THEORY AND EXPERIMENT IN AERODYNAMIC NOISE, WITH A CRITIQUE OF RESEARCH ON JET FLOWS IN THEIR RELATIONSHIP TO SOUND

Alan Powell
University of California

INTRODUCTION

When I accepted the invitation to add to existing surveys (1-6) of the interesting study of aerodynamic noise, I had in mind a more generous coverage than I am offering you today. However it soon became apparent that it would have grown beyond reasonable bounds. So, apart from the generalities of Part I below, I shall discuss only various jet flows and their relationships with sound and concentrate on the debatable or rather vaguely-understood aspects, endeavoring to indicate many research problems that remain, both theoretical and experimental, large and small, and how these fit into the general picture. Consequently there is no attempt to present an encyclopedia on the subject, the references serving only the purpose of providing foundation for my comments. These aspects illustrate well the vagueness of the boundary between "ordinary" fluid motion and acoustics, a boundary not recognized by Lord Rayleigh and Sir Horace Lamb. The general situation was summed up nicely by John Leconte, in that we can "look upon all jets as musically inclined," and although he was alluding mainly to the "sensitive" jets of low Reynolds number, it might be applied to all jets—at least if one's ideas of modern music are liberal enough!

Part I
GENERAL THEORETICAL ASPECTS

There are several types of flow, all sound-producing, that can be distinguished. These are characterized by the absence or presence of a solid surface and if present, whether such surfaces are rigid or not. All these have in common the equations of motion, and the solution as a radiation problem shows how the various types are related. If there is no introduction of matter and no externally applied body forces, the equations of continuity and momentum are

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho v_i}{\partial x_i} = 0$$

$$\frac{\partial \rho v_i}{\partial t} + \frac{\partial \rho v_i v_j}{\partial x_j} + \frac{\partial p_{ij}}{\partial x_j} = 0.$$

These can be manipulated (7) just as if the ordinary wave equation were being obtained, except that no terms are discarded and $a_o^2\nabla^2\rho$ is introduced on both sides, a_o being the speed of sound in regions of still fluid far removed from the primary disturbances whose sound-producing properties we are to investigate. This yields the inhomogeneous wave equation

$$\frac{\partial^2\rho}{\partial t^2} - a_o^2\nabla^2\rho = \frac{\partial^2}{\partial x_i\,\partial x_j}\left\{\rho v_i v_j + p_{ij} - a_o^2\rho\delta_{ij}\right\}$$

Strictly speaking this is an integral equation. But if the sound-generating flow is assumed given (and therefore unaffected by the sound produced) then sound perturbations can be found well away from it. Then the "right-hand side"—in other words the source distribution—is given and the solution is well known, from electromagnetic theory, for example. It can be expressed in a useful form for our purpose by using Gauss' theorem (8) twice over on the complementary function, the result being

$$4\pi a_o^2\,(\rho(y,t) - \rho_o) = \frac{\partial^2}{\partial y_i\,\partial y_j}\int (\rho v_i v_j + p_{ij} - a_o^2\rho\delta_{ij})^*\,\frac{dV}{r} \qquad \text{(a)}$$

$$+\frac{\partial}{\partial y_i}\int (\rho v_i v_j \ell_i + p_{ij}\ell_i)^*\,\frac{dS}{r} \qquad \text{(b)}$$

$$-\int \left(\frac{\partial \rho v_i \ell_i}{\partial t}\right)^*\frac{dS}{r}\,. \qquad \text{(c)}$$

Here r is the distance from a point x in the sound-generating flow to the point y at which the perturbations are estimated, and the asterisk indicates a time retardation corresponding to the transit time over that distance.

The first group (a) alone survives in the absence of solid boundaries and has provided the basis of our understanding of sound production by turbulence. While little has been done for shear flow turbulence, as such, isotropic turbulence has been considered (9) and the results are very encouraging when applied to turbulent jet flow (10). An important effect for a high-order source is the susceptibility of the directional characteristics to motion through the medium—the introduction of moving axes (rather than the resolution into higher-order stationary sources) permits a very simple point of view to explain the gross directionality of the sound field so characteristic of turbulent subsonic jets (7). The question of the noise generated by isotropic turbulence has been the subject of more recent attention (11,12), and shows well the need for some careful experimental work measuring the rather low acoustic output of a stationary mass of isotropic turbulence. Turbulent wakes have not yet been considered theoretically or experimentally, except in connection with the vortex noise of propellers.

The same approach may be used to study the scattering of sound waves by turbulence, or more relevant here, the scattering of acoustic energy from the interaction of turbulence with shockwaves (13,14). An interesting result of this is that most of the acoustic energy tends to catch up with the shockwave, and so be absorbed by it. This rather general approach is compatible with the result of studies of the interaction between a single vortex and a shockwave (15,16), obtained by superimposing shear waves, the effects of which had been considered earlier (17). Although these studies are very approximate, they do account for the characteristic directional effects observed experimentally (18) (Fig. 1). Of course shear waves are just one of the three modes of elementary motion perturbing a uniform flow, the others being sound itself and temperature (entropy) (19,20,21). It is interesting that the shockwave acts as an amplifier for colliding sound waves, but practically absorbs those catching up with it.

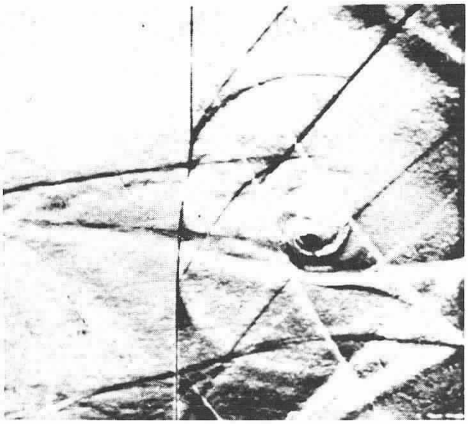

Fig. 1 - Vortex-shock wave interaction. The vortex is the starting vortex shed from an aerofoil off the picture to the left as a shockwave traversed it from left to right. The whirls to the right are entropy fronts associated with this. The shockwave was then reflected from the plane right-hand end of the shocktube, interacting with that starting vortex. The impulsive radiation is in the form of an arc centered on the vortex and intersecting the now distorted shockwave, those parts in its vicinity being the most powerful. (From M. J. Hollingsworth and E. J. Richards (18).)

There are several important applications of the principles just mentioned. The noise in supersonic wind tunnels is one aspect. Another is the interaction of eddies with the shockwaves of supersonic jet flow, being particularly important for cold jets, when the interaction appears to account for almost the whole of the sound output. The situation when the eddy is centered on the edge of a jet—or the related situation when the jet acquires a sinuosity—has not been studied in detail: the overall picture is shown in Fig. 6, in which, however, the details of this particular aspect are obscured.

The second group (b) concerns surface effects, suggesting that surface stresses act like dipole generators, supporting an earlier and more intuitive approach (22). This certainly seems to be the case for the fluctuating forces on circular cylinders (23), and is presumably the case in the edgetone type of phenomena. It is important to notice that the dipole as found is an artifice, for there is no physical dipole supplying energy; this can only come from the volume of the fluid about the obstacle.

But for plane surfaces, the contribution from fluctuating pressures is thought to vanish (24,25) and, with fairly loose restrictions, that from shear stresses also (25). This then suggests that quadrupole generation from the volume of turbulence in a boundary layer may be the most important source of noise when the surface is rigid (26).

