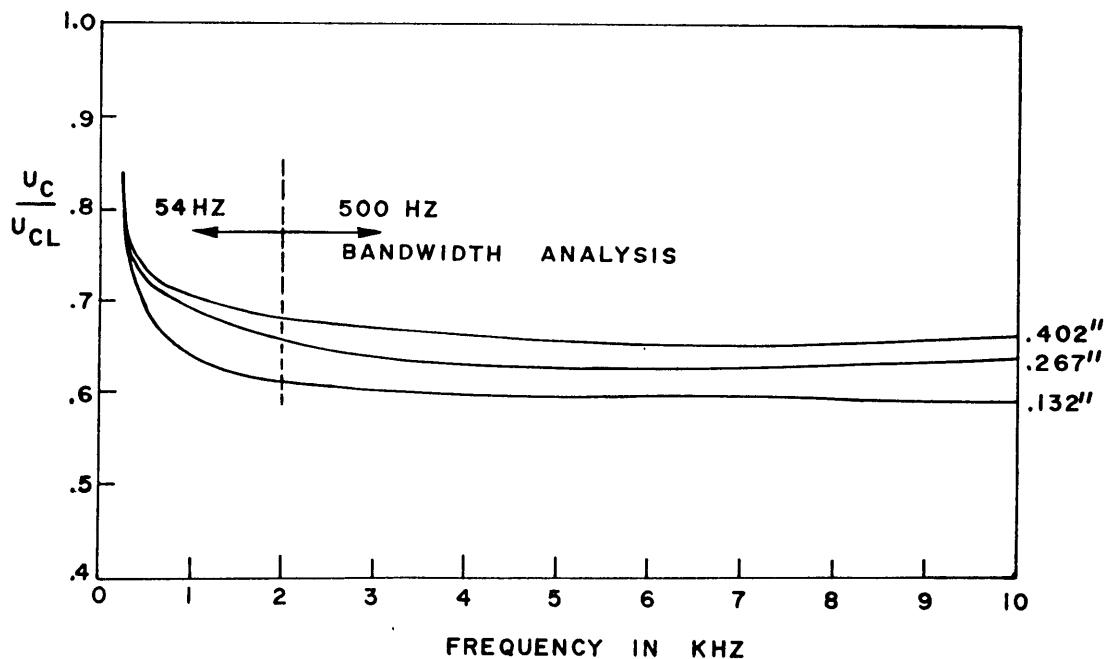


Figure 14 - Average Ratios of Convection and Centerline Velocity for Longitudinal Transducer Separations of 0.132 In., 0.267 In., and 0.402 In. for $U_{CL} = 100$ and 200 Feet/Sec

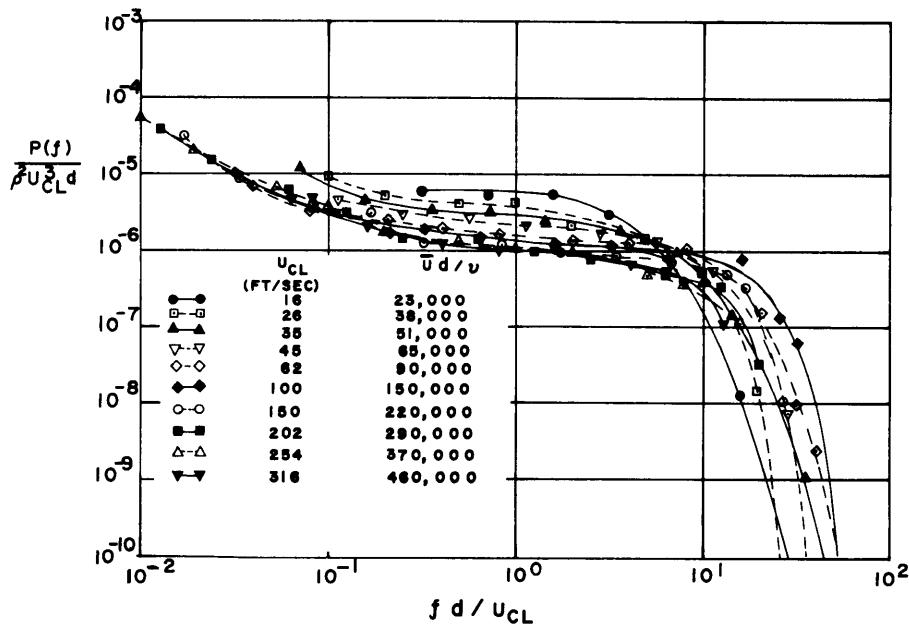


Figure 15 - Dimensionless Spectral Density of the Pressure Corrected for Transducer Size Effects

