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THE SPECTRAL SHAPE OF FLOW NOISE, TURBULENCE AND WALL PRESSURE --ETC(U)
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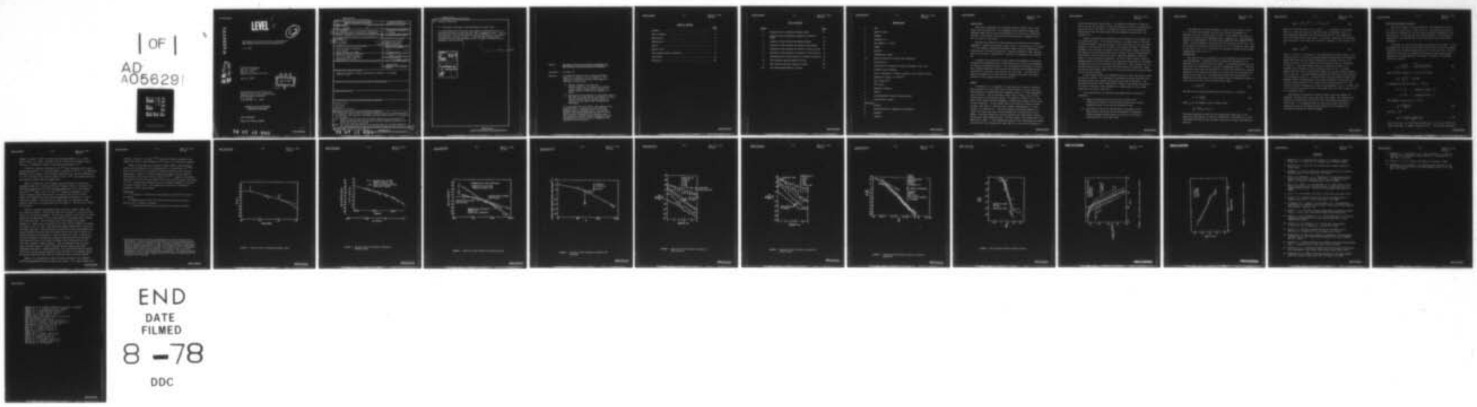

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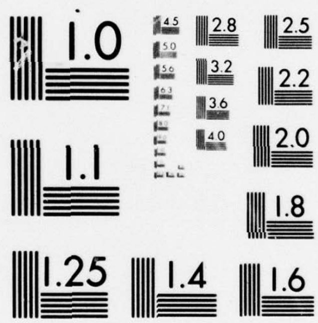

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THE SPECTRAL SHAPE OF FLOW NOISE, TURBULENCE AND WALL PRESSURE FLUCTUATIONS AND INTERRELATION

J. P. Clay

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An elementary model of how a turbulent boundary layer (b.l.) generates noise is analyzed. Two similarity hypotheses are given which relate b.l. turbulence to flow noise.

I. Dynamic pressures come from the forces created by the interaction of eddies on the viscous sublayer where velocity components normal to the wall are brought to rest. and

II. The forces are proportional to the second power of the eddy velocities and the distribution of separation distance between pressure points on → next page

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20. Abstract (Continued)

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It is concluded that flow noise, wall pressure fluctutations and b.l. turbulence all have the same spectral shape in frequency space. Data on wall pressures fluctuations generally have a $f^{-11/3}$ form due to spatial averaging by the pressure sensor. Corrections for pressure sensor averaging are given and experimental data is given to demonstrate the validity of the correction.

f to the -11/3 power

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NOMENCLATURE

A	area
c	speed of sound
D	diameter
f	frequency, Hz
k	wave number, $k = U/2\pi f$
L	length
p	pressure
r	radius/sensor radius
u,v	velocity deviation from mean (one component)
U	mean velocity
α	coefficient for turbulence inertial subrange (~0.55, 1-D)
δ	boundary layer thickness
ε	rate of disipation of kinetic energy per unit volume of fluid
η	Kolmogoroff length, $\eta = (\nu^3/\varepsilon)^{1/4}$
λ	wave length λ=U/f
μ	10^{-6} metres
ν	kinematic viscosity
ρ	density
ϕ	one dimensional velocity energy spectrum
ω	radians/sensor radius

Subscripts

a	acoustic
K	dimensionalized as suggested by Kolmogoroff
m	measured
v	velocity

Introduction

Flow noise is generated by a turbulent boundary layer's (b.l.) interaction with the rigid wall. The experimenal data reported by Haddle and Skudrzyk (1969) show the flow noise falling off at the rate of 5 dB/octave. The data of Clay (1973) illustrates that the spectrum of turbulence falls off at a rate of 5 dB/octave.

The spectral properties of wall pressure fluctuations are not clearly understood. Foxwell and Grandshaw (1968) report a correlation of f^{-4} with an f^{-2} at the highest frequencies and Foxwell (1966) reports an additional f^{-1} correlation at the lowest frequencies. Haddle and Skudrzyk (1969) indicate that the flow noise is dominated by turbulence at frequencies above 200-500 Hz.

A review of the literature on wall pressure fluctuations by the author revealed much experimental data of high quality but a lack of understanding of the basic phenomena involved. It is the purpose of this paper to discuss how turbulence generates flow noise and the statistically averaged spectral properties of turbulence, wall pressure and flow noise. A correction for spatial averaging by the sensor will be presented along with a new interpretation of the measured wall pressure spectra.

