# 22. A STUDY OF EXHAUST NOISE AS IT RELATES TO THE TURBOFAN ENGINE

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## SUMMARY

At the relatively low exhaust velocities of current and projected high-bypass-ratio engines, it may be expected that noise from the free expanding jet will be dominated by sources produced within the engine ducting by the exhaust stream. These sources will result from the highly turbulent flow within the duct and the interaction of this turbulence with surface discontinuities, struts, and the like.

An experimental program has been performed on a laboratory jet to study these new sources of exhaust noise. The influence of the insertion of discontinuities and obstructions into the jet pipe has been examined and related to the flow parameters. Results to date suggest that the acoustic power generated by a flow discontinuity can be correlated with the pressure drop which it produces in the flow.

These studies are felt to have significant bearing on the prediction and control of exhaust noise of current and future turbofan engines.

## INTRODUCTION

Perhaps the most fundamental result that can be elicited from aerodynamic noise theory describes the process whereby the intense turbulence in the exhaust stream of a jet engine generates sound. The theory predicts that the sound from this turbulence will increase with the eighth power of flow velocity. This result has been verified experimentally in the laboratory and by measurement on turbojet engines over much of their operating range.

An eighth-power-of-velocity law suggests immediately that exhaust velocities need only be reduced by a small amount to obtain quite significant reductions in sound output. For example, a 25-percent reduction in exhaust velocity should effect a noise reduction of about 10 decibels; a 50-percent reduction would be accompanied by a 24-decibel reduction in noise.

In the modern generation of turbofan engines, the thrust is developed by accelerating a larger volume of gas-through a smaller velocity range than was typical of the older turbojet vehicles. A silhouette of an engine of the high-bypass-ratio type is shown in figure 1. The turbulent mixing sources are identified as external sources in this figure and, in this regard, the contribution made by the bypass exhaust must not be omitted. It might be supposed that reduction of the velocities in this mixing region would remove, or significantly reduce, the problem of exhaust noise. By judging the increasing concentration of effort on fan- and compressor-noise problems, it might be assumed that the problem has indeed been solved.

A closer look at the problem indicates however that the solution is not quite so simple. Real engines and laboratory jets at low, but still high subsonic, speeds often show a marked deviation from the eighth-power-of-velocity law (refs. 1 to 4). The exponent of the velocity is reduced. At these reduced speeds, it is believed that broadband exhaust noise is no longer dominated by the sources in the freely expanding turbulence, but that sources arise which are associated with the highly turbulent flow in the exhaust ducting itself. These sources are distinct from sources generated by the air-moving equipment within the engine and are identified as internal sources in figure 1.

The significance of the proposed change in source type and location is twofold. Firstly, a reduced velocity exponent means that less benefit will be derived from low tailpipe velocities than might be supposed. Secondly, methods of noise suppression appropriate to the classical jet source may not be effective and, in fact, may be harmful when the dominant sound source is located within the exhaust duct.

The purpose of the study described in this paper is to model in a very simple sense the condition of a highly turbulent flow exhausting into the free atmosphere and to examine the sound generating properties of this flow. The basic form of the experiment is shown in figure 2.

## SYMBOLS

| | |
|---|---|
| c | speed of sound |
| D | diameter of pipe |
| $\tilde{F}$ | fluctuating-force amplitude |
| f | frequency |
| $f_o$ | constant having dimensions of frequency and found to be approximately equal to cutoff frequency for plane-wave propagation |
| I | acoustic intensity |
| k | constant |

| | |
|---|---|
| $k(s), k'(s)$ | spectrum-shape constants |
| $S$ | Strouhal number |
| $U$ | flow velocity |
| $U_c$ | constricted-flow velocity |
| $W$ | radiated power |
| $\Delta p$ | pressure drop across obstruction |
| $\delta$ | geometric thickness of wake |
| $\rho$ | gas density |

## SOURCES OF AERODYNAMIC NOISE

**As a** prelude to subsequent discussions, a brief description of the three fundamental mechanisms of aerodynamic noise generation is presented herein. The relation of these mechanisms to the experiment is illustrated in figure 2.