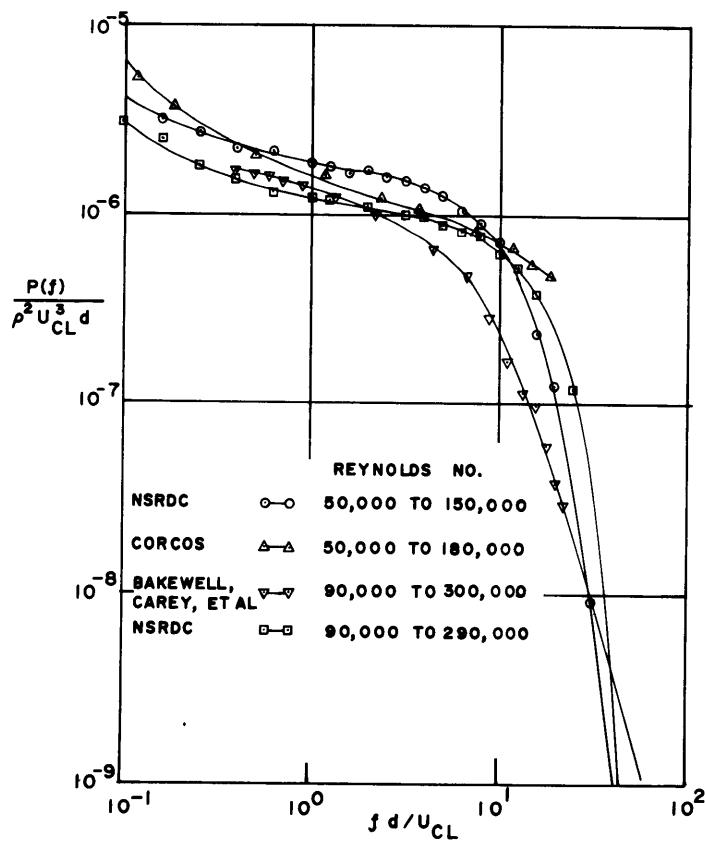


Figure 16 - Comparison of Dimensionless Spectra with Results of Other Investigators