Theory

A turbulent b.l. is composed of a rigid wall and a layer of turbulent fluid separated by a very thin layer of fluid called the viscous sub layer. The turbulence is characterized by a Reynold's stress, or, three dimensional (3-D) vorticies. One can visualize a single eddy as being a cup of coffee stirred about the cylindrical surface. To construct a model of a b.l. one metre thick, suppose one had cylinders of random sizes ranging from one metre to 1 mm in diameter. If one stacked them on the floor on a piece of carpet to make a wall about 1 m high one has a simple representation of a cross section of a turbulent b.l. The floor represents the rigid boundary, the carpet the viscous sub layer and the cylinder the vortical motion of the eddies. The actual eddies are 3-D and therefore have simultaneous vortical motion about three orthogonal axis. For this reason, actual eddies tend to be spherical in shape. In the hypothetical model, an eddy represented by a "drinking straw" may be a "mixing bowl" sized eddy in a cross section displaced a few cm from the model cross section. 3-D eddies are difficult to visualize so we will use the cylinders. If one now visualizes a fork lift rapidly pushing on one end of the "wall" of cylinders such that the top cylinders are moving faster than the bottom ones; one has completed the modeling of the turbulent b.l.

Pressure fluctuations are generated by the interaction of the eddies and the viscous sub layer. If the local velocity of an eddy, normal to the wall, is quickly brought to rest at the wall, a local force equal to the total head pressure of the eddy ($1/2\ \rho v^2$) is made on the viscous sub layer. The energy available to be converted to acoustic noise is the kinetic energy of the eddy. The eddies on the viscous sub layer are not circular, but are flattened where they interact with the viscous sub layer. Where the eddies are flattened there is a local high and low pressure. The local "high" pressure areas are randomly spaced on the wall based on the random size and packing of the eddies. The amplitude of the local pressures are random also. The turbulent flow is a stochastic process but it has clearly defined statistical properties. There are interactions between eddies also but the main interaction is between eddies and the viscous sub layer.

A local "high pressure" area immediately acts to relax the system to make the pressure uniform. The relaxation is performed by moving fluid away from the high pressure area through force equals mass times acceleration. The acceleration process travels "spherically" outward at the speed of sound and is called a sound wave. The collection of a large number of these random sound waves is called "flow noise."

It is proposed that two similarity hypotheses relate flow noise to turbulence:

I. Dynamic pressures come from the forces created by the interaction of eddies on the viscous sub layer where velocity components normal to the wall are brought to rest.

II. The impulsive forces are proportional to the square of the eddy vortical velocities and the distribution of separation distance between pressure points on the wall is the same as the distribution of the eddy sizes.

One consequence of these hypotheses is that the power spectra of the b. l. velocity, wall pressure and flow noise plotted as magnitude vs frequency will have a single spectral form. In this paper, flow noise is defined as acoustic noise originating from a turbulent b.l. These acoustic signals are superimposed on the flow noise to make the total radiated noise field. The wave lengths of turbulence and flow noise are not the same. The wave length of turbulence and wall pressure is $\lambda_v = U/f$ while the wave length of flow noise is $\lambda_a = c/f$. The theory of turbulence discussed below assumes incompressible flow so $U/c \ll 1$.

Spectral Form

The spectral form of turbulence is well established both theoretically and experimentally. Kolmogoroff (1941) proposed two hypotheses on the similarity of all turbulent velocity fields. The hypotheses assume that the flow fields are incompressible, isotropic, homogeneous and $Re \to \infty$. The first hypothesis states that the distribution of velocity fluctuations is uniquely determined by the kinematic viscosity (ν) and the mean rate of energy dissipation per unit mass (ε). This hypothesis implies that fluid motion is dominated by viscous forces at scales smaller than the Kolmogoroff length (η) and by inertial forces at scales larger than η where

$$\eta \equiv (\nu^3/\varepsilon)^{1/4} \quad . \tag{1}$$

The mean rate of energy dissipation per unit volume, ε, is given by

$$\varepsilon \equiv 2\,\nu\,\overline{e_{ij}e_{ij}} \tag{2}$$

where e_{ij} is the symmetric rate of strain tensor

$$e_{ij} \equiv \frac{1}{2}\,(u_{i,j} + u_{j,i}) \quad . \tag{3}$$

The second hypothesis states that for lengths much larger than η, the statistical distribution of velocity fluctuations is determined by ε alone. This hypothesis implies that the power spectrum of velocity fluctuations is given by

$$\phi(k) = \alpha\, \varepsilon^{2/3}\, k^{-5/3} \quad , \quad L^{-1} \ll k \ll \eta^{-1} \qquad (4)$$

where k is wave number given by $k = 2\pi f/U$. The range of k for which eqn. (4) is valid is called the "inertial" power law subrange. There is a third similarity hypothesis which slightly modifies the -5/3 exponent but is not of significance in this paper. If one were to make eqn. (4) dimensionless using ε and ν one obtains the "universal" equation of all turbulent flow of