The process whereby the free turbulence in an expanding jet generates noise has been mentioned previously. The noise sources associated with the turbulence exist in the absence of solid surfaces. These sources are inefficient radiators of sound, having the equivalence of acoustic quadrupoles and, as such, they are generally referred to as aerodynamic quadrupoles. The acoustic intensity $I$ from these sources can be shown to have the parametric dependence

$$I \propto \frac{\rho U^8}{c^5} \qquad (1)$$

where $\rho$ is the gas density, $U$ is the flow velocity, and $c$ the speed of sound.

When turbulence is generated by a surface or when turbulent flow impinges on a surface, fluctuating drag or lift forces are exerted. These forces when applied to the fluid constitute sources of acoustic power. These sources have the equivalence of the acoustic dipole and are sometimes termed aerodynamic dipoles. They are more efficient radiators than the quadrupole sources. It can be shown that the parametric dependence of the acoustic intensity is

$$I \propto \frac{\rho U^6}{c^3} \qquad (2)$$

The aerodynamic dipole thus displays a dependence upon the sixth power of flow velocity.

The final source which can be elicited from current aerodynamic noise theory arises if the turbulence within the jet pipe produces a gross fluctuation of the volume flow across the exit plane of the pipe. Such a source is piston-like in its form and is, therefore, appropriately called the aerodynamic monopole. The monopole is the most efficient of aerodynamic sources that can be postulated, with the dependence

$$I \propto \frac{\rho U^4}{c^3} \tag{3}$$

It should be noted that the intensity relations given in equations (1) to (3) assume that each source is located in a free-field acoustic environment. In a subsequent section of this paper, the influence of the restricting environment of the pipe is discussed.

## EXPERIMENT

A most important requirement of the experiment was that a high degree of measurement accuracy be obtained so that the different source mechanisms could be identified on the basis of the measured velocity exponents.

A schematic of the measurement system is shown in figure 3. Air from the airflow apparatus was passed via a sound attenuating muffler to a 6-inch-diameter pipe which penetrated the wall of the anechoic measurement chamber. This pipe then decreased in diameter to the diameter of the experimental jet, generally 2 inches. The airflow in the pipe was measured by a Pitot-static tube some distance upstream from the test section which carried the flow disturbance. The pipe was constructed in such a way that the spoiler could be readily inserted and removed. The distance of the spoiler from the exit plane could also be changed. Throughout most of the experiments the spoiler was located three pipe diameters (6 inches) from the exit plane. The total length of jet pipe (following the transition) was some 36 inches. Thus fully developed pipe turbulence was established before the spoiler location.

The sound field in the anechoic chamber was scanned in a single (horizontal) plane centered on the pipe exit. A simple traverse for each flow condition was used, the total noise signal being recorded on magnetic tape. The reduction of these data into octave bands of frequency was made subsequently. A graphic computer technique was used to compute the radiated sound power.

## OVERALL RADIATED SOUND POWER

In the preliminary studies, attention was focused on the overall sound power (that is, measured over the entire frequency range) radiated by the system. The principal findings can be summarized as follows: The level of the overall radiated sound power from a plain unobstructed jet is shown in figure 4 as a function of the exit-plane velocity. Results are shown for three separate experiments made over a 4-month period. These results demonstrate the high order of repeatability made possible by the experimental equipment. The plain pipe radiation shows an eighth-power-of-velocity dependence at the higher velocities but tends, however, to a sixth-power dependence as the velocity decreases. The eighth-power dependence is identified with free jet turbulence and agrees closely with theoretical predictions (solid-line curve in fig. 4) based on constants determined experimentally by Fitzpatrick and Lee (ref. 3). The sixth-power dependence may be identified with aerodynamic dipole mechanisms within the pipe - perhaps associated with the exit lip.

When a flow obstruction is inserted into the pipe, the radiated power increases as is shown in figure 5 and a sixth power of velocity becomes established over the total operating flow range. This result is typical in that a sixth-power-of-velocity law was consistently and accurately observed throughout the studies for most cases in which the pipe flow was obstructed. If this velocity exponent is assumed to be indicative of an aerodynamic dipole mechanism within the pipe, at least two possible locations of the noise sources can be postulated. These locations are:

(1) On, or close to, the flow obstruction associated with turbulence generation

(2) At the exit plane associated with the interaction of the highly turbulent wake with the exit lip

Figure 6 shows the result of an experiment, the object of which was to define the location of these sources. An acoustic muffler was placed immediately downstream from the spoiler. The purpose of the muffler was to attenuate the acoustic energy propagating downstream from the spoiler without influencing, sensibly, the form of the downstream turbulence. The data in figure 6 indicate that the spoiler-generated sound must be located in the vicinity of the spoiler rather than at the exit lip. In a second experiment, the muffler was replaced by flow straighteners which attenuated the downstream propagating turbulence without significantly interrupting the acoustic propagation path. The same conclusion was reached; that is, the sources of obstruction-generated sound are located on, or close to, the surface of the obstruction.