When the surface is not rigid, the boundary layer stresses—particularly pressure—set the surface into motion (27-30) and in several practical systems this may be the predominating effect. Although the general principles are now clear, more information concerning the pressure fluctuations at the wall is required. So far spectra and a few space (31) and space-time (32) correlations at subsonic speeds have been made. The patterns of pressure convected across the "fixed" surfaces do not appear to be as "frozen" as might be necessary for some simple theoretical concepts to apply. A convection effect is certainly present, the convection velocity being a rather large fraction (0.8 or so) of the free stream velocity. This tends to draw attention to the region of irregular vorticity fronts of the boundary layer. The surface becomes a sounding board, and radiates into the space away from the flow according to expression (c). On the other side the presence of the flow itself may influence the radiation; and if the flow is at anything but a very low Mach number the directionality effects will be influenced by the moving source effects. In addition the first term of expression (b)

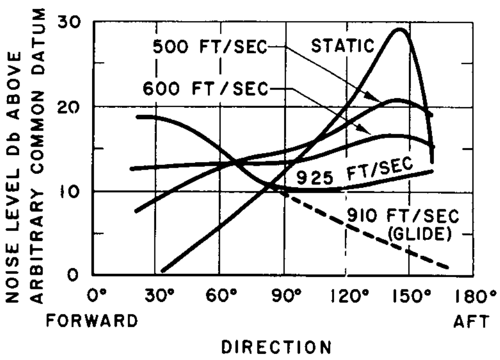

Fig. 2 - Noise of a jet aircraft in flight. As the forward speed of the aircraft increases, the jet noise, mainly radiated rearwards, decreases and the noise due to the motion of the airplane through the air increases and is radiated in the forward direction. (Constructed from unpublished data kindly supplied by Dr. H. E. von Gierke.)

suggests that the motion of the surface results in a dipole radiation because of the effective introduction of momentum across the fixed surface of the integral—this aspect seems to have been overlooked.

The noise sources due to the passage of an airplane through the air are complex in character—all of the above types being present to some degree. Its motion through the ambient atmosphere results in the generated noise having a marked preference for forward radiation, increasing with flight speed; while the jet noise displays a lessening of its downstream preference, its level naturally decreasing because of the reduced relative jet velocity. These effects are shown very well in Fig. 2.

The distributions of simple sources represented by expression (c), already mentioned, can be used in connection with fluctuating flow from an orifice, such as for pulse jets or organ pipes. On the other hand, the continuity equation could be supplemented by a source of matter term, and the result could be used in the same cases by employing suitable boundaries for the integrals; and it should be supplemented by a dipole term if the surrounding fluid is in motion, corresponding to its deficit of momentum.

Although the general theory of the relationships between vorticity, pressure and entropy (21,33) cannot come within the scope of this survey, it seems to me that the development of such aspects is likely to be very revealing and should lead to a better understanding of many scattered facets that so far have not been too closely knitted together.

Part II
JET FLOWS DISPLAYING DISCRETE FREQUENCIES

THE SENSITIVE JET AND FLAME

The sensitivity to external disturbances of a jet, operating somewhat below its critical Reynolds number for early turbulent development, seems to be a key to more than one phenomenon. Thus it is useful to mention the well-known sensitive jet or flame, although in itself it has little to do with the generation of sound.

The visible dipping of the flame, say of coal gas, is an indicator that increased jet mixing has taken place prior to the original flame front, tripped by certain disturbances of the jet. These disturbances are traditionally acoustic—thus indicating that the jet is really sensitive!—and ordinarily arise from distortion of the jet as it leaves the nozzle (34,35). This is confirmed by the fact that sound waves propagating along the jet axis are usually ineffective, as are the pressure antinodes of a standing-wave system and laterally propagating waves shielded from the orifice. Contrary to earlier reports (34), it appears that vibration of the orifice itself results in effects

Fig. 3 - The "sensitive" jet. A laminar flow jet emerges from the slit exit and is disturbed by sound waves whose particle velocity is in a horizontal direction across the picture. The disturbance amplitude presumably grows exponentially until it is large enough to result in vortex development ultimately disintegrating into turbulence. (This photograph was taken by G. B. Brown (35).)

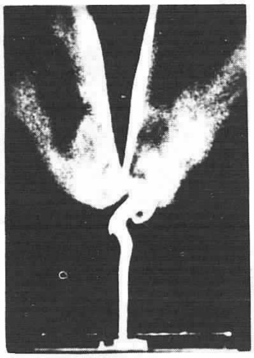

Fig. 4 - Low-speed edge tones. The disturbed jet flow is very similar to that of Fig. 3, the action of the edge replacing the externally applied acoustic disturbances. (G. B. Brown took this photograph using a stroboscopic method (36).)

quite similar to those caused acoustically (35). This is a necessary requirement if ideas based upon the classical dynamics of jet instability are valid. Provided that a small sinuosity of the jet, caused by distortion as it leaves the orifice, lies in the unstable regime,* it will develop to produce the beautiful (nonlinear!) vortex forms shown in Fig. 3, which sooner or later degenerate into a mass of turbulence. The phenomenon takes place at relatively small Reynolds numbers when, lacking externally applied disturbances, a substantial portion, if not all, of the jet flow would be of a laminar character. Thus small periodic disturbances in the pertinent range of Strouhal number can completely alter the appearance of the jet flow; the disturbed jet produces sound, but it is of quite negligible proportions. However, an undisturbed laminar jet can produce <u>no</u> sound: it is steady flow.

*It is worth mentioning that such jets have a very unstable regime. For example, assuming a square velocity profile and neglecting viscosity, "for a frequency of 126 cps and a slit width of 1 mm, stream velocities of 380, 150, and 100 cm/sec result in disturbance amplifications over a distance of 5 mm of 30.8, 8400, and 54,000 respectively" (Ref. 8).

EDGE TONES

The edge-tone phenomenon occurs over more or less the central region of the ranges of Strouhal and Reynolds number which limit the sensitivity characteristic just described (36), and the disturbed flows have a visual likeness that is hard to deny, except of course in the neighborhood of the edge itself. A pair of photographs showing this are Figs. 3 and 4. This fact is important, and recent (37,38) ideas on the mechanism of edge tones rely upon it. There has been a considerable controversy concerning edge tones (36), and although the recent ideas are derived from rival camps, and are so developed, I think they do in fact amount to the same thing.

One method (37) develops earlier observations (39) that vortices are cast off, or at least move along the edge, from the boundary layer adjacent to the edge itself as a result of the passage of the disturbances in the stream. These new vortices fit in with those of the jet, already developed. This redistribution of vorticity around the edge results in an induced velocity at the jet orifice, supposedly giving rise to a new vortex springing from it; the rest follows.

The other (38), working from Schlieren photographs of the high-speed variety of the phenomenon, suggests that the stream disturbances result in sound being radiated from the edge, of opposite phase on each side of the jet as shown in Fig. 5. As a consequence the stream is disturbed as it leaves the exit, adopting an unstable sinuous form as it does in the case of sensitive jets. (The perturbation of the former uniformly distributed vorticity presumably could be crudely represented by a series of point vortices—this additional simplification then corresponds to the first mentioned point of view.)

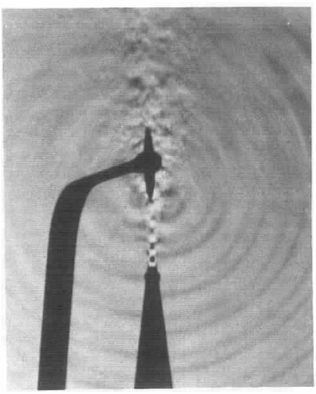

Fig. 5 - High-speed edge tones. The acoustic radiation is powerful enough to be photographed. It clearly emanates from the vicinity of the edge and is of opposite phase on each side of the initially supersonic jet, being asymmetric like the stream disturbances. The structure of the wavefronts is interesting, being far from sinusoidal (which it sometimes is), and the stream appears to offer a high enough impedance to inhibit the formation of a simple dipole field (after A. Powell (38).