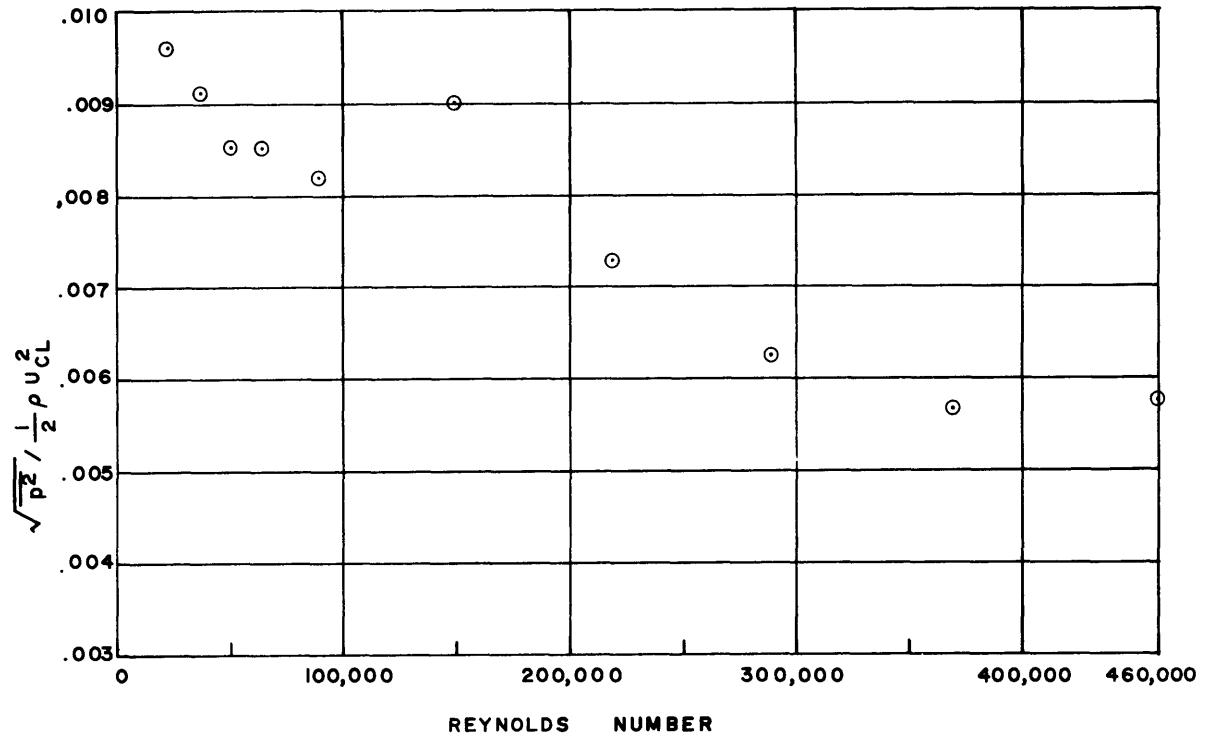


Figure 17 - RMS Pressure versus Reynolds Number

REFERENCES

1. Schlichting, H., "Boundary Layer Theory," Sixth Edition, McGraw-Hill, New York (1968).
2. McCormick, M. E., "Turbulent Boundary-Layer Induced Vibrations of Ribbons," Ph.D. Dissertation, Catholic University, Washington, D. C. (1966).
3. White, P. H., "Cross-Spectral Density of Pressure Field Behind an Infinite Plate Excited by Boundary Layer Turbulence," Measurement Analysis Corp., Report 602-1, Contract N167-275 (X), (Aug 1966).
4. White, P. H., "Transduction of Boundary-Layer Noise by a Rectangular Panel," JASA, Vol. 40, No. 6, pp. 1354-1362 (Dec 1966).
5. Maidanik, G., "Domed Sonar System," JASA, Vol. 44, No. 1 (Jul 1968).
6. Heckl, M., "Sound Radiation from Plates Excited by Oscillating Hydrodynamic Pressure Fields," NAVSHIPS translation 1139 (Aug 1968).
7. Strawderman, W. A. and Brand, R. S., "Turbulent-Flow-Excited Vibration of a Simply Supported, Rectangular Flat Plate," JASA, Vol. 45, No. 1 (Jan 1969).
8. Powell, A., "Aerodynamic Noise and the Plane Boundary," JASA, Vol. 32, No. 8, pp. 982-990 (Aug 1960).
9. Corcos, G. M., "Resolution of Pressure in Turbulence," JASA, Vol. 35, No. 2 (Feb 1963).
10. Gilchrist, R. B. and Strawderman, W. A., "Experimental Hydrophone-Size Correction Factor for Boundary-Layer Pressure Fluctuation," JASA, Vol. 38, No. 2, pp. 298-302 (Aug 1965).
11. Chandiramani, K. L., "Interpretation of Wall Pressure Measurements Under a Turbulent Boundary Layer," Bolt Beranek and Newman Report 1310 (Aug 1965).
12. Geib, F. E., Jr., "Measurements on the Effect of Transducer Size on the Resolution of Boundary-Layer Pressure Fluctuations," JASA, Vol. 46, No. 1, Pt. 2, pp. 253-261 (Jul 1969) and NSRDC Report 3286 (Jan 1970).
13. Geib, F. E., Jr. and Remmers, G. M., "Measurement of Wall Pressure Fluctuations with a Wave-Vector Filter," NSRDC Report 3370 (Apr 1970).

14. Maidanik, G. and Jorgensen, D. W., "Boundary Wave-Vector Filters for the Study of the Pressure Field in a Turbulent Boundary Layer," JASA, Vol. 42, No. 2, pp. 494-501 (Aug 1967).
15. Kinsler, L. E. and Frey, A. R., "Fundamentals of Acoustics," Second Edition, John Wiley and Sons, New York (1962).
16. Revin, A. N. and Cheysak, V. A., "Soviet Physics Acoustics," Vol. 26, Pt. 2, p. 246 (Oct-Dec 1960).
17. "Development of Noise Measurement Techniques and Procedures for Use in Fluid Piping Systems," CONESCO, Inc. Report F-123-1 (Apr 1964), p. 48.
18. Corcos, G. M., "Pressure Fluctuations in Shear Flows," University of California, Inst. of Engr. Research, Berkeley, California, Series 183, No. 2 (Jul 1962).
19. Jorgensen, D. W., "Measurements of Fluctuating Pressures on a Wall Adjacent to a Turbulent Boundary Layer," David Taylor Model Basin Report 1744 (Jul 1963).
20. Hodgson, T. H., "Pressure Fluctuations in Shear Flow Turbulence," College of Aeronautics, Cranfield University of England, COA Note 129 (May 1962).
21. Taylor, G. I., "The Spectrum of Turbulence," Proc. Roy. Soc. A., Vol. 1964, p. 476 (Feb 1938).
22. Von Winkle, W. A., "Some Measurements of Longitudinal Space-Time Correlations of Wall Pressure Fluctuations in Turbulent Pipe Flow," University of California, Inst. of Engr. Research, Berkeley, California, Series 82, Issue 20 (Sep 1961).
23. Bakewell, H. P. et al., "Wall Pressure Correlations in Turbulent Pipe Flow," Naval Underwater Sound Laboratory Report 559 (Aug 1962).
24. Maidanik, G., "System of Small Size Transducers as Elemental Unit in Sonar System," presented in part at the 74th Meeting of the Acoust. Soc. of Am., Miami Beach, Florida (13-17 Nov 1967) also JASA, Vol. 42, No. 2, pp. 494-501 (Aug 1967).
25. Carey, G. F. et al., "Acoustic Turbulent Water-Flow Tunnel," JASA, Vol. 41, No. 2, pp. 373-379 (Feb 1967).