Sound-power data for three different obstruction geometries are presented in figure 7. The data are presented as a function of exit-plane velocity. While each geometry displays an approximate dependence upon the sixth power of velocity, a very considerable scatter occurs between the data of one geometry and another. Exit-plane velocity is apparently not a good correlating parameter for obstruction-generated sound.

When, however, these same data are plotted against the total pressure drop that occurs across the flow obstruction, the degree of correlation is excellent as shown in figure *8*. The sound power from a pipe-immersed obstruction can, apparently, be expressed in terms of the third power of the pressure drop across it. . The dimensions of the obstruction seem to be of little importance.

The result demonstrated in figure 8 was found to hold for a wide variety of obstruction geometries and sizes. It seemed that herein lay the basis for a prediction scheme for obstruction-generated sound. A physical model on which to base the analysis was needed to help derive the appropriate prediction formula.

The observed dependence of obstruction sound upon the sixth power of flow velocity is a strong indication that the source mechanism is the aerodynamic dipole. It can therefore be postulated that the acoustic source is the fluctuating force field exerted by the flow on the obstruction.

The schematic of the jet pipe appropriate to this model is shown in figure 9. Airflow passing along a pipe is constricted as it passes the flow obstruction. The flow then expands to form a highly turbulent wake behind the obstruction. The process of vortex shedding by the obstruction causes fluctuations in the drag and lift forces exerted on it. These fluctuating forces form the dipole source of sound.

The power radiated from a force field in a free-field acoustic environment is given by

$$W \propto \tilde{F}^2 f^2 \tag{4}$$

where $\tilde{F}$ is the amplitude and $f$ is the characteristic frequency of the force. For this model, equation (4) is assumed to be valid even in the confines of the pipe. Furthermore, the drag forces, rather than the lift forces, are assumed to be primarily responsible for the radiation.

The characteristic frequency of vortex shedding from the obstruction is given by the quotient of the constricted velocity $U_c$ and the geometric thickness of the wake 6. If constant proportionality between the steady and fluctuating drag components is assumed, then the fluctuating force field can be expressed by the product of the constricted velocity pressure $\frac{1}{2}\rho U_c^2$ and the area of the wake. Thus, the expression for radiated power can be derived as

$$W = \frac{k\,\Delta p^3 D^2}{\rho^2 c^3} \tag{5}$$

where Ap is the pressure drop across the obstruction, $D$ is the diameter of the pipe, and $\rho$ and $c$ are, respectively, the density and speed of sound of the air, and $k$ is a constant. Equation (5) is identical in form with that developed by Yudin (ref. 5) some years ago from studies of air-duct elements (related to low-velocity ventilating systems). This equation is observed to provide a good degree of overall-power data correlation in the present study. Indeed, for this study the value of $k$ (for overall power) has been observed to lie close to $2.5 \times 10^{-4}$.

## FREQUENCY SPECTRUM

The result of the dipole model is found to describe quite accurately the overall noise radiation from many different obstruction configurations. Its correctness as a physical model is less certain, however, when the frequency spectrum of the obstruction-generated sound is examined.

The octave-band spectrum, for a typical obstruction geometry, normalized in accordance with the dipole-model formula of equation (5) is presented in figure 10. As is usual, the normalizing frequency is the Strouhal number. In the present study the Strouhal number is based on the constricted velocity $U_c$ and the geometric thickness $\delta$ of the wake. The data collapse is quite good at low Strouhal numbers but is less complete at high Strouhal numbers. At this stage of the study it was concluded that the dipole model of obstruction-generated sound as formulated in equation (5) was less powerful than had been hoped. The next step in the analysis was to search for a means of improving the data correlation.

