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C. G. GORDON

The Problem of Duct-Generated Noise and Its Prediction

There is increasing interest today in the problem of noise generated by fluid flow. This interest covers not only the assorted problems of aero-engine noise, but extends also into that less spectacular, but nonetheless critical, field of ventilating and air-conditioning equipment. It is an unfortunate fact that until recently the latter area has been, by comparison, all but neglected.

In this paper we will present some of the more fundamental notions of the phenomena classified as "subsonic aerodynamic noise." In light of these, we wish to discuss the mechanisms of noise generation responsible for the self-noise of sound-traps, dampers, diffusers and other duct-located flow discontinuities. Furthermore, we will suggest, on the basis of some recent experimental studies, that the intensity and frequency spectrum of self-noise in ventilation systems can be predicted in a general sense. Tentative formulae are presented to this effect. Finally, recommendations are presented for future work in this area.

AERODYNAMIC NOISE AT LOW FLOW VELOCITIES

The intrinsic tendency of fluid flow to generate noise has been recognized for many years. It is only recently, however, that the subject of aerodynamic noise generation has been tackled theoretically.[1] The impetus for the work was provided by the advent of the gas-turbine engine. As a consequence, mathematical and experimental interest has tended to concentrate on those mechanisms of noise generation peculiar to high subsonic, transonic and supersonic flow conditions. The region of low velocity flow has received scant attention, yet it is this area that is pertinent for ventilation systems.

If we limit our attention solely to subsonic flow, we find that current aerodynamic theory provides three fundamental mechanisms of noise generation. Typical locations and descriptions of these three mechanisms for a terminal-duct carrying air are illustrated schematically in Fig. 1.

When the air leaves the duct environment, it enters a medium of zero flow velocity. High velocity gradients existing at the interface of the moving and stationary media produce shear forces in the fluids which generate turbulent mixing and noise. The noise sources are distributed spatially along and across the regions of mixing. They have the radiation equivalence of acoustic quadrupoles. This phenomenon is generally referred to as "jet" noise. It is found theoretically and observed experimentally that the radiated sound power in a free-field environment is proportional to the eighth-power of flow velocity. Sources of turbulence-generated (jet) noise may occur, also, within the ducted system. These are associated with local high velocity gradients, - in the spoiler wake, for instance.

In the flow system of Fig. 1, a flow spoiler has been inserted within the duct some distance upstream from the exit plane. When turbulent flow interacts with a solid surface, or when turbulence, in the form of a wake, is generated by a solid surface, time-varying changes in the mo-

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C. G. Gordon is a Senior Consultant at Bolt, Beranek and Newman, Inc. This paper was prepared for presentation at the ASHRAE Semiannual Meeting, Columbus, Ohio, February 5-8, 1968.

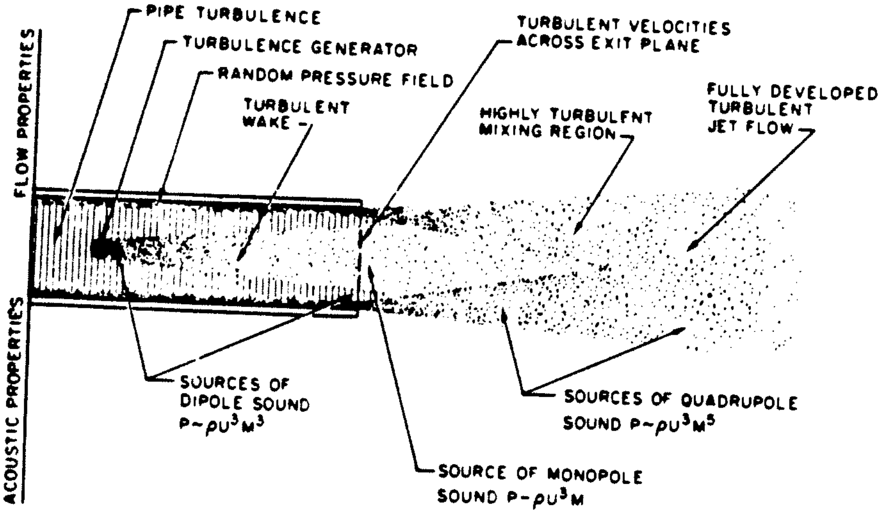


Fig. 1 Schematic illustration of the noise produced by flow turbulence in a terminal duct

mentum field around the spoiler are clearly generated. Such changes require fluctuating forces and, in general, these must exist on the solid surface. The forces may be described as fluctuating "lift" or "drag," and they form sources of acoustic noise. Fig. 1 also indicates the possibility that the turbulent wake from the spoiler may impinge on the duct wall at the exit plane. Here, again, we might anticipate sources of surface noise. In a free-field environment these sources have the equivalence of acoustic dipoles. The radiation intensity from them is observed theoretically and experimentally to obey a sixth-power-of-velocity law. In this paper, noise of this sort will be referred to as "surface-induced" noise.

The final mechanism of noise radiation, which we can identify in our subsonic flow model, requires perturbation of the net mass-flow through the duct system. Such a condition might arise from fluctuating stall in the air-moving equipment or, less likely, from net compressibility of the ducted air flow. The noise source here has the equivalence of the acoustic monopole, and it can be demonstrated that the intensity of sound radiation should be proportional to the fourth-power of mean flow velocity.

It is pertinent to note at this stage that the mechanisms described are not dependent upon the physical movement of the solid environment that contains or impedes the flow. Thus, for example, surface-induced noise does not arise from physical motion of the surface. Indeed, the radiating force field may excite surface vibration, but generally with insignificant effect upon the sound power generated with the duct.

It is not clear how these fundamental aerodynamic noise sources might behave in the restricted environment of a duct - as opposed to the free-field environment assumed theoretically. One might anticipate that when the duct diameter-to-wavelength ratio is greater than unity, the free-field environment might be approximated. For lower ratios, however, this can hardly be the case. Recent theoretical discussions[2] have indicated that the effect of enclosure might indeed be quite drastic.

THE NOISE OF VENTILATING SYSTEMS

The prime source of noise in any ventilating system is generally the fan. As the fan blading rotates in the scroll, it interacts with and generates turbulence. The cut-off lip does likewise. Thus, we must associate the fan with broadband and narrow band surface-induced noise. In fact, experiments seem to confirm that the velocity-law governing fan sound power has an exponent close to six. The location of the fan within the system, however, does allow the application of effective noise control. Also, in recent years, some excellent work on the empirical prediction of fan sound power has been undertaken. For this reason we do not intend to discuss fan noise in this paper.