$$\phi_K(k) = \alpha\, k_K^{-5/3} \qquad (5)$$

where $\alpha \simeq 0.55$ for a 1-D spectrum. The experimentally measured values of 1-D α range from 0.3 to 0.6 with low numbers generally coming from "low" Reynold's number (Re) flows with the author estimating the "correct" value as 0.55. Actual turbulent b.l. have a finite Re and the spectral form is illustrated in Figure 1. The largest length scale of the inertial subrange is the boundary layer thickness (δ) and the smallest scale is 10η. At scales smaller than 10η, viscous forces become significant and the spectrum exponentially "rolls off." An experimentally measured and normalized velocity spectrum is illustrated in Figure 2. A radiated noise spectrum reported by Haddle and Skudrzyk (1969) is superimposed on the velocity spectrum. The acoustic spectrum was shifted parallel to the x and y axis to obtain the best fit. The curve fit implies a frequency of 46 kHz as corresponding to η or $\eta = c/20\pi f = 50\mu$. It is the author's experience that η will range from 10 to 100μ in water so 50μ is a reasonable value.

The dilemma is illustrated in Figure 3 which illustrates Haddle and Skudrzyk's original three curves with slope lines added. The radiated noise curves fit the predicted -5/3 slope but the wall pressure spectrum fits a -11/3 slope. It is suggested that the actual wall pressure spectrum is identical in form to the radiated noise spectrum but the measured wall spectrum is distorted by sensor averaging.

Wall Pressure Sensor Correction

The data of Figure 3 was obtained with D = 2.54 cm sensors. At 30 kHz $L_a = 2c/\pi f = 3.2$ cm but $L_v = 2U/\pi f = 0.03$ cm. The spatial resolution of the sensors is adequate for the flow noise but grossly inadequate for the wall pressure. If one knew what the sensors measured, one could apply a correction to the measured data to get the spectral form of the actual phenomenon.

The sensor is a flat circular disk in contact with a 3-D eddy. It will be assumed that the eddy has a circular cross section and that the pressure distribution of the eddy is given by cos ωr for $-\pi/2 \leq \omega r \leq \pi/2$. For this analyses all distances are normalized by the sensor radius and pressure amplitude by the peak amplitude of the eddy of interest. The measured pressure is given by

$$p_m = \frac{\int p\, dA}{A} = \frac{\int_o^1 \cos(\omega r)\, 2\pi r\, dr}{\pi} \quad . \tag{6}$$

With a variable change of $u = \omega r$, eqn (6) becomes

$$p_m = \frac{2}{\omega^2} \int_o^{\omega} u \cos u du \quad . \tag{7}$$

A constraint on eqn (7) is that $\omega \leq \pi/2$ so

if $\omega > \pi/2$, integration limit = $\pi/2$

$\omega < \pi/2$, integration limit = ω .

The integral of eqn (7) for $\omega \geq \pi/2$ is

$$p_m = \frac{2\,(\pi/2 - 1)}{\omega^2} \tag{8}$$

and for $\omega < \pi/2$

$$p_m = 2\,\frac{(\cos\omega + \omega\sin\omega - 1)}{\omega^2} \quad . \tag{9}$$

For $\omega = \pi/4$, $p_m = -0.7$ dB (re actual value), at $\omega = \pi/2$, $p_m = -3.35$ dB and falls 6 dB/octave at higher frequencies (f^{-2}). The critical diameter or length of a sensor (-3dB) for velocity pressure measurements is $\eta_v = 2U/\pi f$ and for sound, $\eta_a = 2C/\pi f$. From Eqn. (8) it is seen that for sensors larger than $\eta_{v,a}$, the measured signal is attenuated proportional to ω^{-2}.

If one has a spectral distribution of $f^{-5/3}$ and measures it with a sensor having sensitivity of f^{-2}, one will measure a spectrum of $f^{-11/3}$ or ~-11 dB/octave. Referring back to Figure 3, the location labeled $U/\pi D$ at ~ 200 Hz corresponds to $\omega = \pi/4$ (= 10.7dB) so one could not expect to get a $f^{-5/3}$ wall pressure spectrum, the sensor was larger than the largest eddy.

Figure 4 illustrates a wall pressure spectrum measured by Foxwell and Grandshaw (1968) with a 0.3175 cm (1/8 inch) diameter sensor. The region from 100-1500 Hz approximates an $f^{-5/3}$ inertial subrange and 1.5-2.5 kHz approximates an $f^{-11/3}$ slope. The $f^{-5/3}$ and $f^{-11/3}$ lines are separated by 3.3 dB at the frequency labeled $2U/\pi D$ which is consistent with the above theory. Foxwell and Grandshaw also made similar measurements with sensors 2, 4 and 8 times this diameter. The curve for the sensor twice as large had the same spectral shape with the break between the two slopes at ~ 750 Hz and at ~ 350 Hz for x4 sensor.

Figure 5 illustrates experimental data reported by Foxwell (1966) taken on a rotating cylinder. The data was taken with 4 sensors, D = 0.3175 cm (1/8 inch), x2, x4 and x8 in diameter. The data was corrected on the basis of +6 dB/octave with an additional +6 dB for each doubling of the sensor size to obtain the "corrected" data. The "corrected" data of the smallest two sensors collapse to a single line as expected but the data from the largest two sensors fall short of the -5/3 line. The reason the largest sensors fail is that they are simply too large. After applying the corrections to many experimental data curves the writer has found that the corrections are only valid to 40-45 dB. The corrections are not reliable at values in excess of 45 dB. A similar set of data by Foxwell is illustrated in Figure 6 with corrections by the author. The "corrected" data of the larger two sensors falls further short of the -5/3 line in Figure 6 than in Figure 5. This is consistent with the theory since the higher speed of Figure 6 produces smaller length scales which exacerbates the spatial averaging problem. The "corrections" made in Figures 5 and 6 are relative corrections made to keep the data on the original graphs. The actual corrections would shift the "corrected" data vertically upwards.