## A QUADRUPOLE MODEL OF OBSTRUCTION-GENERATED SOUND

The data collapse shown in figure 10 is incomplete. These same data take the form shown in figure 11 when the normalizing formula is modified to

$$W = k'(s) \frac{\Delta p^3 D^2}{\rho^2 c^3} \left[1 - \left(\frac{f}{f_o}\right)^2\right] \tag{6}$$

where $f$ is the center frequency of the band, $k'(s)$ is the spectrum-shape constant, and $f_o$ is a constant having the dimensions of frequency. The constant $f_o$ takes a value approximately equal to the acoustic cutoff frequency (for plane-wave propagation) of the jet pipe. The degree of data collapse is quite excellent, and equation (6) has been equally successfully applied to spectrum data for several different flow obstructions. In each case the range of data scatter lay within ±2 decibels.

The first term of equation (6) is similar to equation (5) and as such is derivable from the dipole model described previously. The second term, however, has an additional frequency-squared term. For aerodynamic noise mechanisms, frequency is proportional to velocity, and thus the second term has the velocity dependence of a quadrupole source. At first sight, therefore, both dipole and quadrupole source mechanisms are involved, the dipole dominating at frequencies below the cutoff frequency $f_o$ and the quadrupole at frequencies above cutoff. Both mechanisms appear under the same spectrum-shape constant $k'(s)$, thus implying a strong interrelation between the two.

An acceptable physical model of the sound generating process can be developed as follows. Throughout the preceding discussion the assumption is made that the aerodynamic source phenomena within the confines of the pipe can be described in terms of their free-field radiation formulas. This assumption is justifiable primarily on the basis that much of the measurement data show a sixth-power-of-velocity dependence for a physical setup that, one might intuitively feel, should be dominated by aerodynamic dipole sources.

Theoretical arguments presented in reference 6 indicate that enclosure of aerodynamic sources within a pipe will quite drastically change their radiation characteristics. This argument is discussed briefly with reference to figure 9. The dipole force field existing on the obstruction is accompanied, for a hard-walled pipe, by an array of wall images. From the viewpoint of an observer situated farther down the pipe, these images serve to reinforce the sound field to which he is exposed – particularly those images that are phase-correlated with the primary source. It can be shown that the effect of this reinforcement is to introduce a frequency-squared term into the denominator of the free-field source equation. It can also be argued that this frequency-squared term disappears for frequencies above the plane-wave cutoff frequency of the pipe.

The argument may be summarized as follows: Below the cutoff frequency for the pipe the dipole field can be expected to display the velocity dependence appropriate to a monopole source. Similar reasoning applies to a pipe-enclosed quadrupole field; below cutoff the quadrupole field will radiate with the velocity dependence of a dipole source. Above the acoustic cutoff frequency, when the presence of the pipe ceases to influence the radiation impedance seen by the aerodynamic source, the quadrupole and the dipole sources will revert to their normal free-field behavior.

Such a conclusion is presented for an aerodynamic-source field located in an infinitely long pipe. A complication arises when the pipe is truncated and the energy that passes through the exit plane of the pipe into the free field beyond is considered. Acoustic theory indicates that below the plane-wave cutoff frequency for the pipe the transmissibility of the exit plane varies directly with the second power of frequency, thus canceling completely the modification to the sound source imposed by the pipe enclosure. In most practical situations in the experiment and in the real engine, however, the exhaust-flow velocities across the exit plane are quite high. It can be argued that under these conditions the acoustic transmissibility (and reflection) influences of the exit plane will disappear.

The arrangement shown in figure 12 is now considered. The dominant sources are assumed to be associated with the intense turbulence in the wake of the obstruction. These sources are therefore quadrupole in character, and at frequencies above the cutoff of the pipe will radiate according to the expression

$$W \propto \frac{\rho U^8 D^2}{c^5} \tag{7}$$

Equation (7) may be written in terms of the pressure drop across the obstruction

$$W \propto \frac{\Delta p^4 D^2}{\rho^3 c^5} \tag{8}$$

Below the cutoff frequency equation (8) is modified to the form

$$W \propto \frac{\Delta p^4 D^2}{\rho^3 c^5}\left(\frac{f_o}{f}\right)^2 \tag{9}$$

The generalized expression for radiated power may thus be derived as

$$W \propto \frac{\Delta p^3 D^2}{\rho^2 c^3}\left[1 + \left(\frac{f}{f_o}\right)^2\right] \tag{10}$$

Equation (10) is precisely the expression used for data correlation.