As we move away from the fan, the sources of noise become more nebulous and harder to define. For some distance from the fan the flow is highly turbulent. Fan design requires the ducting to turn corners, to change cross-section, to have branch points, to be fitted with volume control dampers, to incorporate sound traps (for fan-noise control), and to have terminal diffusers. All these geometrical discontinuities may react with turbulence and in themselves cause turbulence to be generated. How can one predict and, if possible, minimize the extent of noise generation? This question is particularly relevant at a time when ventilation system velocities and pressures are increasing, building materials and structures becoming lighter and environmental criteria becoming more critically low.

The following paragraphs describe an experiment in which the noise of a flow system, approximating in many ways a ventilation system, was studied as a function of the flow parameters. The study was primarily aimed at some aspects of aero-engine noise and, consequently, the range of velocities investigated lies somewhat above those normally associated with ventilating systems. There is no reason to believe, however, that the mechanisms of noise production should be significantly different at the lower velocities. The experimentation is felt, therefore, to be quite relevant to the current discussion. The study also in-

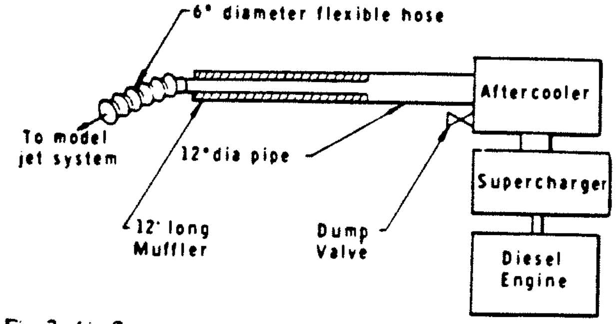


Fig. 2 Air flow equipment schematic

volved fairly small scale dimensional modelling. This is primarily a course of convenience, since the scaling laws of aerodynamic noise are fairly well established.

AN EXPERIMENTAL STUDY

In a recent experimental study,[3] we examined the broadband noise radiation from a thick-walled cylindrical duct, carrying subsonic air flow into which flow spoilers of various shapes and sizes were inserted. The source of air flow consisted of the supercharger section of a Pratt and Whitney model R-2800 aircraft engine, driven by a 600 HP Cummins diesel engine. The equipment was capable of producing air flows up to 6000 standard cubic feet per minute at pressures up to 15 psig. The air output from the supercharger was passed through an aftercooler, a 12 in. diameter pipe, and a 12 ft long sound muffler, into the measurement chamber via a 6 in. diameter flexible hose. A schematic of this system is shown in Fig. 2. The flow of air was controlled by a combination of speed control of the diesel engine and by dumping air from the aftercooler.

The measurement chamber used in these studies was about 12 ft sq and 7 ft high. It is shown in Fig. 3. The walls of the chamber were partially treated with 18 in. deep anechoic wedges to suppress the major reflections. The remaining surfaces (including duct and support-brackets) were treated with a 4 in. thick sound absorptive blanket. Tests showed that with the duct located (as shown), at a distance of about 2 ft from the chamber wall, with a source-microphone distance not exceeding 4 ft, the chamber was effectively anechoic at sound frequencies above 250 Hz.

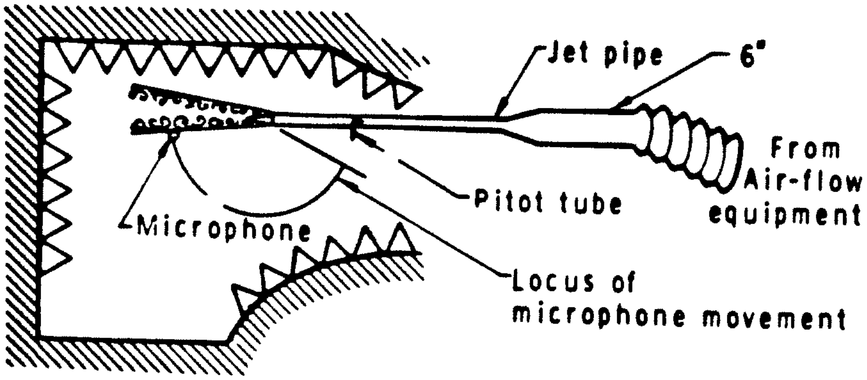


Fig. 3 Measurement chamber schematic

Fig. 4 is a photographic view of the measurement chamber showing the absorptive treatment, the experimental duct, and microphone boom.

The radiated sound from the open duct was scanned using a continuous-traversing microphone boom. The boom was located close to the ceiling and the microphone suspended in the horizontal plane of the duct exit. Throughout the studies, the distance between the microphone and the exit plane was 3 ft and the speed of rotation about 1 rpm. It was established that for all test configurations the sound field was closely axially symmetric. Movement of the microphone was limited, therefore, to only half of the radiation field; in fact, it was limited to between 10 and 150 deg relative to the downstream axis of the duct. The lower limit was set by the need to keep the microphone clear of the exhaust air stream.

Air was supplied to the test duct via the 6 in. diameter hose and area-transition section shown in Fig. 3. Throughout most of the studies the duct internal diameter was 1.875 in. The total length of the duct from transition to exit plane was 36 in.

The experimental duct was designed to allow easy insertion and removal of the experimental spoilers. Furthermore, the design ensured that any particular configuration could be reassembled exactly at any stage during the study. The design is shown in Fig. 5. Each spoiler configuration was constructed at one end of a 6 in. long unflanged pipe. This section could be inserted into the duct using the removable flanges and 'O' rings as shown. The construction also allowed the distance of the spoiler from the exit plane to be adjusted over a range of 0 to 18 in.

Fig. 6 shows a selection of flow spoilers used in the study. The spoilers were constructed of two layers of aluminum, sandwiching a layer of structural damping material. This construction minimized structural vibration. Two principal forms of flow spoiler were studied: "strip" spoilers, which diametrically cross the duct, have variable width and present variable angle of attack to the flow; and "ring" spoilers, which form a peripheral ring of spoiler around the inside wall of the duct, and have variable, radial depth. The studies also included a grid-like spoiler geometry and abrupt contractions and expansions of duct diameter.