Figure 7 is a compilation of data of several scientists' wall pressure spectrum measurements with slope lines by the author. It's clearly evident that the data converges to a single $f^{-11/3}$ line at the highest normalized wave numbers and there is some evidence of $f^{-5/3}$ data at the lowest wave numbers.

Figure 8 illustrates data reported by Kirby (1968) on wall pressures spectra that illustrates that the measured data is proportional to $f^{-11/3}$. All of the data points to a problem of spatial averaging on wall pressure measurements. Figure 9 illustrates some recent data by Patrick (1977) on wall pressure spectra with spectral slope of $f^{-11/3}$*. Figure 10 illustrates some recent flow noise data by Lauchle (1977) with acoustic signal proportional to $f^{-5/3}$. The data was obtained from a flush mounted transducer in a region of laminar boundary layer. This minimizes the problem of superimposed pressures of eddies and acoustics.

Conclusions

1. The spectra of turbulence, wall pressure and radiated flow noise are similar.

2. Measured spectra falls of 6 dB/octave from the actual spectra when the data is spatially averaged.

3. A valid correction factor for large circular sensors is given.

* The power spectrum of velocity has dimensions of velocity squared per Hz. One obtains a pressure spectrum by multiplying the velocity power spectrum by $\rho/2$ to get units of pressure per Hz. The power spectrum of pressure has units of pressure squared per Hz. Most of the papers reviewed used pressure spectral density with units of pressure per Hz which has a 1:1 correlation to the velocity power spectrum density. The concept of dB is not very appropriate to use in correlating velocity and sound. The ordinate labeling of Patrick's data has been changed from dB (p^2/Hz basis) to p/Hz form to be consistent with the paper.