## CONCLUDING REMARKS

The principal result of the present study is perhaps the development of a prediction formula for obstruction-generated sound. This prediction formula seems to have relevance to a wide range of current problems such as the exhaust noise of turbofan engines and the noise of components in low-velocity ventilation systems. The results of this study also seem to be pertinent to the problem of noise generation in fluid piping systems.

Some confusion still exists as to the exact physical model by which the sound-generating mechanism can be described. The dipole model

(1) Is based on a conceptually acceptable physical model of the aerodynamic dipole

(2) Provides a good, but not outstanding, fit to the experimental data

(3) Suggests that the shed turbulence, rather than the impacting turbulence, is responsible for the radiating force field

The quadrupole model

(1) Is based on a mechanism somewhat at odds with what might be intuitively expected

(2) Provides an excellent fit to the experimental data

(3) Hinges on unproven theories relating to the influence of pipe enclosure upon aerodynamic sources

This work specifically relates to the exhaust noise of the turbofan vehicle in the following manner. It may be anticipated that the combined parameters of high exhaust turbulence and relatively low exhaust velocity will conspire with surface discontinuities in the exhaust duct (including the exit lip) to generate noise at a level significantly higher than that associated with the free expanding jet. Unless these sources are accounted for in engine-noise prediction techniques, estimates of the exhaust noise levels of future vehicles may be significantly underestimated. Also, the application of current methods of jet noise suppression (multijet nozzles, and so forth) to these vehicles may increase the level of exhaust noise by intensifying the exhaust-duct sources.

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**LOCATION OF AERODYNAMIC NOISE SOURCES ASSOCIATED WITH TURBOFAN EXHAUST**