Unfortunately these theories were respectively styled "hydrodynamic" and "acoustic" by their authors, which seems to have resulted in an emphasis on their detailed differences (4) at the expense of their essentially common theme. At very high speeds, the influence at the orifice can be justly called "acoustic," since the wavelength of the disturbances from the edge is relatively short; but at lower speeds—traditionally, that is—the orifice is only a fraction of a wavelength from the edge and so is in the near field. Thus here the action has little relation to the compressibility of the fluid, and so "hydrodynamic" is more appropriate. It is simply a question of "far" and "near" fields of an acoustic source. Surely the vortex formations springing from the edge must be directly associated with the fluctuating, and principally lateral, force on the edge itself, occurring when the cross flow at the edge causes separation. Incidentally they cannot always be distinguished in the published photographs (38,40), so "vortices" may be a rather restrictive description of the redistribution of vorticity which undoubtedly takes place at the edge (and this probably applies to the orifice too). Schlieren photographs (38) in the high-speed case show the seat of the acoustic motion to be on the surfaces of the edge and this is probably confirmed by low-speed hot wire measurements (41).

Microphone surveys reveal directional properties which are characteristic of dipoles (42). This is just what one would expect from theoretical reasoning, (indicated by the pressure part of $p_{ij}\ell_i$ in group (b) of Part I). However, the directional pattern sometimes displays an apparently more complex form than the dipole's figure of eight, in the classical low-speed case (42); in the high-speed case the radiation is much more suggestive of simple source radiation, the high-velocity stream apparently offering sufficient impedance to the lateral motion to prevent a dipole forming from the generation of the sources arising from differential flow on either side of the edge. Sometimes the sound wave radiated away is far from sinusoidal (38,42) (see Fig. 5, for example). It would be particularly interesting therefore to study the details of the flow about the edge and to measure the forces acting upon it. It is interesting to note in passing that the edge may be relatively large or quite small, from the point of view of the circulation about it, since it can be replaced by a wire (39). In the latter case the connection between the new eddies springing from the wire and the force upon it is evident: there is clearly some analogy to aeolian tones, for which the effective dipole concept is now quite well established (23). It is relevant—indeed, it seems essential—that the vortex system shedding from a cylinder can have its frequency forced to be in step with that of externally applied disturbances (43), if they are large enough.

The foregoing type of mechanism of edge tones has been subject to doubt in the past because of a few "crucial" tests. For example, a jet having no edge was placed near one having an edge (41). The failure of the edgeless one to show vortex development was taken as evidence that the feedback from edge to orifice was not propagated as a wave; but, the disturbing signal at the edgeless one would be reduced, because of the increased distance from the assumed effective dipole at the edge, to not more than about 1/125 of its proper value (judging from the published data). The test is therefore not so crucial as it would seem at first sight. Again, concerning the intensity required of a loudspeaker to produce similar vortex formation in an edgeless jet (36), "the loudspeaker had to be easily audible, whereas no audible edge tone occurred." This would have been a very impressive argument had the velocity fluctuations at the orifice been directly compared, an experiment worthy of attention.

It is interesting that a very much simplified model of the jet-tone flow yields disturbances having an encouraging likeness to some of those photographed (44). Here the jet is considered as a continuous stream of particles of mass subjected to transverse pressure gradients proportional to the displacement of the "stream" at the edge (45). The apparent success of the method lies partly in the suitable choice of a necessary arbitrary function, and also in that the instability of the jet photographed was relatively very small as such jets go.

I hope that this attempt at bringing together the "rival camps" is of some avail, and that most of the numerous theories ("acoustic," "hydrodynamic," "impulse," "vortex street," etc.) will be recognized as being different emphases upon the same essential theme. There seem to me to be no surviving conflicts of any import, some of the very earliest theories containing the essence of the matter, despite the considerable experimental difficulties of those times. However, while I think the overall picture is taking shape, we are still far from fully understanding the details of it. In particular, the sound intensity cannot yet be calculated,* ab initio. Since this is

*However, definite progress along the lines indicated is being made and there is hope of an early approximate solution. A development of the "gain criterion" (36) reveals the particular importance of a certain nondimensional parameter $h^3\omega/Vb\delta$. Here h is the effective orifice-edge distance, ω the angular frequency, and V is the jet velocity from the orifice of width δ and length b. The appearance of the slit length b is interesting since formerly no significance had been attached to it.

supposed to be a result of a feedback mechanism, it would seem necessary for nonlinear effects to play an essential part in determining the amplitude. This role may be played by the stream disturbances becoming "large" (developing into vortices), perhaps by the flow about the edge becoming less effective: in any event the "gain round the cycle" must exceed unity during establishment of the motion, but clearly must equal unity when established (38).

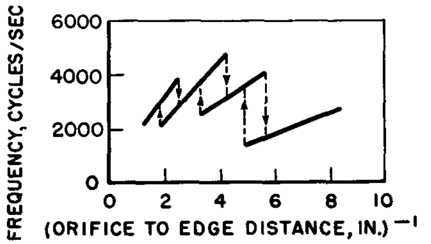

Fig. 6 - Edge-tone frequencies. The wavelength of the disturbances of the jet stream increases steadily as the edge is moved away from the orifice, but after a certain point a jump occurs when another disturbance wavelength fits itself in between the orifice and the edge, restoring the wavelength to that corresponding to the most unstable regime. Note the prominent hysteresis effect. (Data from G. B. Brown (36).)

Most edge-tone studies have been concerned with the flow itself, and especially with the frequency characteristics, a distinguishing feature being the jumps in frequency (Fig. 6). These occur when either the height of the edge or velocity is varied, in such a manner that the disturbance wavelength is never far removed from that of maximum instability. What few sound intensity measurements are available (42) indicate that the acoustic power is of the order of a hundredth of the jet kinetic power: a surprisingly high figure in view of the extremely low speeds involved, although the presence of a baffle may have increased the acoustic efficiency above its normal value.

The proximity of reflectors or resonators greatly influences the edge-tone characteristics (38,42,46). The overall picture is now much more complex; the salient feature is that the pressure fluctuations at the edge may disturb the stream at the orifice more effectively via the action of the reflector or resonator, and so impress upon it their characteristic frequencies. This situation is clearly related to the steady tone of an organ pipe, although its establishment is another matter (47).

In some unreported tests using a 4:1 elliptic nozzle at a Reynolds number of about half a million, the author found it easy to produce edge-tone phenomena, and also to demonstrate the effects of reflectors. The acoustic power generated was uncomfortably high, since the jet exit had a minimum dimension of one inch, and the exit velocity was near sonic! The acoustic power was an appreciable fraction of the jet power, perhaps a tenth.

OTHER DISCRETE VORTEX PHENOMENA IN SUBSONIC JETS

There is another class of jet phenomena in which the development of discrete vortices is a characteristic; however, the situation differs from the foregoing in that while appreciable sound is generated, the effect of the sound* so generated on the jet itself is not of recognized importance.

"Jet tones" are intimately connected with the vortex shedding of jets issuing from orifices. These orifices must have a sharp entrance (48), so that flow separation occurs within the orifice. The vortices are thought to be conceived in this region of separated flow and escape periodically in the embryo stage, resulting in the toroidal vortex structure of the jet (49), as shown in Fig. 7. The nature of the sound-generating

*This word is used loosely!

mechanism has yet to be investigated: it seems probable that the flow rate fluctuates in sympathy with the eddy shedding, so giving rise to a "simple source" type of sound generation. When a circular orifice is this, the characteristic frequency is roughly proportional to the exit velocity and inversely proportional to the axial thickness of the orifice (51,52). When it is comparatively thick the frequency is more dependent on the diameter instead of the thickness. But now a very interesting facet emerges: the frequency for a given geometry is not unique, since there is a choice of several frequencies for a given velocity. There are such that if the thickness is altered by one or two times the diametral dimension then the choice of frequencies remains substantially the same. This naturally leads one to contemplate on the eddy structure, in the stagnant region within the orifice, and what controls it. These phenomena range over Reynolds numbers from some hundreds to about 10,000 for various configurations. When the orifice is preceded by a pipe, the situation is analogous in some ways to the edge-tone system supplemented by a resonator. The pipe has its set of resonant frequencies depending upon the geometry, and the formerly continuously varying jet-tone is greatly reinforced at these frequencies, sounding "pipe tones" (53,51). No data appear to be available concerning the efficiency by which jet tones or pipe tones give rise to acoustic energy.