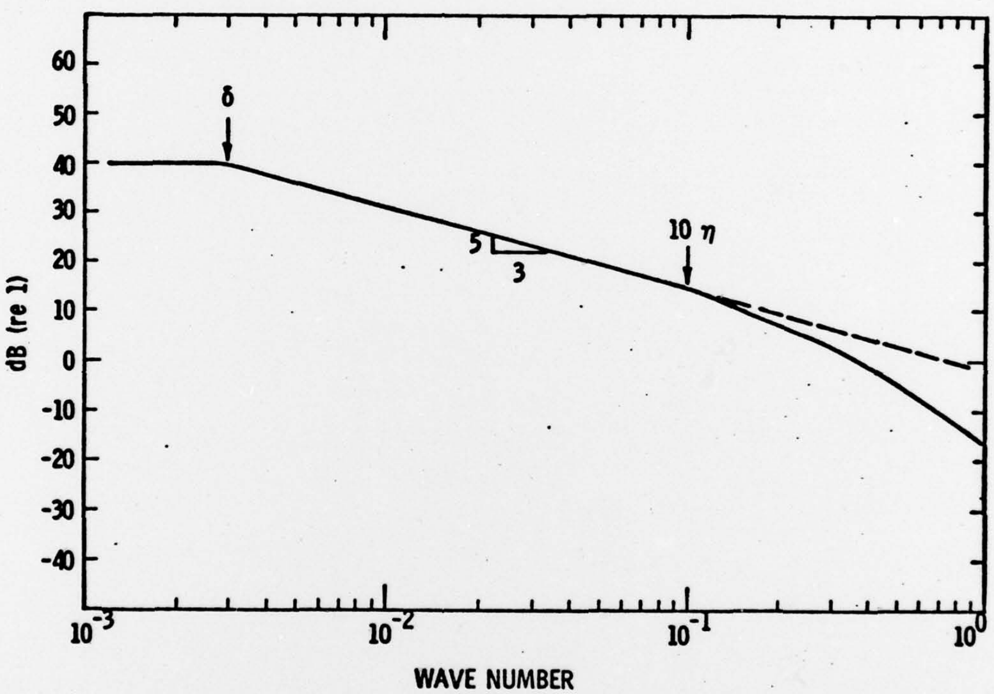

FIGURE 1. Spectral Form of Turbulent Boundary Layer

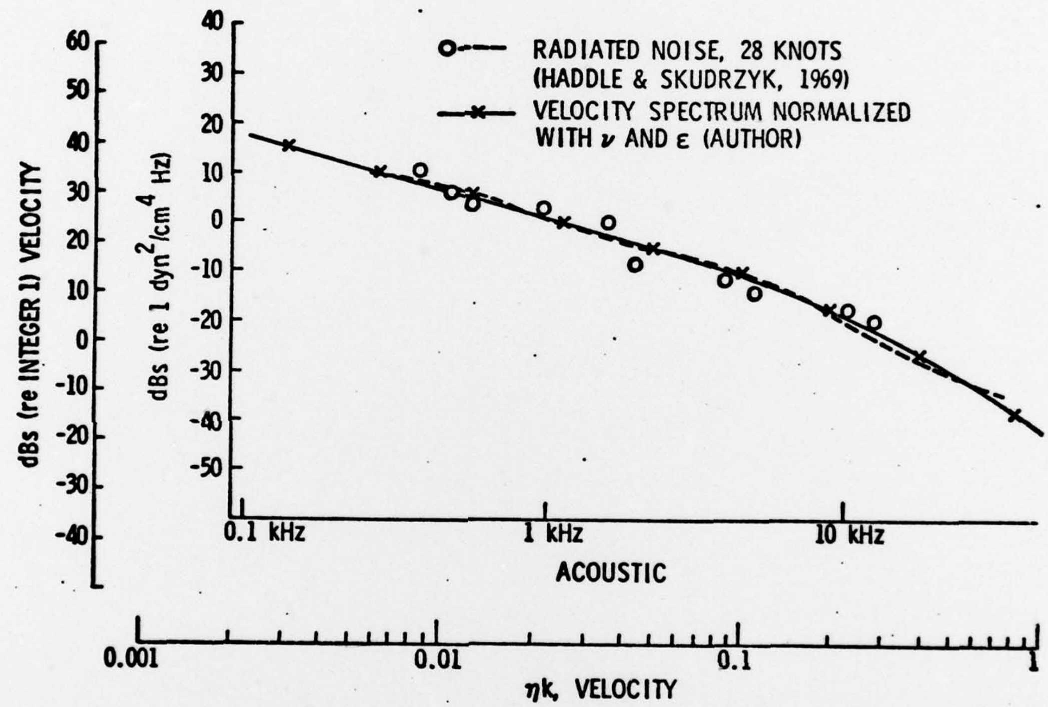

FIGURE 2. Spectral Form of Turbulence Compared to Radiated Noise

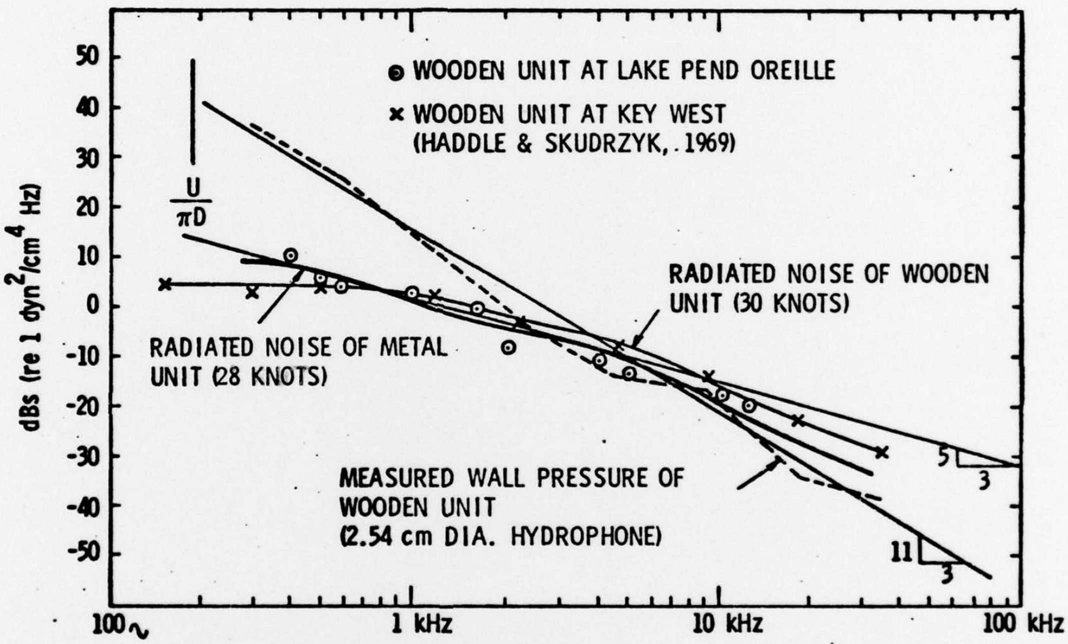