Fig. 7 shows a block diagram of the instrumentation. The signal from the traversing

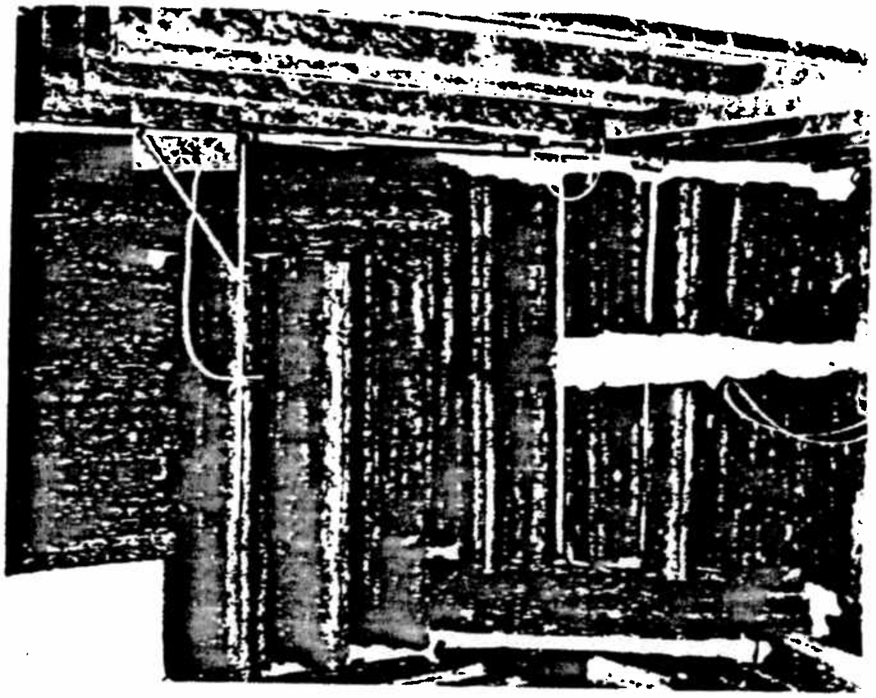


Fig 4 View of measurement chamber

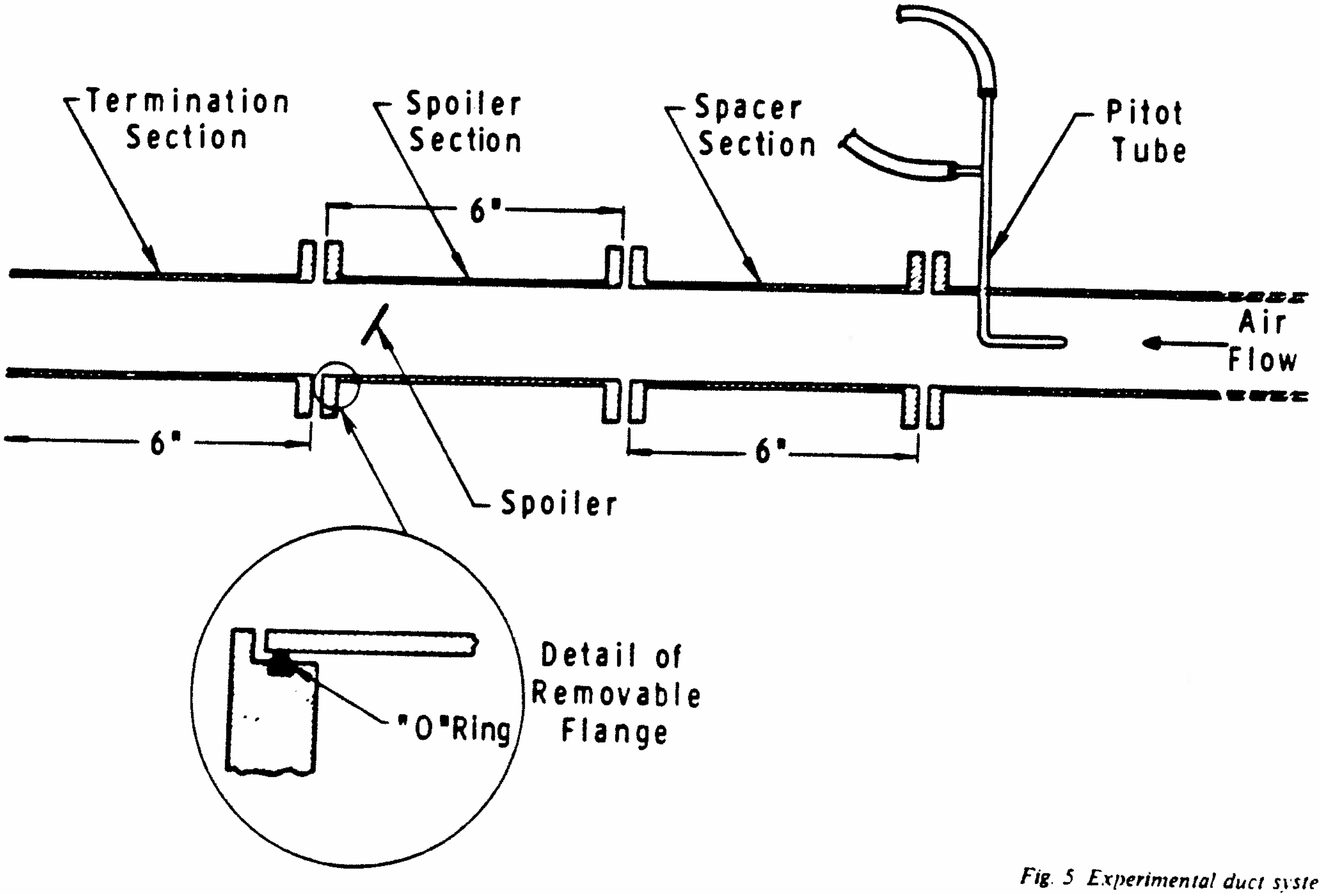


Fig. 5 Experimental duct system

Fig 6 Selection of flow spoilers

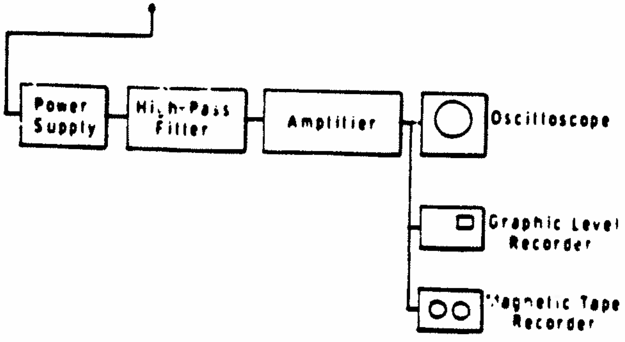
microphone was fed, via amplifiers and a high-pass filter, to a magnetic tape recorder and graphic level recorder. The high-pass filter served to remove that part of the acoustic signal below 250 Hz, for which the measurement chamber was not anechoic. The frequency response of the total system was linear from 250 Hz to 20 kHz.