Fig. 7 - The flow of jet-tones. Flow separation occurs within the orifice and the periodic shedding of the vortices with the associated fluctuation in flow results in the characteristic toroidal vortex formations. (From a photograph by W. H. Darlington (50).)

An interesting variation on this scheme is to replace the sharp entrance to the orifice by a carefully designed throat to eliminate flow separation there, but opening out the nozzle exit to cause flow separation from the curved surface. At a Reynolds number of the order of 800,000, regular though turbulent vortex formations were disclosed by Schlieren photographs (54) (one of which is shown in Fig. 8) accompanied by an increase in sound output of up to nearly a hundredfold (55), thus raising it to nearly a hundredth of the jet power. The turbulent jet noise was quite swamped by the latter, which had a discrete frequency of roughly 0.4 V/d. The directional property of this radiation is much more uniform that for turbulent jet noise, and so is suggestive of the vortex formations being associated with a fluctuation of the mass flow, constituting a simple acoustic source. (The simple source effect almost certainly overpowers the dipole effect arising from the momentum fluctuations.) To account for the acoustic power on this basis the mass flow would have to fluctuate by roughly $\pm 1/20$ of the mean value, which seems reasonable. The interesting question is: do the disturbances of the vortex formations control the point of flow separation from the nozzle wall so giving rise to embryo eddies, or can it be that a nozzle

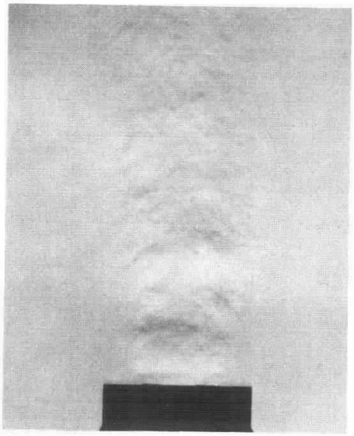

Fig. 8 - Vortex formations at high speed. In this case the separation occurs at the diverging nozzle exit, and the Reynolds number is sufficiently high (800,000) for the flow to be in the turbulent regime except for a narrow "laminar collar." The regular vortices do not have the clear definition of the jet tone flow of low Reynolds numbers. (From A. Powell (54).)

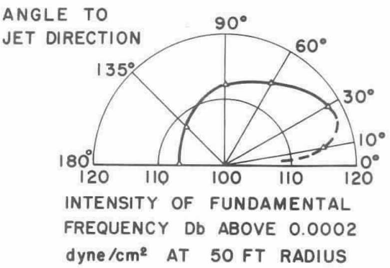

Fig. 9 - Directional distribution of pulse-jet noise. The diagram refers to the radiation at the fundamental frequency. The average value can be calculated by assuming the action to be that of a classical simple source, but the deviations from that average are not easily accounted for. Refraction of the sound seems to occur very close to the jet direction. (Reconstructed from data by A. Powell (56).)

contraction results in convected pressure waves being reflected to a sufficient extent,* and so yield "resonant" frequencies?

The last variation to be discussed in this section concerns the pulse jet. The periodicity superimposed upon the mean flow is in this case controlled by resonance properties of the combustion chamber and exhaust nozzle; it is maintained by the periodic combustion of fuel, again controlled by the resonance properties. Thus, while the heat supply is variable, and the flow through the engine likewise, the whole process is self-governed and so bears a strong resemblance to "pipe tones." Presumably the fluctuating velocity results in toroidal vortex formations. It is logical therefore to include the pulse jet under the present grouping. The pulsating flow can be looked upon as constituting a simple source (either expression (c) taken over the jet exit, or a source of matter distribution enclosed in the volume in the neighborhood of the exit) and this leads to a good approximation to the acoustic power produced (56,57). While the energy of the fundamental is apparently easily dealt with, the same is not true for the harmonics—and sometimes the acoustic power is very rich in harmonic structure (58,59), presumably because any harmonics of the flow rate would be amplified, relatively, as a consequence of the higher radiative efficiency of higher frequencies. In practice the directional properties are nowhere near as uniform as for the simple source, the levels close to the jet direction exceeding those in the opposite direction by a noticeable amount, as indicated in Fig. 9. In the particular case considered (56), this asymmetry could not be accounted for either by taking into account the pulsations of the intake or the fluctuating thrust (expression (b) in one form or another). This is really not remarkable, since the acoustic approximations, requiring small amplitude fluctuations, can hardly be expected to be very good when the velocity pulsations actually exceed the ambient speed of sound. Perhaps the real question rather concerns why the simple acoustic theory should yield such good results! Two other features are worth noting. Firstly, the levels close to the jet fall very sharply, presumably because of refraction effects; and secondly, it appears that turbulent

*Sound waves entering a nozzle with the flow certainly undergo a large reflection according to the author's nonlinear one-dimensional approach. Calculations for the inverse case are not complete at the time of writing.

mixing may account for an appreciable contribution to the high-frequency end of the noise spectrum. Thus while the dominating feature can be readily accounted for, many details remain for further investigation.

It is interesting that the classical jet tones and edge tones, with or without resonators, being essentially laminar flow phenomena, all appear again in one form or another in turbulent flow regimes. Further, a close analogy with edge tones exists with certain highly supersonic jets, as will be discussed next.

Finally, before turning to high-speed phenomena proper, I would like to pose the following question. Wakes and jets have a great similarity, one often being considered the inverse of the other. Does this similarity extend, in some way or another, to the details of the flow mechanisms governing the vortex production behind bluff bodies and in jets? Again, would the placing of an edge in the vortex street behind a cylinder result in a flow having any similarity to edge tones? This seems a very worthwhile experiment, which I do not think has been done. Finally, is it at all possible that the eddy formations in turbulent jets exert any influence on the creation of embryo disturbances, in "ordinary" circumstances? Such questions are very fundamental and their joint study may well yield a more complete understanding than would result from their being treated separately.

THE CHOKED JET

When a jet is operated at a sufficiently high pressure ratio, shockwaves exist in the jet stream (unless the nozzle happens to have just the correct amount of divergence). These shockwaves form at more or less regular intervals along the jet in connection with the "cellular" structure of the flow. The phenomenon with which we are now concerned happened to be discovered by optical means (55) for choked (nondivergent) slit-type jets. For these the frequency of the characteristic motion is very steady (60,61), setting in quite suddenly at a pressure somewhat higher than the critical and remaining until pressure ratios of about seven are reached (62).

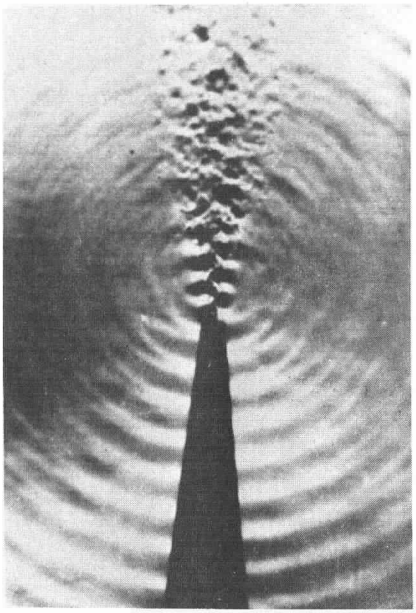

Fig. 10 - Choked-jet noise. The flow is very similar to that for high-speed edge tones; but here the interaction of the eddy formations with the regularly spaced standing shockwaves produces the sound. The jet pressure is considerably higher than the edge-tone case of Fig. 5. (This photograph is by M. G. Davies (62).)