FIGURE 3. Spectra of Wall Pressure and Radiated Noise

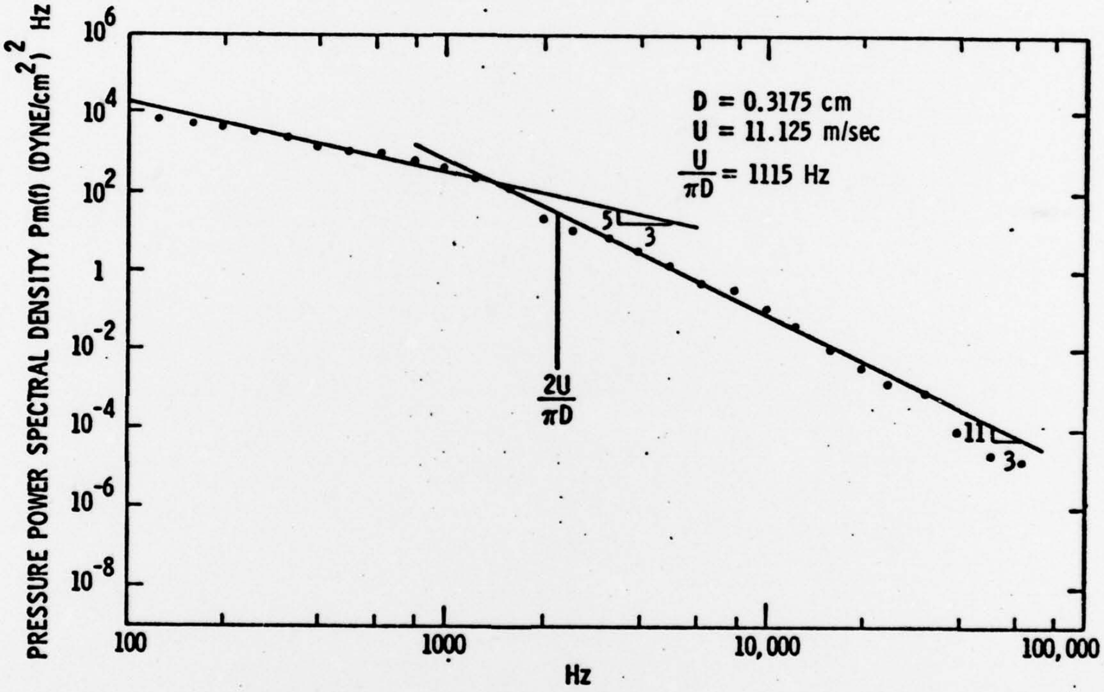

FIGURE 4. Spectrum of Wall Pressure by Foxwell and Grandshaw

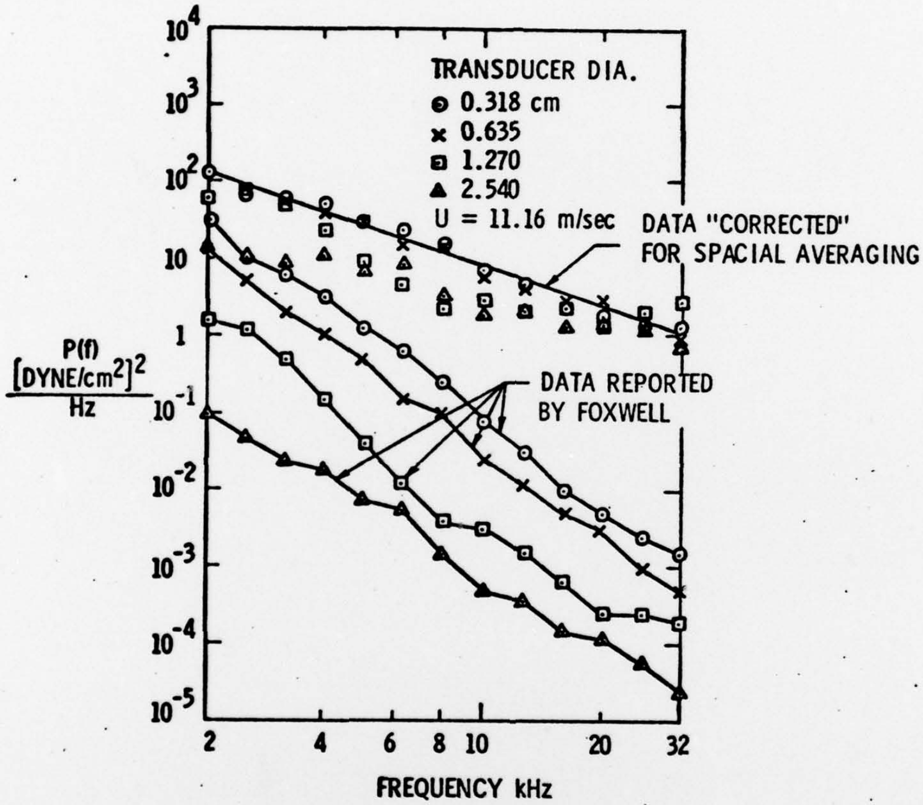

FIGURE 5. Spectrum of Wall Pressure by Foxwell at U=11.16 m/sec