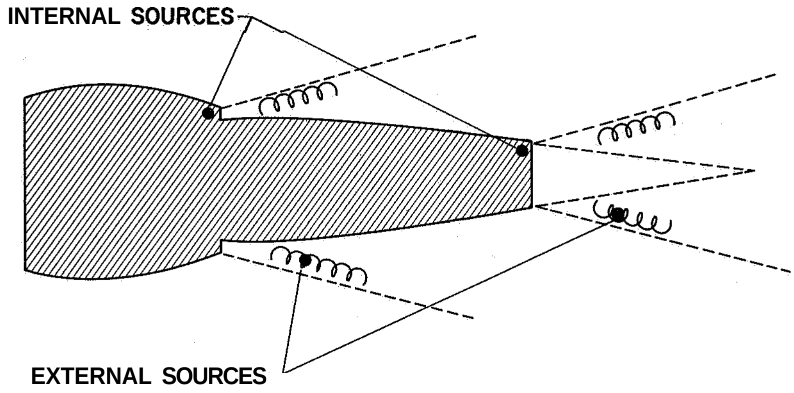


Figure 1

**AERODYNAMIC NOISE SOURCES IN TURBULENT JET FLOW**

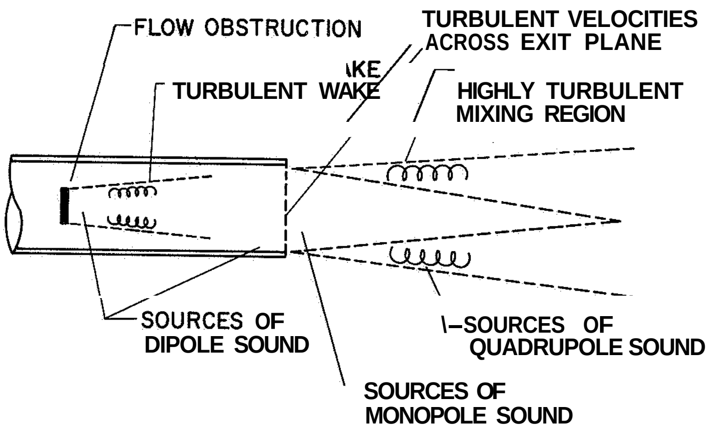


Figure 2

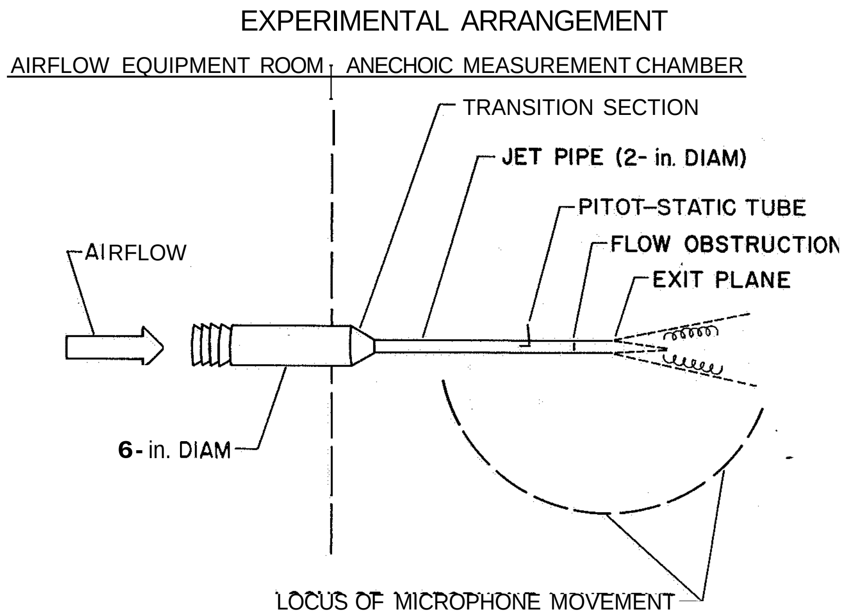


Figure 3

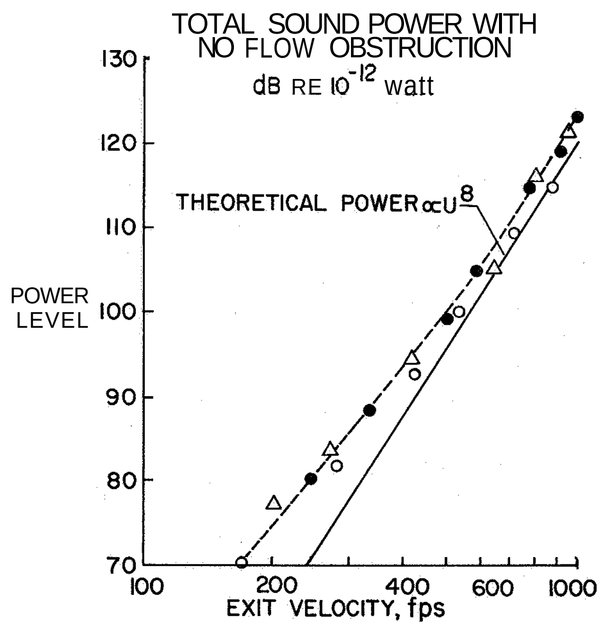


Figure 4