The direction of the flow leaving the edge of the orifice is governed by the external atmospheric pressure there, and hence by fluctuations of that pressure. Thus eddies in the flow are born, and these grow and their motion along the jet results in sound being generated as they pass through the shockwaves, since the boundary of the jet at these positions moves so as to accommodate the varying flow conditions. If a train of eddies is present, then their spacing can be such that the sound waves arriving at the orifice from the various shockwaves reinforce each other, sometimes having the appearance shown in Fig. 10. Careful measurements of eddy spacing and velocity show that this is in fact the case (60-62). It is interesting

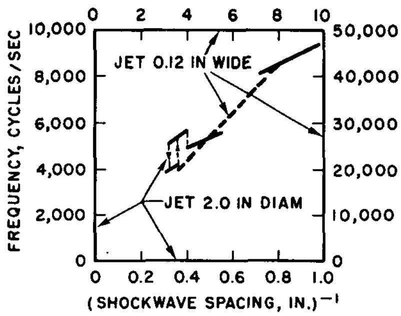

Fig. 11 - Choked jet frequencies. The jumps in frequency arise from a rearrangement of the eddy pattern so that the disturbances propagated from each shock reinforce each other at the orifice. The two-dimensional (slit) jet displays no such discontinuities. (Data reconstructed from A. Powell (61).)

that while most of the fundamental radiation is thus in the upstream direction, the same conditions resulted in the prediction that sound of twice that frequency would have a sharp preference for radiation at approximately right angles to the jet stream and this, happily, was found to be the case (60). The efficiency by which the kinetic energy of the jet stream is converted to acoustic energy is high, being of the order of from a hundredth (61) to a tenth (62)—a very high figure.

For jets having circular orifices, the phenomenon bears a closer analogy to edge tones in that jumps of frequency take place (61) (Fig. 11). While the eddy formation for the slit jet is always of an alternate structure, it appears that just the first stage for the round jet has toroidal vortices (63). It appears to be a fortuitous circumstance that the increase of spacing of the shockwaves with pressure ratio happens to be such that no jumps are present in the case of the slit jet.

There are several reasons why this "screech" may not make an appearance in a supersonic jet. Clearly the absence of shockwaves will guarantee this; a properly designed convergent-divergent nozzle thus will exhibit a limited range over which "screech" is absent (64), while the equalization of pressure at the nozzle by a perforated sleeve achieves the same result over a wider range of pressures (55,65). Like the jet tones of a completely different flow regime, any roughness of the edges of the orifice tends to inhibit the mechanism (55), presumably by thickening the boundary layer and so decreasing the instability of the eddy formation. This of course is suggestive from the point of view of noise-reduction devices (66). Not only does the mechanism display features in common with edge tones, but also the status of research is similar: the essentials of the mechanism are understood, and certain isolated aspects of it are amenable to analysis under simplifying conditions. The frequencies can be found; but the calculation of sound intensity, ab initio, is quite beyond our present means.

This characteristic motion appears to be confined to "cold" jets. There are probably two reasons for this. A hot choked jet has a much higher velocity, and this results both in increased stability of the jet boundaries and greatly increased noise due to the inevitable turbulent mixing process, which would also tend to mask any discrete frequency phenomena. Certainly indications so far are that it is not of importance for jet engines (67) or rockets (68). Here the noise from turbulent mixing is all important, and in the next section the question of how much of the experimental data can be explained by theory is dealt with.

Part III
JET FLOWS DISPLAYING NO DISCRETE FREQUENCIES

THE TURBULENT JET

In recent years the turbulent jet has received much attention, and this section will be devoted to aspects concerning noise generation in the absence of the discrete frequency phenomena associated with the periodic vortex formations discussed in the preceding section.

The overall picture of the spread of a turbulent subsonic jet is now well established (69,70). Initially the turbulence springs from the shear layer adjacent to the exit, spreading outwards and inwards at a steady rate. After about four-and-a-half-diameters distance the turbulence reaches the axis, so annihilating the cone of "potential" flow, after which the axial velocity commences to fall in a roughly hyperbolic manner with the distance from the exit. The profiles of mean velocity soon become similar, suggesting profitable techniques of analysis; but unfortunately the turbulence levels do not fall in line until much further downstream, due to the persistence of the high-turbulence levels at positions corresponding to the original high-shear layers. This basic structure of course suggests that intense high-frequency radiation emanates from the region of high turbulence and shear near the exit, the frequency falling in the downstream direction. The intensity would be expected to commence to fall sharply in sympathy with the axial velocity in downstream locations. Indeed, early exploratory experiments (71) indicated just this. The success of similarity ideas on the mixing problem probably encouraged the application to noise generation (72,73); but it is apparent that the proper form of the similarity rules is not yet known to us, despite the theoretical concepts at our disposal, and that existing efforts should be regarded as first attempts.

Perhaps the principal difficulty lies in the fact that it is far from easy to design an experiment to yield the distribution of sound sources (of varying frequency bands) within the volume of the jet. Space, or space-time, correlations can indicate effective regions associated with the areas where the noise leaves the jet boundaries (74). Measurements very close to the jet flow itself (75) mainly concern the very local turbulent fluctuations, so that the connection with the noise sources distributed throughout the volume of turbulence must be regarded as being rather vague, at least until proved otherwise. A method of some promise (in principle at least) seems to be the correlation between points in the turbulent field itself with a point(s) in the acoustic field. (The difficulty, of course, is with Doppler effects, but I imagine this might not be insuperable.) But then one might just as easily (?) measure the correlations required by the general quadrupole theory (7).

The quadrupole theory certainly yields acoustic powers of the right order of magnitude, and it accounts for the gross radiation characteristic of marked asymmetry (10). There are, however, many aspects that are not yet fully understood, and it is upon these I wish to dwell.

The directional properties of the radiation from turbulent jets appear to follow no simple law, although the principal characteristics can be easily stated and accounted for in a general manner. Most of the radiation from jets of low or moderate speed occurs at angles noticeably less than 45 degrees to the jet axis (71,76,55,77), the lower frequency being found closest to the axis, as illustrated in Fig. 12. Theoretical ideas are in accord with this, since both convected lateral quadrupoles associated with the shear layer and convected assemblies of longitudinal quadrupoles associated with regions of weak shear further downstream will display this property. However, additional sources, especially longitudinal quadrupoles normal to the axis, have to be postulated to obtain a satisfactory agreement at all angles (65,76). The possible influence of convection and refraction effects upon the directional properties have not been very seriously considered (2) although there is almost certainly some effect in view of the very noticeable decrease in noise levels as one approaches the jet in positions where the energy of the jet is almost spent.

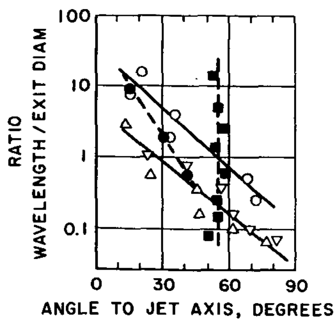

Fig. 12 - Angles for most intense radiation. The radiation of any frequency band (here represented by the ratio of wavelength to jet exit diameter) reaches its maximum intensity at a definite angle from the jet axis. The pair of parallel lines refers to jet engine noise, the dotted one between them to cold air jets. Here, the higher the frequency, the greater will be the angle from the jet axis at which the maximum occurs. Rocket noise, represented by the vertical line, displays its maximum for all frequencies at about the same angle. (Data respectively collected from F. B. Greatrex (57), H. E. von Gierke et al. (77), L. W. Lassiter and H. H. Hubbard (78), and J. N. Cole et al. (68).)