INITIAL DISTRIBUTION

Copies	Copies
1 NAVSHIPS (037)	1 Res and Dev Div, Mech Tech, Inc., Latham, N. Y. Attn: Dr. Thomas J. Black
1 NRL	1 The Book Home Colorado Spring, Colorado
2 ONR 1 Technical Library 1 Code 468	1 Ling Electronics, Eng Lib Attn: Miss Diana R. Allen
2 NAVUWSYSCEN NLON 1 Code 2112 1 Code 2113	1 Acoustical Consultants, Inc. San Francisco, Calif
1 U.S. Naval Academy, Annapolis, Md. Attn: Dr. Bruce Johnson	1 Lockheed Missiles & Space Co. Huntsville Res and Eng Center Attn: Mr. W.H. Craft
1 NAVSEARAND CEN Pasadena Code 2501	1 Bolt Beranek and Newman, Inc. Attn: Mr. Peter A. Franken
1 Purdue University School of Mech Eng Attn: Mr. Robert C. Chanaud	1 Worthington Corp., Harrison, New Jersey Attn: Mr. J. Biheller
1 Herrick Laboratories School of Mech Eng Purdue University Attn: Mr. H. Khosrovani	1 Vickers Inc., Detroit, Mich Attn: Mr. Don E. Kennamer
1 University of California Dept of Mech Eng Attn: Prof. W.W. Soroka	1 Esso Res and Eng Co., Florham Pk, N. J. Attn: Mr. W.M. Cooper, Jr.
1 University of Minnesota Inst of Technology Attn: Librarian	
1 Colorado State University Fort Collins, Colorado Attn: Dr. L. V. Baldwin	
1 Boeing Co., Missile and Information System Div Attn: Dr. J.M. Hermanson	

CENTER DISTRIBUTION

Copies	Copies	Code
1 19 D. Ross	1 194 G. Franz	
1 1901	16 1942	
1 1908	10 F.C. DeMetz	
1 1935	5 D.W. Jorgensen	
	1 J. Shen	

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Naval Ship Research and Development Center Bethesda, Maryland 20034	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED
	2b. GROUP

3. REPORT TITLE

MEASUREMENT OF THE BOUNDARY-LAYER PRESSURE FLUCTUATIONS ASSOCIATED WITH TURBULENT AIR FLOW IN A RIGID PIPE

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Report

5. AUTHOR(S) (First name, middle initial, last name)

Fred C. DeMetz and Donald W. Jorgensen

6. REPORT DATE October 1971	7a. TOTAL NO. OF PAGES 27	7b. NO. OF REFS 25
8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S) 3707	
b. PROJECT NO SF 35 452 007 c. Task 01356 d.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	

10. DISTRIBUTION STATEMENT

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY NAVSHIPS Code 037
-------------------------	---

13. ABSTRACT

This report gives the results of an experimental investigation of the pressure fluctuations associated with turbulent flow in a rigid pipe. Measurements were made of the power-spectral and cross-spectral densities of the pressure fluctuations on the pipe wall for fully developed turbulent air flow over a Reynolds number range of approximately 20 to 1. The variation in Reynolds number was achieved by variation in flow velocity; in this experiment the centerline velocity U_{CL} was varied from 16 ft/sec to 316 ft/sec. The spectral content of the pressure field was investigated for frequency components from 10 to 10,000 Hz. Special attention was given to obtaining spectral levels for the low-frequency components of the pressure field because of the nature of the power spectral density in the low wave-number region for turbulent pipe flow is still uncertain.

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Pressure Fluctuations						
Turbulent Pipe Flow						
Boundary-Layer Pressure Fluctuations						
Turbulent Pressure Field						
Fully Developed Turbulent Pipe Flow						
Forcing Function						
Pipe Flow						

MIT LIBRARIES

DUPL



3 9080 02753 7379