Air flow was measured using a single Pitot-static tube centrally located in the duct, as shown in Fig. 5.

RESULTS

The level of overall radiated sound power from the unspoiled duct flow is shown in Fig. 8 as a function of the exit-plane velocity. The results of three separate experiments made over a four-month period are indicated. These demonstrate the high order of repeatability made possible by the experimental equipment. A sixth-power-of-velocity dependence at the lower velocities changes into an eighth-power dependence at the higher velocities. The former may be identified with surface-induced noise generated within the duct or at the exit plane. The latter is identified with the free-jet turbulence, and the levels agree closely with work of earlier experimenters.[4]

Fig. 7 Instrumentation schematic



When a spoiler is inserted in the duct, the radiated power increases sharply, as shown in Fig. 9, and a sixth-power law becomes established over the total operating flow range. It is typical of these studies that a sixth-power-of-velocity law has been consistently and accurately observed for most spoiled-flow configurations. If we accept, for the moment, the assumption that a sixth-power-of-velocity is indicative of surface-induced noise, as described earlier, at least two source locations for this noise can be postulated; one, in the close vicinity of the spoiler, the other, at the exit plane of the duct.

Fig. 10 shows the result of an experiment in which an acoustic muffler was inserted immediately downstream of the flow spoiler. The purpose of the experiment was to remove the acoustic energy propagating downstream, without significantly affecting the turbulence level. The experiment indicates that the dominant surface-induced noise must be located close to the spoiler rather than at the exit lip. In a second experiment, flow straighteners were inserted to attenuate the turbulent wake without influencing the acoustic wave. In this case no sensible reduction of radiated noise was observed, confirming the conclusion that noise induced by a spoiler is generated in the vicinity of the spoiler itself. Spoiler generated noise propagates, therefore, as an acoustic wave, and the acoustic parameters of the duct must play a part in the radiation process.

The next step was to examine the nature of overall power radiation from the duct for a variety of spoiler configurations. The results for three

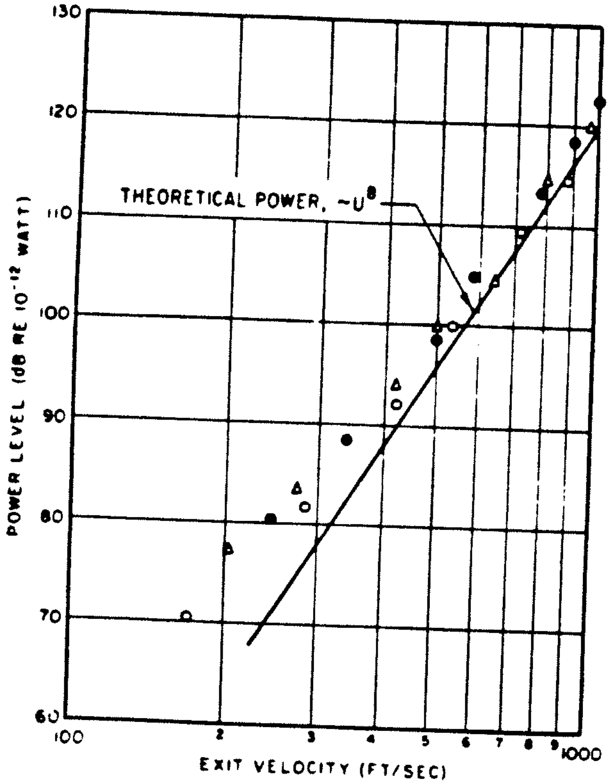


Fig. 8 Noise radiation from unspoiled duct flow

configurations placed 6 in. from the exit plane are shown in Fig. 11. A sixth-power-of-velocity dependence occurs for each. It is observed and, indeed, is not surprising, that no sensible correlation between one configuration and the other occurs when the data are plotted against exit-plane velocity.

Studies of these and other data have shown that a striking correlation between unlike spoiler configurations is possible on the basis of the total pressure drop across the spoiler. The total pressure drop as used here is that value read on a manometer connected between the upstream Pitot tube and the ambient atmosphere. The same degree of data collapse was not observed using upstream static, as opposed to total, pressure.

The data of Fig. 11 are shown plotted to this abcissa in Fig. 12. The overall acoustic power radiated from a variable spoiler immersed in an open-ended duct of fixed size is solely dependent upon the third-power of total pressure drop across the spoiler. This conclusion is significant in the prediction of ventilation system noise.

EMPIRICAL DESCRIPTION OF SURFACE INDUCED NOISE

Earlier, we described the mechanism whereby the interaction of a surface with fluid-flow leads to a fluctuating force-field on the surface and, hence, to noise radiation. It is possible to construct a simple theoretical model of this interaction. For the purpose of this discussion let us consider a surface in the form of a strut (strip spoiler) lying diametrically across the duct and immersed some distance within it. The free-field relation describing the sound power (P_A) radiated by an unsteady force-field (F) is given by the formula