As the eddy convection velocities increase for faster jets, the eddy structure will more and more tend to generate its own system of shockfronts (65,60,10) and this may account for fast jets (i.e., those probably having eddy convection at supersonic speeds) displaying maxima at increasing angles from the axis. A helium jet exhausting at 2600 ft/sec displays the maximum intensity at very nearly 45 degrees to the axis (78), while rockets, having exhaust velocities of upwards of 5000 ft/sec, have maxima, apparently for all frequency bands, at angles between 50 and 60 degrees (68). The main directional properties of these three types of jet are shown in Figs. 12 and 13. If the radiation in these cases is essentially associated with the eddy shocks, then it is implied that the eddies accounting for the major noise contribution have a convection velocity of rather less than half the exit velocity. That does not seem unreasonable.

Another outstanding characteristic of turbulent jet noise is its rapid variation with jet velocity. The quadrupole theory yields the well known similarity form $\rho_j^2 d^2 V^8/\rho_o c_o^5$ when the field of quadrupoles is not convected. By some fortuitous circumstance, experimental data produce not only the d^2 but also the V^8, to a good approximation. However it should really be looked upon as an empirical result, since in accounting for the characteristic directionality the convection effects (10) necessarily supplement the above form by a not at all negligible positive power of Mach number V_j/c_o. Of course any such form should also be supplemented by an unknown function of Reynolds, Mach number, temperature ratio, density ratio, and any other parameter that may have a bearing upon the noise production.

One naturally tends to think of characteristic frequencies of the radiated sound in terms of Strouhal numbers (79,80). One might choose the peak of the spectrum (on an "energy-per-cycle-per-sec" basis) as the characteristic frequency. Although the spectra are rather flat, there is a definite tendency for this peak frequency of the total acoustic power to increase less quickly than the velocity (resulting in a decreasing Strouhal number), as shown in Fig. 14. Most of the energy however is contained by frequencies higher than the true spectral peak, the peak of an octave analysis being more representative of the overall noise produced, since it corresponds roughly to the median of the energy-frequency distribution. On this basis the departure from proportionality is marked, both at individual points (55) (Fig. 15) and for the total sound power (76). The more pronounced effect in the latter cases arises because of the dependency of the spectral shape on the velocity, it being much flatter at low speeds. This is in itself a noteworthy fact and is clearly shown in Figs. 14 and 15. It also raises the question of what is the most significant choice for a "characteristic frequency"; the peak of the energy-per-cycle-per-sec spectrum, the peak of the energy-per-octave (or similarly proportional) spectrum, or the frequency corresponding to the median of the energy? A departure from Strouhal concepts also arises in connection with the directionality of various frequency bands of the noise. The angle of the peak seems to be more dependent upon the ratio of wavelength to exit diameter (2,76), rather than upon Strouhal number.

It has been suggested that there is some possibility that the turbulence is "damped" at high Mach numbers (10), and since presumably the smallest eddies would be most affected, it may affect the shape of the spectrum and so be contributory to the failure of proportionality with Strouhal number. There is some experimental evidence that this may be so (70,81) (at least for rms turbulence levels) although there will remain some doubt until suitable Mach number corrections have been applied (82).

Density and temperature effects of the jet flow itself are still somewhat uncertain. Experiments using different gases (air, helium, and Freon) at essentially the same

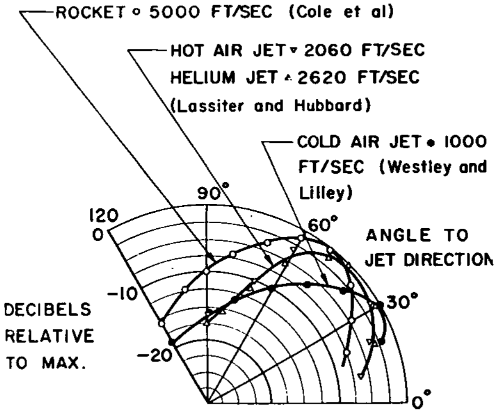

Fig. 13 - Directional characteristics for overall radiation. This plot concerns the directional distribution of the total noise output. As the jet velocity increases, the maximum moves outward from the jet axis. The cold helium jet and the hot air jet have very similar distributions. (Data obtained from the following sources: cold air jet from R. Westley and G. M. Lilley (71), hot jet from L. W. Lassiter and H. Hubbard (84), helium jet from L. W. Lassiter and H. H. Hubbard (78), rocket from J. N. Cole et al. (68).)

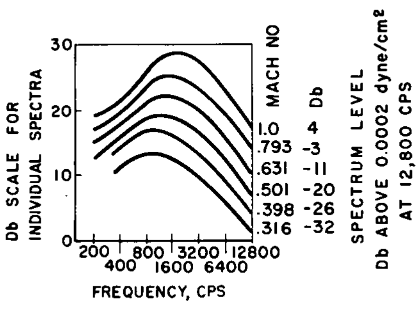

Fig. 14 - Spectrum of jet noise power. Note the change in the shape of the spectrum as the velocity increases. The peak does not shift in frequency proportionally to velocity, so the Strouhal number falls. The spectrum is on an energy-per-cycle basis (constructed from data, concerning jet flow from a pipe of appreciable length, published by J. H. Gerrard (74).)

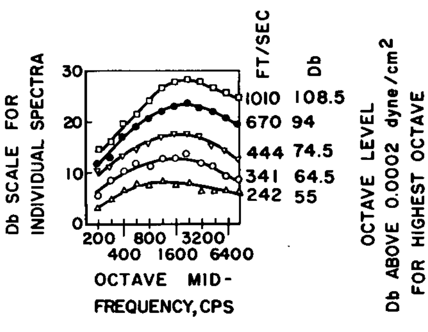

Fig. 15 - Octave spectra at given position. The peak frequency of an octave spectra corresponds roughly to the median of the energy-frequency distribution when the octave spectra display fairly symmetrical peaks. Thus the peak is fairly representative of the overall noise. Its frequency varies only slowly with velocity. The change in spectral shape is marked in this case at 30° to the jet axis and 24 diameters distance from the jet exit. (Constructed from data by A. Powell (55).)

temperature certainly tend to confirm the density factor (of ρ_j^2) arising from the similarity argument, although the only reported measurement (78) concerns positions at right angles to the jet axis (where convection effects would be expected to be least).

Temperature effects have yet to be fully investigated. Early indications that the effect was small (2) seem to be confirmed by recent experiments (78,83). The acoustic power seems to be hardly affected, implying that care should be taken in the interpretation of the ρ_j^2 factor, for which there is some verification for different gases. Thus the introduction of the molecular weight (to replace jet density) might be expected to yield a useful empirical rule. So far as frequency is concerned it seems to me that the statement of decreasing characteristic Strouhal number with temperature (80) (at a given pressure ratio) is less significant than the fact that the "median-energy" frequency did not change much with velocity. This means that it seems to make little difference whether the velocity increase is due to increasing temperature at a constant pressure ratio, or vice versa. Apparently the effects of reduced gas density are just about offset by increased noise-generating capacity (10). Directional effects, however, have yet to be thoroughly investigated, but again it looks as though jet velocity is more important than temperature, per se, since a helium jet and a hot air jet display similar directional properties at the same speed (84) (Fig. 13).

So far there is hardly any data throwing light on the validity of the $\rho_o c_o^5$ of the ambient fluid in the denominator of the similarity form. Ambient temperature and density effects are normally rather small but may have a measurable influence—at least some full-scale measurements suggest that possibility. It would therefore be most interesting to perform an experiment in the atmosphere of another gas, for example helium, (remembering that most microphone techniques give a measure of $\overline{p^2}$, while the acoustic power is connected with $\overline{p^2}/\rho_o c_o$).