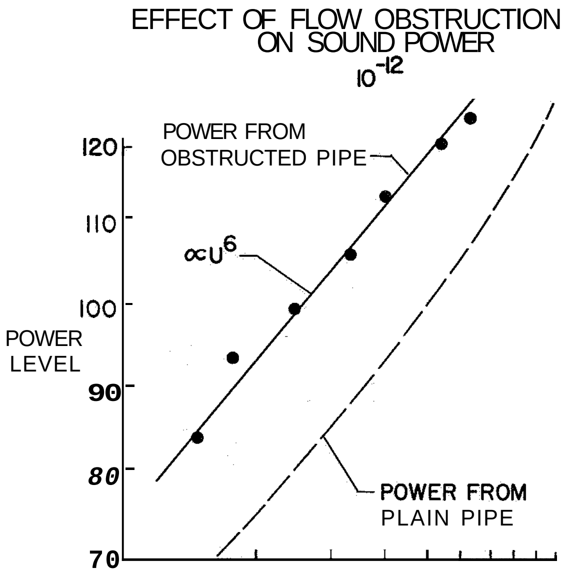


Figure 5

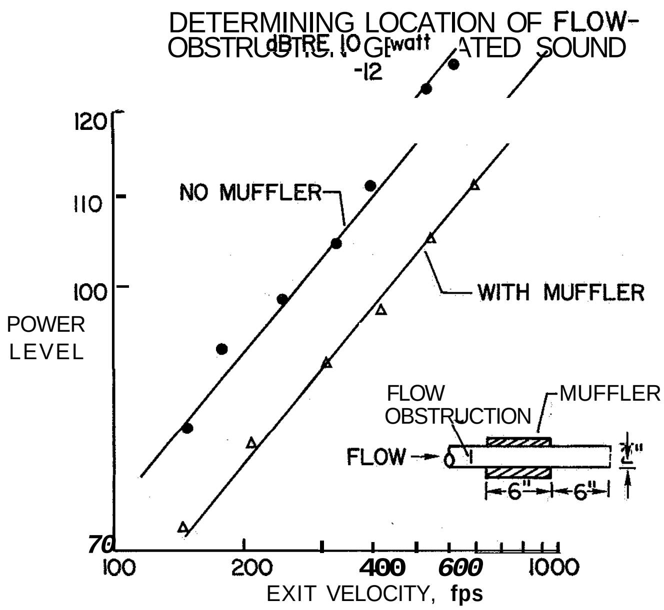


Figure 6

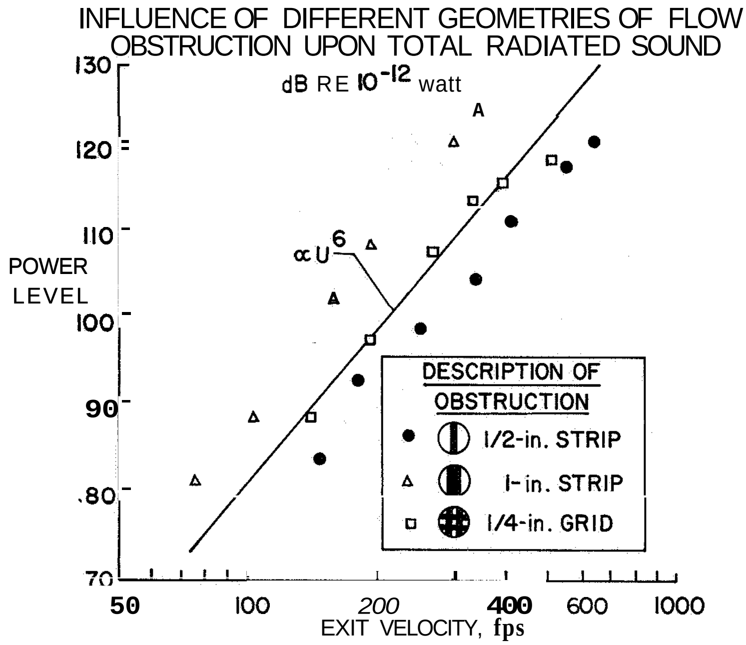


Figure 7

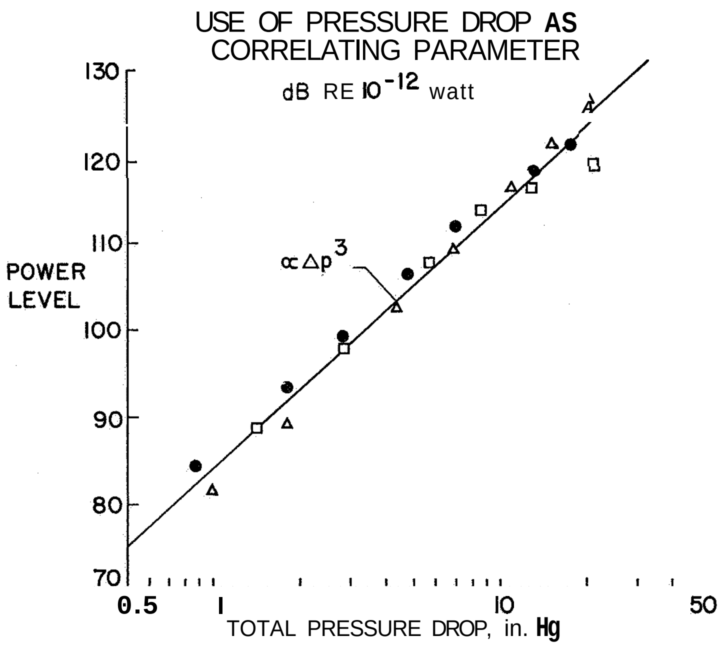


Figure 8

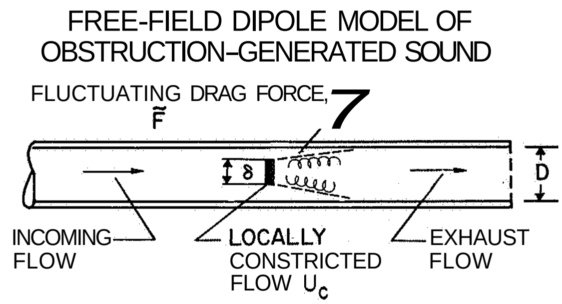


Figure 9