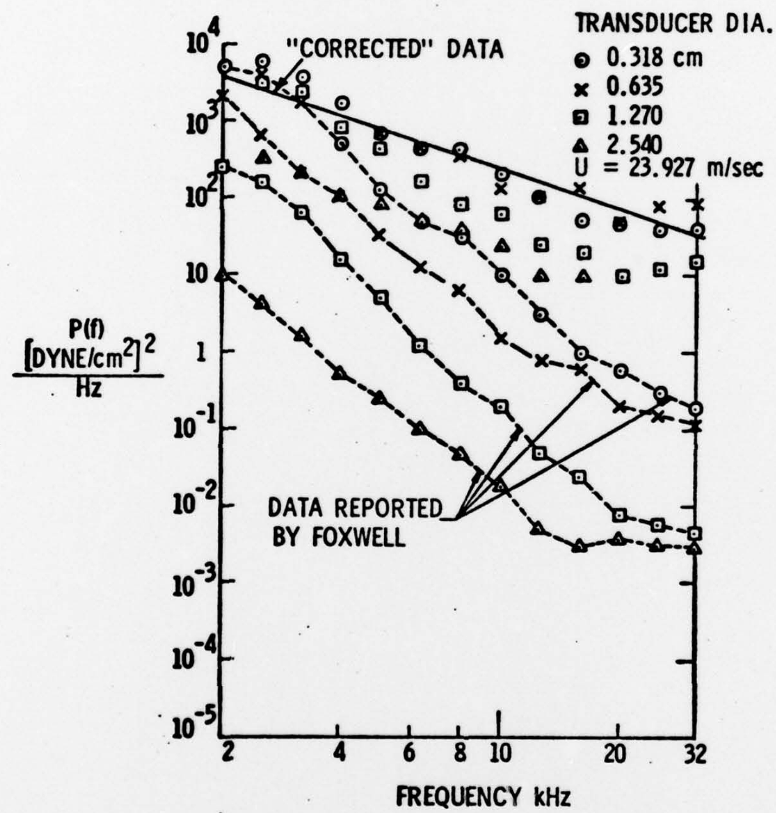

FIGURE 6. Spectrum of Wall Pressure by Foxwell at U=23.93 m/sec

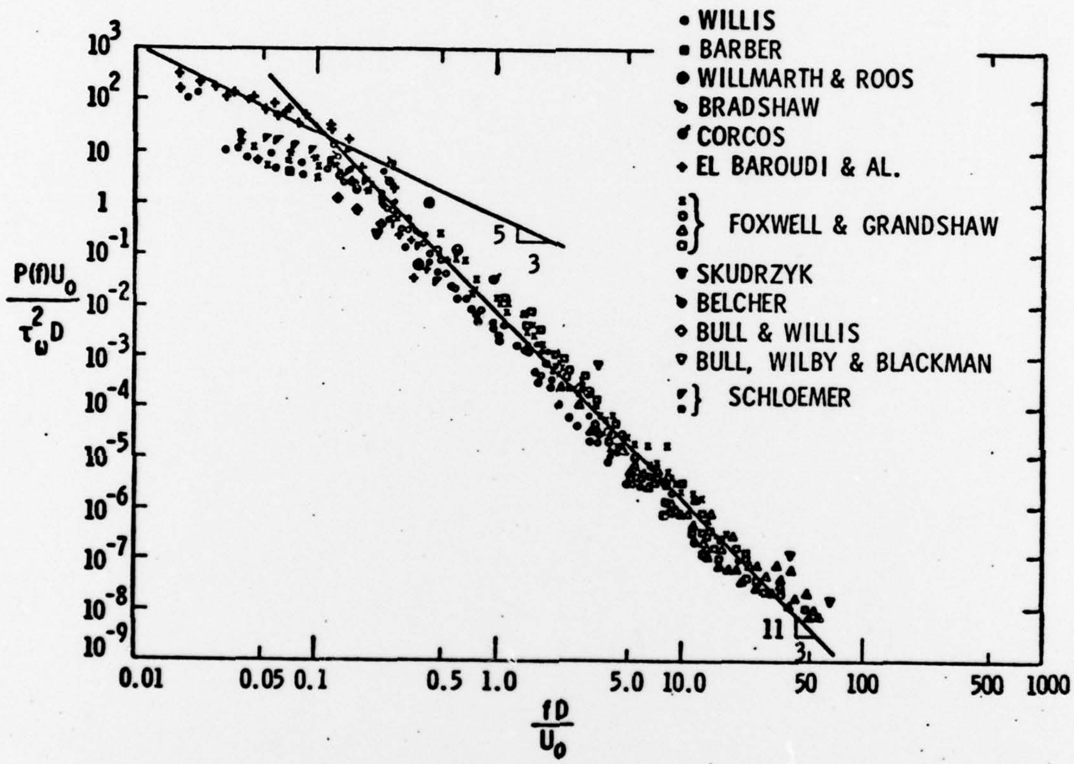

FIGURE 7. Normalized Wall Pressure Spectra of Various Scientists

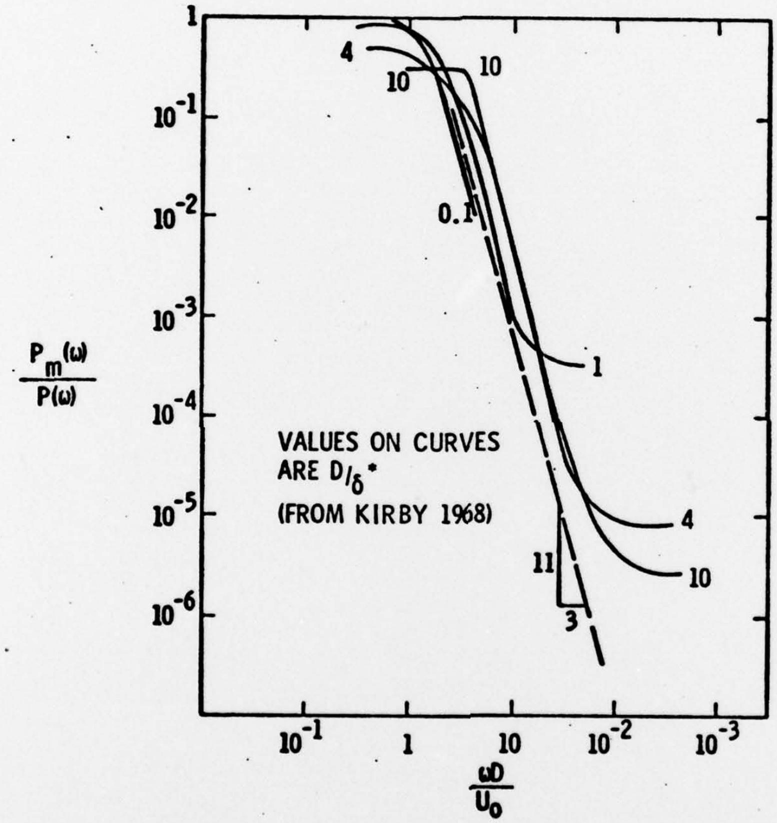