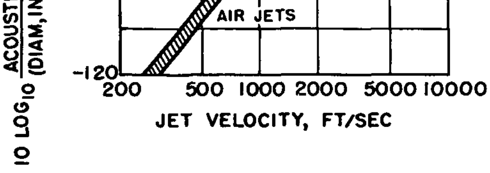

Fig. 16 - Power output and velocity. The rapid increase in noise-producing efficiency for low-speed air jets cannot prevail for very high speeds, otherwise the noise power would become ridiculously high. For cold air jets the efficiency is about $10^{-4}M^5$ (M being the exit Mach number) while for rockets it appears to be about one hundredth, far below the extrapolation of the low-speed efficiency. No allowance has been made for the gas density whose effects are yet uncertain. (Data collected from many sources, especially J. N. Cole et al. (68).)

The noise of rocket effluxes is particularly interesting. The low-speed dependency on velocity must be superseded by another form, otherwise the acoustic power would become impossibly large. Presumably the acoustic power is likely to be asymptotic to some fraction of the total power, in contrast to the low-speed case where the conversion to acoustic power depends on about the fifth power of the Mach number. It turns out that this fraction appears to be about a hundredth of the total power (68,86). This is shown in Fig. 16, where a comparison is made with cold air jets, jet engines, and jet engines with afterburners. In view of the foregoing comments concerning temperature effects, no allowance has been made for density variations. The essential characteristic of the rocket efflux is its high absolute velocity. It seems to me that model tests using supersonic cold air jets may be very misleading in relation to rocket-noise because of the limited velocity, whatever the pressure ratio. For example, the turbulence noise level of an unheated air jet still appears to follow the velocity to about the power of eight, provided the "expanded" velocity is used if the jet is choked (55), up to pressure ratios of thirty (85). There is an indication (86) that the bulk of the noise energy generated by rocket jets emanates from relatively far downstream, possibly where the jet velocity falls from supersonic to subsonic speed (but this is not in accord with the idea that supersonic eddies may be responsible, as discussed earlier). Another interesting feature of rocket noise is that radiations from all the frequency ranges so far measured display the maxima between 50° and 60° to the jet axis.* (Low-speed jets display a much wider variation (Fig. 12).) Does this imply that the major part of the noise production is by supersonic eddies lying within a comparatively small speed range? What is the nature of the mechanism which limits the fraction of available energy convertible to acoustic energy? (I cannot appreciate the argument that because there is only about 1 percent of the jet power resident in turbulent kinetic form, then this must be a limit to the acoustic power (87). By the same token would it not also be a limit to dissipation?) Close to such jets the pressure amplitudes are great enough to invalidate linear acoustic theory—is this responsible for any gross effect, e.g., by increased dissipation? Another (and possibly associated) feature of interest is that while the spectrum of turbojet engine noise is quite broad, the pressure maxima do not possess a Rayleigh distribution; the highest peaks reach at least four times the rms level (88). This aspect is very important in respect to fatigue troubles; corresponding data for rocket noise is not yet available, but will be of interest from more than one point of view. Knowledge concerning these aspects no doubt will cast light on a curious fact that has been observed (68). While the jet flow, delayed combustion effects, and near-by pressures are greatly affected by upsetting the stream at the nozzle, the noise radiated away is not appreciably altered.

It is interesting to reflect upon the changes that the immersion of a turbulent jet in a moving fluid would effect. Again, similarity arguments (73) come to mind, but, to judge by the limited experimental data available, yield results less satisfactory even than for the static case. There is some evidence that the reductions in the peak and low frequencies are much greater than such arguments suggest (89), although all measurements do not show this (90).

THOUGHTS ON JET NOISE REDUCTION

As the biggest financial expenditure on jet noise has been directly aimed at methods for its reduction, it is perhaps appropriate to mention a few major features. Study of some of the results of this work soon convinces one that our understanding of the overall problem is still very sketchy (although partial explanations are invariably forthcoming after any particular experiment!).

Perhaps the most simple variation on the jet having a circular orifice is that having an elliptical orifice. Experiments (91) with a 4:1 exit showed the increase in high-frequency noise in positions along the minor axis. This would be expected, yet the anticipated corresponding reductions along the major axis were absent; low-frequency changes were small but unexpected. Another simple variation concerns a change of the velocity profile at the exit, most easily obtained by using a long pipe prior to the exit (92,93). Here the high frequencies suffer reduction, but the overall reduction is not great. In particular if the jet velocity is increased to restore the thrust to its original value, there is a net increase in noise. There is now a little

*A recent report (86) casts some doubt on this, reporting maxima between 30° and 45° to the jet axis, but details are not available at the time of writing.

better understanding why this should be so (73,74) (for example, because the most intense part of the spectrum apparently emanates from the region at the end of the potential cone which would be little effected by the reduction of velocity gradients at the exit).

Those faced with the practical problem, not lacking in urgency, have tried numerous ad hoc devices. One might illustrate their diversity by reference just to nozzles having axially corrugated walls (67), a multiplicity of separate jets (94,95), combinations of several rectangular orifices (95), or the combination of the corrugated type with ejectors (97). Of course, for devices to be used in flight the question of net propulsive efficiency (98,99) is very important, and this is an essential factor in their design.

Our understanding of the mechanism by which the noise suppression is obtained is sketchy to say the least, although it has been the subject of much conjecture. The views that follow are by no means entirely original and are quite tentative, but seem (to me at least!) to be the most satisfying and, I hope, do not invite counter arguments of comparable strength. I shall conclude my lecture on this controversial (and challenging?) note.

First, confine attention to those variations of nozzle shape which eject all parts of the jet in a direction essentially parallel to the axis, for example that of Fig. 17.

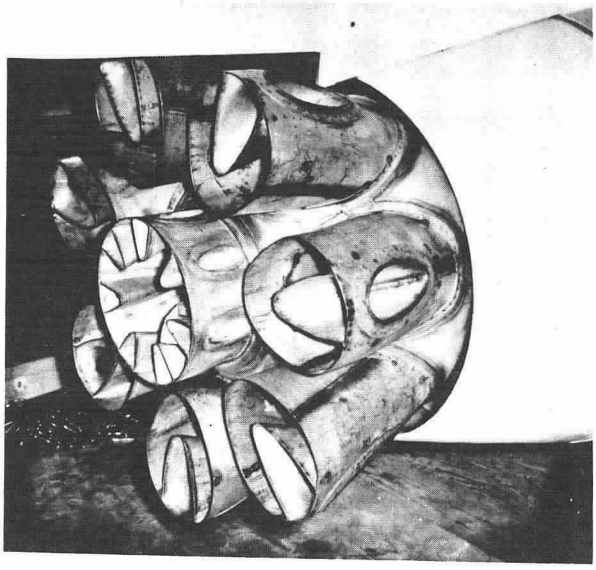

Fig. 17 - Jet noise-reduction device. There is a wide variety of nozzle designs which are known to give less noise than a simple circular one. They all eject the initial axial momentum in a distributed manner so as to minimize the transverse turbulent diffusion process and encourage induced flow between the high-velocity regions so as to reduce the turbulence levels. This particular nozzle evolved from a logical engineering development (67) and is used for the flight trials of the Douglas DC-8 airliner. (Photograph by courtesy of Douglas Aircraft Co.)

There will be a considerable amount of induced flow between the jet flows from the various segments, greater than in the absence of neighboring segments. The result of this is to reduce the rate of mixing, i.e., the individual potential cores persist longer than they would individually (100); the observed reduction in turbulent velocity fluctuations, and in the frequency (100,101) more than offset the greater volume of turbulence so far as the noise production is concerned, at least according to existing similarity arguments (73). The greatest reduction will occur at frequencies corresponding to the regions where the induced velocity is the most effective: this view is consistent with the selectivity associated with nozzles having various numbers and depths of corrugations around the periphery (67).

This alsc sheds some light on the noise-reducing action of ejectors. The flow leaving an ejector forms a new, larger, but slower jet of lower noise-producing capacity. The answer to the question of why less noise is made in the ejector than in the corresponding section of a free jet seems to lie at least partly in the fact that the action of the ejector directs the induced flow so as to reduce the total shear of the mixing region, and this is the most important single parameter so far as noise production is concerned.