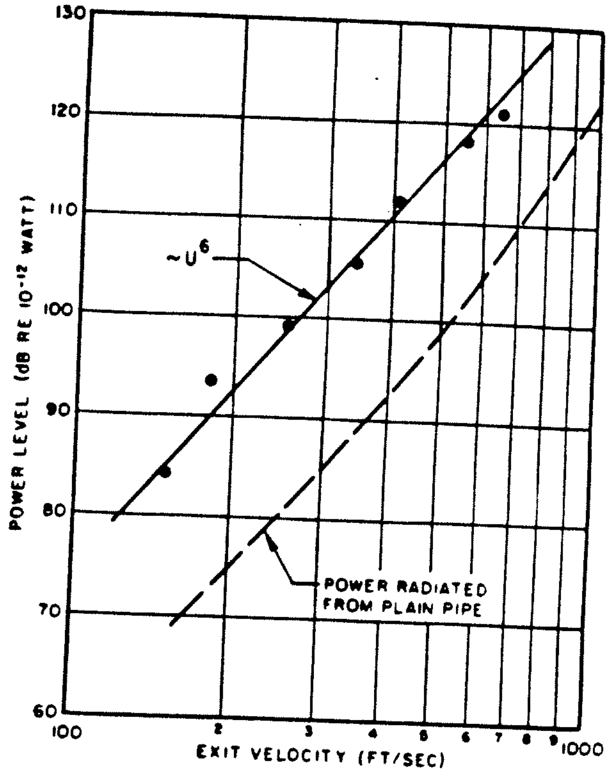


Fig. 9 Effect of flow spoiler upon power radiation

$$P_A \sim F^2 f^2/\rho c^3 \tag{1}$$

where f is the characteristic frequency of the unsteady force spectrum and ρ and c are atmospheric density and sound velocity, respectively. We assume a constant proportionality between the sound radiating force-field and the steady hydrodynamic drag exerted by the flow on the spoiler.

In our model we express this hydrodynamic drag by the product of the constricted velocity-pressure, (between the spoiler and the duct wall), and the projected area (wake area) of the spoiler. We express the characteristic frequency of the force-field by the quotient of the constricted flow velocity with the projected thickness (wake thickness) of the spoiler. (We assume that the thickness of wake generated by a blunt body is independent of flow velocity, and is given by the width of blockage offered to the flow by the body.)

If the flow is virtually potential down to the constriction point and the atmospheric pressure penetrates up towards the spoiler location, the constricted velocity-pressure is given by the quantity $p_o - p_a$, where p_o is the upstream total (stagnation) pressure and p_a is atmospheric pressure.

It thereby transpires that Eq (1) can be replaced by the expression:

$$P_A = k\,(p_o - p_a)^3 D^2/\rho^2 c^3 \tag{2}$$

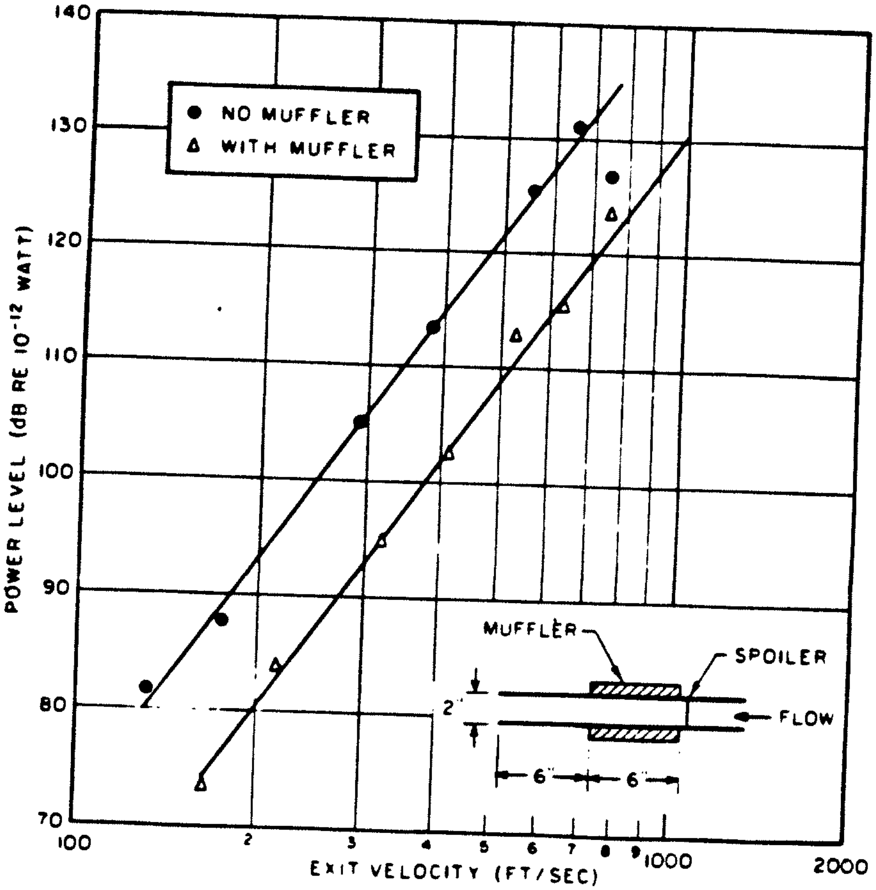


Fig 10 Effect of muffler on radiated sound power

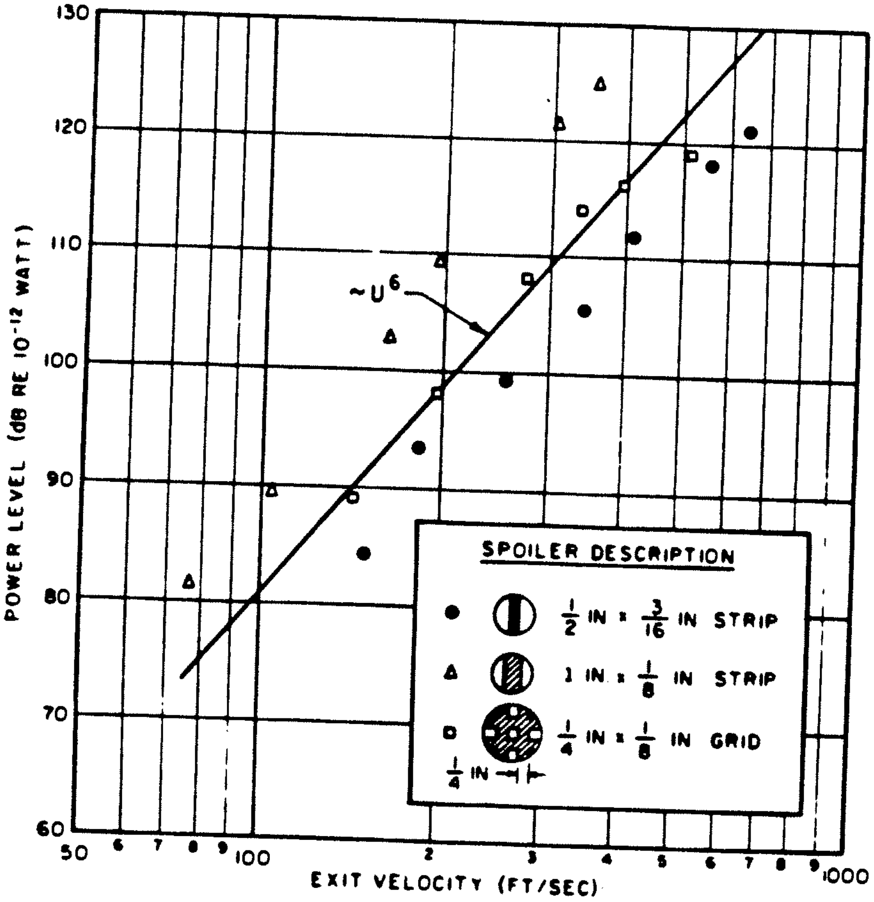


Fig. 11 Effect of spoiler dimension on radiated power

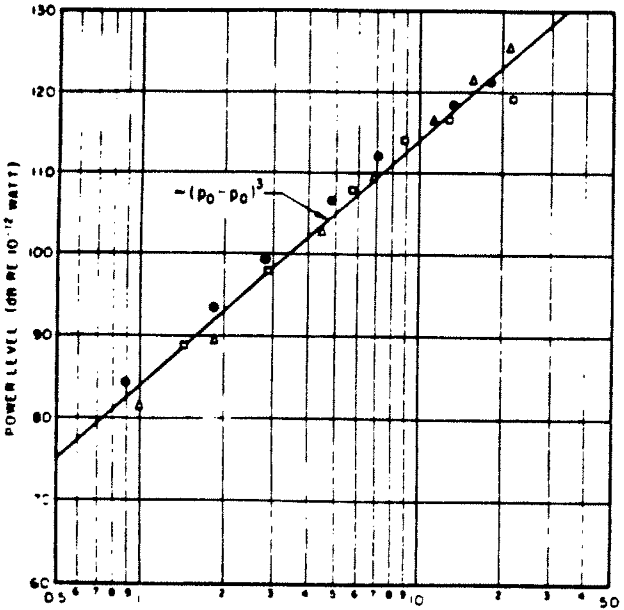


Fig. 12 Collapse of data of Fig. 11 when plotted against the total pressure-drop across the spoiler system

where k is a constant and D is the duct diameter.

This formula for total power agrees with the experimental results shown in Fig. 12. It is also observed to hold for a wide variety of different spoiler geometries and sizes. In general k is found to have a value close to 2.5 x 10^{-4}.

FREQUENCY SPECTRA OF SPOILER NOISE

A description of the overall sound power generated by an in-duct flow discontinuity is, in itself, not sufficient. It is necessary also to define the frequency spectrum.

In Fig. 13 we present the results of octave-band analyses of the sound power radiated from a 1-in. wide strip spoiler placed across the flow at an angle of incidence (α) of 67.5 deg. The spoiler was located at a distance (x) from the exit plane of 6 in. This plot is presented in normalized units. The ordinate has the form,

$$PWL_N = 10 \log P_A \rho^2 c^3/(p_o - p_a)^3 D^2 \qquad (3)$$

and, therefore, represents the value of 10 log (k) where k is the constant of Eq (2). The abcissa is presented as a Strouhal Number based on the relation,

$$\text{Strouhal Number} = f\delta/U \qquad (4)$$

where f is the octave-band center frequency, δ is the thickness of the wake (projected thickness of the spoiler) and U_ℓ is the constricted flow velocity between the spoiler and the duct wall. The presentation of frequency as a Strouhal Number is necessary for the successful presentation of aerodynamic spectrum data.

The data collapse, although reasonable in the lower Strouhal range, shows significant divergence at the higher Strouhal Numbers. Such divergence is typical of much of the data obtained during these studies. Therefore, Eq (2) does not in itself provide the degree of correlation that was anticipated following the overall sound analyses.

Studies of Fig. 11 and of these other data, have consistently shown that the radiated power is well correlated by the modified expression,

$$P_A = \frac{k(p_o - p_a)^3 D^2}{\rho^2 c^3} \left[1 + (f/f_o)^2 \right] \qquad (5)$$

where f_0 is some constant frequency related to the dimensions of the duct/spoiler system. The data of Fig. 13 are shown replotted on this basis in Fig. 14. The degree of data collapse is excellent. The value of f_0 employed was 4 kHz. A similar degree of data collapse was obtained on most of the other spoiler configurations using the modified power formulation of Eq (5).

Let us look briefly at Eq (5). The first term of this equation conforms with our theoretical description of surface-generated sound in Eq (2). The second term, however, has an additional frequency-squared term. At constant Strouhal Number, this is equivalent to an additional velocity-squared term and the second term of Eq (5) thereby resembles the aerodynamic quadrupole source of classical jet noise theory. The equation, in effect, provides two mechanisms for noise generation; one, which is entirely dominant at frequencies below f_0, and the other, which is dominant at frequencies above f_0. It is observed that the frequency chosen for f_0 lies close to that value for which the diameter of the duct is about a half-wavelength, thus defining the onset-frequency at which cross-modes may occur in the duct. Experiments using a 4-in. diameter round duct required a value of f_0 of about 2 kHz for data collapse, thus strengthening the hypothesis that the value of f_0 defines the onset-frequency for cross modes in the duct.

It is not clear at this time whether the divergence frequency f_0 truly defines a change-over from one source mechanism to another, or whether it marks a transition in the velocity exponent (and, hence, in the radiation efficiency) of a single source mechanism. The latter conclusion would certainly be in agreement with recent theoretical observations,[2] and would suggest quite strongly that the dominant source mechanism in our studies is turbulence-generated rather than surface-induced. Confirmation of this conclusion, however, must await further study.

From the viewpoint of the present discussion it is sufficient to note that the spoiler-generated noise can be correlated quite accurately both below and above the cross-mode onset frequency. It is suggested that herein lies the basis of a predictive scheme of relevance to duct-generated noise.

FURTHER OBSERVATIONS

The form of Eq (5) is not sufficiently understood at the present time to allow us to present it, even tentatively, as a tool for the prediction of level and spectrum of duct-generated noise. It has been observed in our study, however, that the total radiated sound power can be satisfactorily described using the simpler form of Eq (2), with a value of k of about 2.5×10^{-4}. The following discussion offers some tentative comparisons between this equation and empirical relations and data relating to real ventilating systems.