FIGURE 8. Wall Pressure Spectral Shapes by Kirby

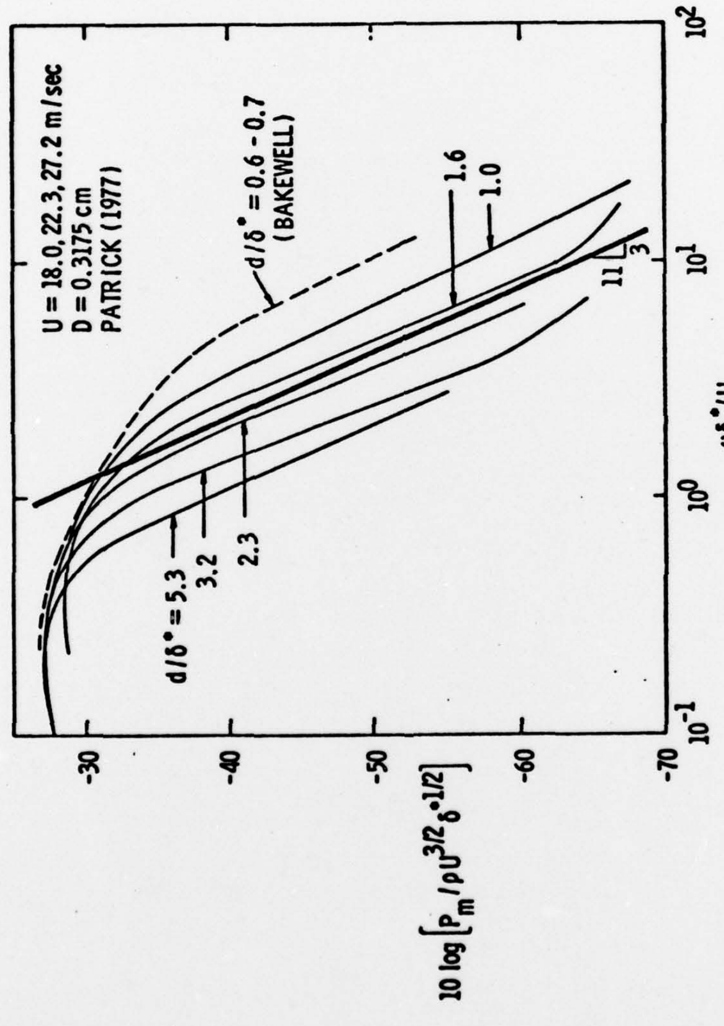

FIGURE 9. Wall Pressure Spectral Shapes by Patrick

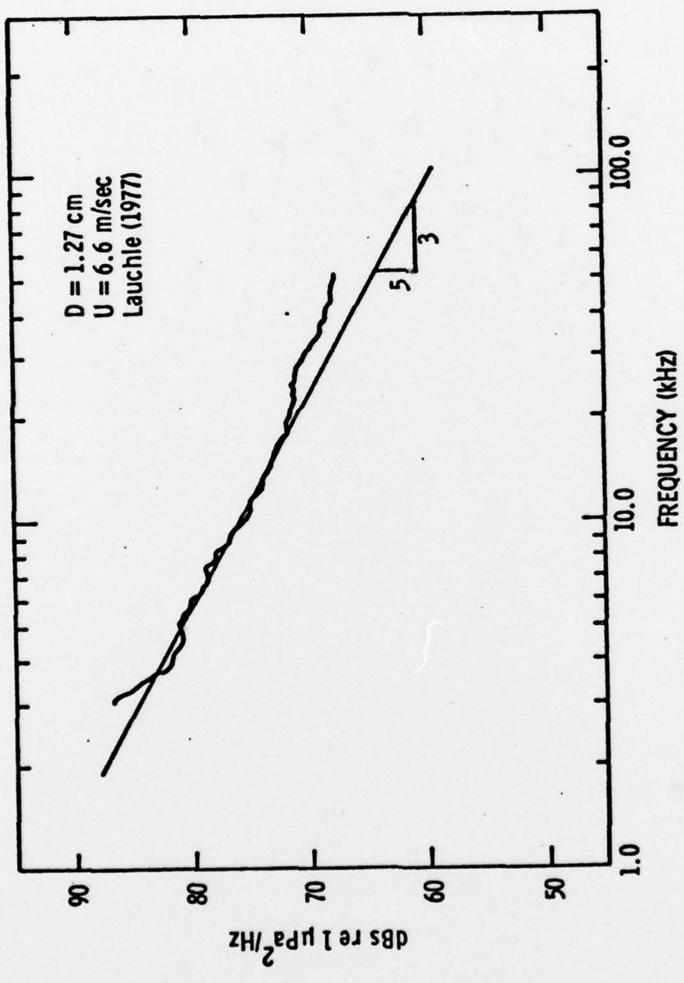

FIGURE 10. Flow Noise Measurements by Lauchle

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