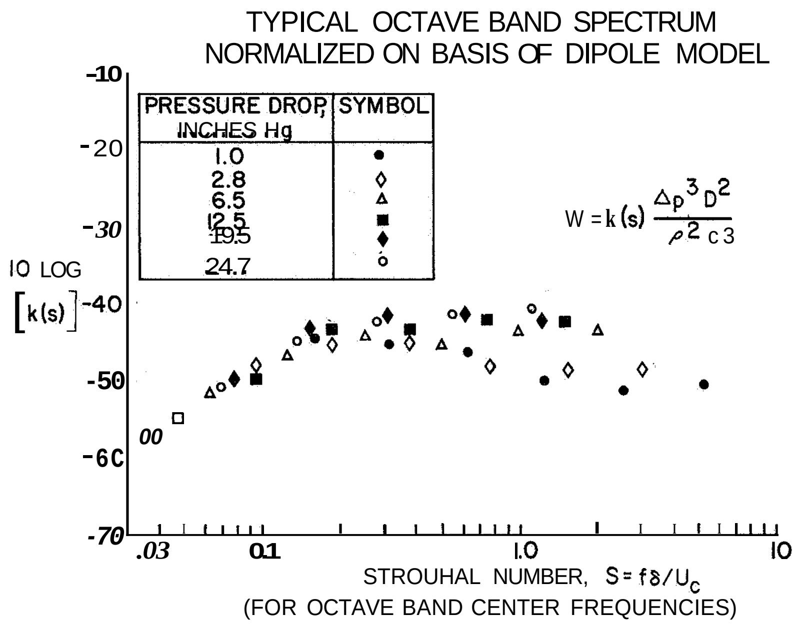


Figure 10

OCTAVE BAND SPECTRUM OF FIGURE 10
RENORMALIZED FOR IMPROVED COLLAPSE

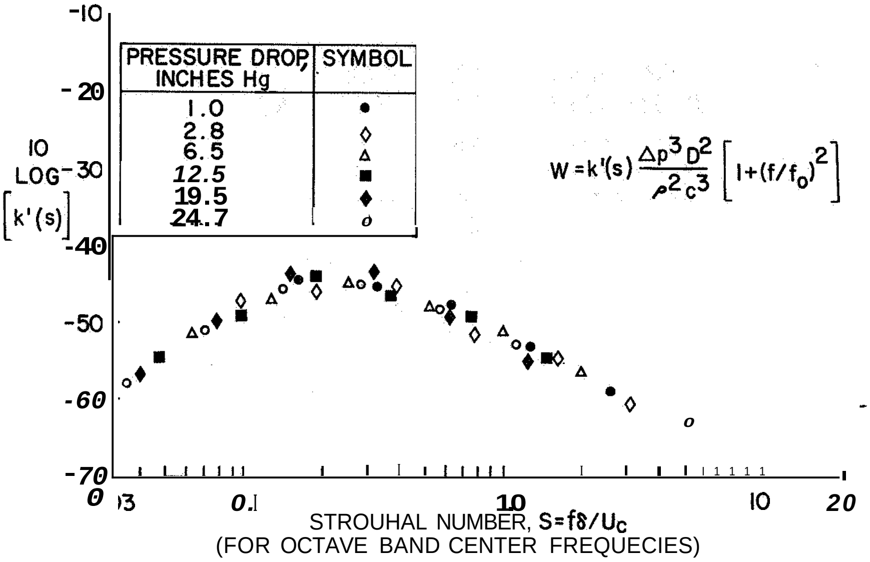


Figure 11

PIPE-ENCLOSED QUADRUPOLE MODEL
OF OBSTRUCTION-GENERATED SOUND

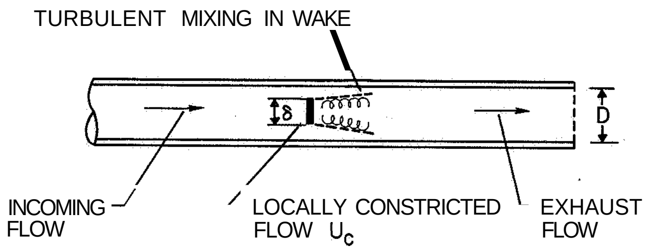


Figure 12