Equation (2) can be rewritten in the following engineering forms:

$$PWL = 70 + 10 \log A + 30 \log \Delta p \qquad (6)$$

$$PWL = -40 + 10 \log A + 60 \log U_\ell \qquad (7)$$

$$PWL = 34 - 10 \log \epsilon + 10 \log Q + 25 \log \Delta p \qquad (8)$$

where

A = the duct area, sq ft,
Δ_p = the pressure drop across the spoiler, in H_2O,
U_ℓ = the constricted (maximum) flow velocity, ft/sec,
Q = the total volume flow, cfm, and
e = the effective open/total area ratio created by the spoiler for the flow.

Sound power (PWL) is expressed in dB re 10^{-12} Watt.

It is noted that Eq (7) has the same form as the following equation derived by Chaddock,[5] in consistent units, from studies of diffuser noise:

$$PWL = 12 + 13 \log A_{min} + 60 \log U_\ell \qquad (9)$$

where A_{min} is the minimum open area through the diffuser. Even accounting for the difference in the area terms used, there is a significant discrepancy between the constant terms of Eqs (7) and (9). No reasonable explanation can be offered at this time. It should be noted, however, that the validity of Eq (2) has not been established for a spoiler lying, like a diffuser, at the exit plane of the duct.

Better agreement is obtained when we compare our tentative prediction formula with grill noise data published by Marvet.[6] Marvet quotes static pressure losses across the various grills studied, although he makes no attempt to derive an empirical formulation on this basis. For example, the grill designated by Marvet as No. 2 produces a static pressure drop of about 0.5 in. H_2O at a face velocity of 20 ft/sec. The quoted grill area is about 0.6 sq ft. Eq (6) gives, for these values, a total radiated sound power of about 59 dB re 10^{-12} Watt. Reconstructing Marvet's sound pressure level data and assuming an effective radiation area of 3 sq ft at a distance of 1 ft from the grill face, we estimate that, under these flow conditions, the diffuser generates a sound power level of about 57 dB re 10^{-12} Watt.

Two final examples serve to further illustrate the possible relevance of Eq (2) as a noise prediction tool. The first of these, taken from information supplied by Langley Research Center, involved an environmental noise facility in which high pressure air was blown through a 15 in. diameter duct which passed through a series of right-angle turns to produce a high intensity random noise source. It was observed that the total radiated sound, in the subsonic flow region, increased approximately with the third power of the operating pressure. On the basis of the quoted reverberation time of the test cell (about 2 sec), and the quoted sound pressure level in the reverberant field (137 dB re 0.0002 μ bar), the power generated under an operating pressure of 10 in. Hg is computed to be about 146 dB (re 10^{-12} Watt). Eq (2) for a value of $(p_o - p_a)$ of 10 in. Hg. gives an estimated total power radiation of 144 dB (re 10^{-12} Watt). The agreement is good.

The second example comes, again, from the opposite end of the scale - low velocity flow through an air-conditioning duct terminal. The form of the terminal was an initially cylindrical section making a constant area transition to an exhaust slot. The purpose of the unit was to inject comparatively high-velocity air from the side-walls of an auditorium. Tests conducted by the manufacturer showed about 50 dB (re 10^{-12} Watt) of sound power in the middle frequency range at the planned operating pressure. It was apparent from examination of the unit that this part of the noise spectrum was associated with a thin reinforcing ring on the inside periphery of the diffuser. The application of Eq (2) at the quoted operating pressure (about 0.75 in. H_2O), gives a radiated power level of 55 dB (re 10^{-12} Watt). Again, the agreement is satisfactory.

It is interesting to note, in passing, the similarity of form between Eq (8) and Allen's fan equation.[7]

RECOMMENDATIONS FOR FURTHER WORK

The studies to date have been limited to broadband source phenomena with spoilers under relatively smooth in-flow conditions. Undoubtedly, noise levels will increase as the incoming flow is made more turbulent. The static pressure losses will also increase, however, and the same formulation constants might still be anticipated. The interaction of a particular scale of incoming turbulence with a spoiler can be a source of discrete frequency noise. Such a phenomenon is often observed for integrated damper/diffuser terminations. Pure tones have not, however, been examined in the present study.

In this paper we have presented the basic form of a scheme that might have relevance to the prediction of the level and spectrum of sound power generated by flow discontinuities in ducts. In spite of the tentative nature of our formulation at this time, we have demonstrated that good agreement is possible with actual data measured on terminal devices and duct-turns.

It is felt that much more is to be learned from model studies of the sort that have been described above. In particular, we feel that the following steps would be relevant at this stage:

1. extend the experimental velocity range to lower velocities more in keeping with normal design;

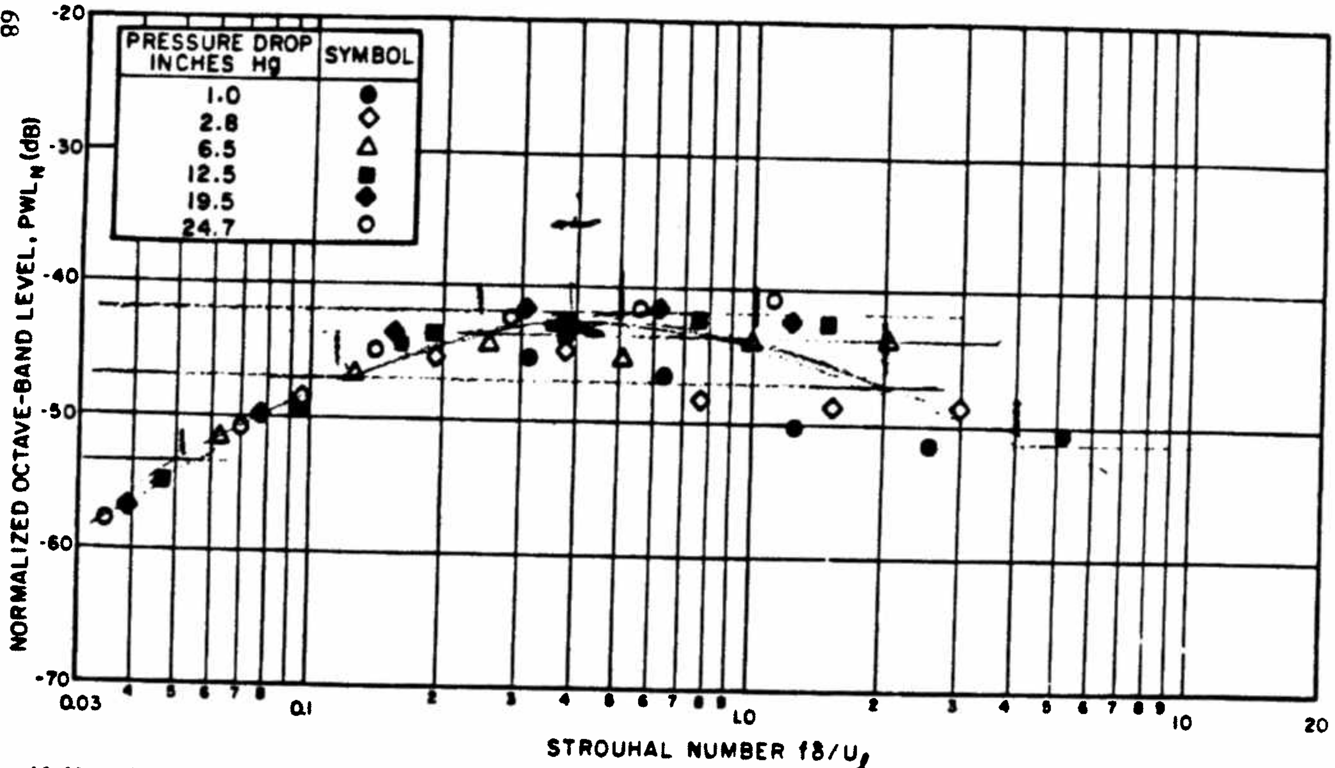
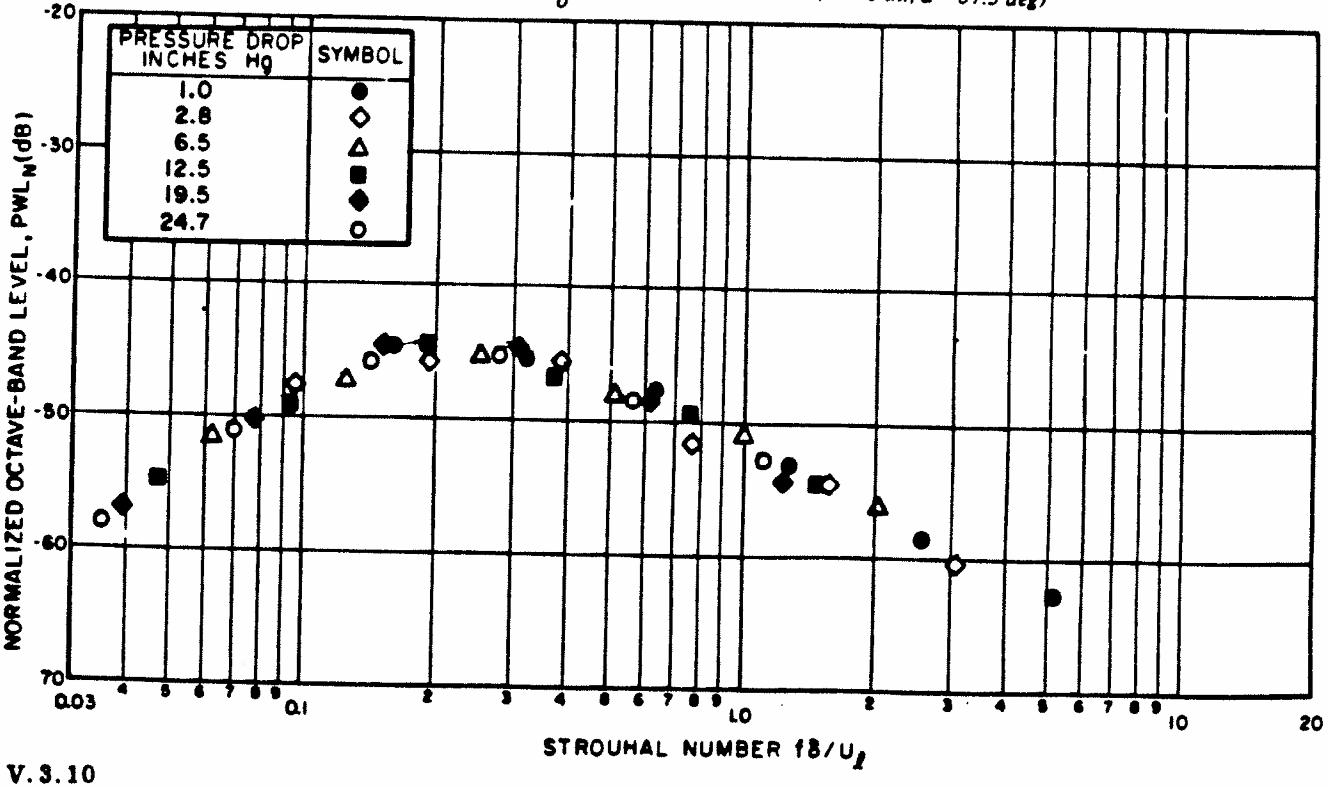


Fig. 13 Normalized octave-band power level vs Strouhal number for 1-in. wide strip spoiler (D = 1.875 in., x = 6 in., a = 67.5 deg)

Fig. 14 Modified normalization of the result of Fig. 13 (f_o = 4000 cps, D = 1.875 in., x = 6 in., a = 67.5 deg)



2. study interaction effects and, in particular, the influence of upstream turbulence upon the nature and level of noise radiation;
3. further develop Eq (5) to more clearly resolve the aerodynamic source mechanisms involved and establish the part played by the parameter f_o;
4. study geometries more pertinent to ventilation systems such as duct-turns, area changes and various diffuser-like termination devices;
5. study the effects, if any, of locating the flow spoiler at the exit plane rather than at some distance upstream;
6. investigate the effect of changes in experimental duct diameter upon the sound power formulae, and
7. relate the experimental studies to real system measurement data.

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2. Recent and as yet unpublished theoretical studies by J. E. Ffowcs Williams and H. Davis at Imperial College, London, have shown that close enclosure of these aerodynamic sources within an infinitely long pipe would tend to reduce the velocity exponents of quadrupole, dipole and monopole mechanisms to six, four and two, respectively. These observations have not been studied experimentally.

3. NASA Contractors Report, CR-679, January 1967.

4. H.M. Fitzpatrick and R. Lee, Measurements of Noise Radiated by Subsonic Air Jets, D.T.M.B. Report 835, 1952. The solid line plot shown on Fig. 8 is based on constants presented in this paper.

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