Another point of view—which does not seem to have attracted previous attention—hinges on the fact that the predominant effect of turbulent mixing is the diffusion of momentum in transverse planes. Is it not reasonable to argue that the noise produced is connected with the amount of diffusion that has to take place? (There is some theoretical backing in this direction, in that the transverse velocity fluctuations are presumably connected with the amount of diffusion, and fluctuations across shear layers serve to amplify the noise output (7).) And all the fancy exit shapes considered do reduce the amount of diffusion, because some momentum is ejected from the exit at greater distances from the axis. While it may be useful to think of these as separate effects, of course they are inseparable in practice. Perhaps the optimum configuration is a nice balance between these two points of view, namely to spread out the initial momentum, yet taking care to lessen the total shear by induced flow.

The addition of a slower moving sheath of air has not proved very effective (102), less effective than some measurements (73) suggest for the flight case of jet engines, even for very moderate aircraft speeds. The reason seems to be that the part of the jet responsible for the peak of the noise spectrum—the most important single region—probably lies rather far from the exit (at the end of the potential cone, or a little farther downstream (73)) and that the outside sheath has already been annihilated. In other words, to be really effective one would expect that the sheath should certainly exceed the jet diameter in thickness—an arrangement the airplane designer is unlikely to welcome, compared, say, to an ejector arrangement.

There is another class of nozzle in which the efflux does not all leave the nozzle parallel to the axis, and which is known to result in diminished noise output. Typical of these is the one in which a parallel pipe has axial slots at the ends, some of the resultant "teeth" or "fingers" being bent inwards, some outwards. The situation here is less easy to see. The jet spreads at a faster rate (103), thus reducing the volume of noise-producing turbulence, but why is it not offset by the presumably higher turbulence levels? Firstly, some efflux is ejected outwards from the axis, and would not this reduce the "work" the turbulence would have to do in achieving the necessary diffusion? Also, may not secondary flows be set up, like vortices with their axes lying along the mean velocity surface of the jet, this rotation being a direct help to the diffusion process, since it would provide a mean flow between regions of high and low velocity and vice-versa? Finally, the effect of the teeth is to corrugate the jet leaving the nozzle: then is not the induced flow argument just as effective in these circumstances? The conjectural nature of the foregoing suggestions is all apparent—the practical reduction of jet-engine noise is clearly still more an engineering art than science!

I appreciate very much having been invited to undertake the task of preparing the survey I have just presented to you, a task which proved to be both pleasant and revealing (at least to myself!), and I regret only that time did not permit me to include phenomena involving solid boundaries and heat. This also seems an opportune time to express my appreciation to all the many who have helped me in many ways at one time or another and have given me so much encouragement. Of these, Professor E. J. Richards is directly responsible for my interest in the field and he gave me limitless help and encouragement while I worked at the University of Southampton. Since my association with the Douglas Aircraft Company, Mr. M. M. Miller has given me encouragement that I am glad to place on record. A third name is that of Mr. H. B. Irving, lately of the Ministry of Supply who, in his quiet gentlemanly manner, I am sure has achieved much by way of encouraging those, including myself, pursuing noise research in England.

REFERENCES

1. Richards, E.J., "Research on Aerodynamic Noise from Jets and Associated Problems," J. Roy. Aero. Soc., 57:319-342 (1953)

2. Powell, Alan, "Survey of Experiments on Jet-Noise," Aircraft Engineering, 26:2 (1954)

3. Fowell, L.R., and Korbacher, G.K., "Review of Aerodynamic Noise," U. of Toronto, Inst. of Aerophysics, U.T.I.A. Review No. 8, 1955

4. Richardson, E.G., "Acoustics in Relation to Aerodynamics," J. Aero. Sci., 22:775-780 (1955)

5. Richards, E.J., "Noise Research in the United Kingdom," Canadian Aero. J., pp. 341-357 (1957)

6. Nyborg, W.L., "Self-maintained Transverse Oscillations of a Jet," Paper delivered at Acoustical Society Meeting, Washington, D. C., May 1958

7. Lighthill, M.J., "On Sound Generated Aerodynamically, Part I-General Theory," Proc. Roy. Soc. A211:564-587 (1952)

8. Curle, N., "The Influence of Solid Boundaries upon Aerodynamic Noise," Proc. Roy. Soc. A231:505-514 (1955)

9. Proudman, I., "Generation of Noise by Isotropic Turbulence," Proc. Roy. Soc. A214:119 (1952)

10. Lighthill, M.J., "On Sound Generated Aerodynamically, Part II-Turbulence as a Source of Sound," Proc. Roy. Soc. A222:1-32 (1954)

11. Meecham, W.C., and Ford, G.W., "Acoustic Radiation from Isotropic Turbulence," J. Acoust. Soc. Am. 30:318-322 (1958)

12. Kraichnan, R.H., "Sound Radiation from High Reynolds Number Turbulence," (abstract) J. Acoust. Soc. Am. 30(No. 7):675-678 (1958)

13. Lighthill, M.J., "The Energy Scattered from the Interaction of Turbulence with Sound or Shockwaves," Proc. Camb. Phil. Soc. 49:531 (1953)

14. Kovasznay, L.S.G., "Interaction of a Shockwave and Turbulence," 1955 Heat Transfer and Fluid Mechanics Institute, Univ. of Calif., 1955

15. Hollingsworth, M.A., and Richards, E.J., "On the Sound Generated by the Interaction of a Vortex and a Shockwave," Aero. Research Council Paper 18257, 1956

16. Ram, G.S., and Ribner, H.S., "The Sound Generated by Interaction of a Single Vortex with a Shockwave," U. of Toronto, Inst. of Aerophysics, U.T.I.A. Report (to be published)

17. Ribner, H.S., "Convection of a Pattern of Vorticity through a Shockwave," N.A.C.A. Report 1164, 1954 (formerly T.N. 2864, 1953)

18. Hollingsworth, M.A., and Richards, E.J., "A Schlieren Study of the Interaction between a Vortex and a Shockwave in a Shocktube," Aero. Research Council Paper 17985, 1955

19. Burgers, J.M., "On the Transmission of Sound through a Shockwave," K. Nederland, Akad. v. Wetenschappen, Vol. 44, 1946

20. Powell, Alan, "A Note on the Sound from Weak Disturbances of a Normal Shockwave," Aero. Research Council, Current Paper No. 194, 1955 (to be revised)

21. Kovassnay, L.S.G., "Sound, Vorticity and Entropy," (abstract) J. Acoust. Soc. Am. 30(No. 7):689 (1958)

22. Yudin, E.Y., "On the Vortex Sound from Rotating Rods," N.A.C.A. TM 1136, 1947

23. Phillips, O.M., "The Intensity of Aeolian Tones," J. Fluid Mech. 1:607-624 (1956)

24. Powell, Alan, "Thoughts on Boundary Layer Noise," Aero. Research Council Paper No. 16727, 1954

25. Phillips, O.M., "On the Aerodynamic Surface Sound from a Plane Turbulent Boundary Layer," Proc. Roy. Soc. A234:327-335 (1956)

26. Phillips, O.M., "Aerodynamic Sound Radiated from a Turbulent Boundary Layer," (abstract) J. Acoust. Soc. Am. 30(No. 7):680 (1958)

27. Ribner, H.S., "Boundary Layer-Induced Noise in the Interior of Aircraft," U. of Toronto, Inst. of Aerophysics, U.T.I.A. Report 37, 1956

28. Kraichnan, R.H., "Noise Transmission from Boundary Layer Fluctuations," J. Acoust. Soc. Am. 29:65-80 (1957)

29. Corcos, G.M., and Liepmann, H.W., "On the Contribution of Turbulent Boundary Layers to the Noise inside a Fuselage," N.A.C.A. TM 1420, 1958

30. Powell, Alan, "On Structural Vibrations Excited by Random Pressures, with Reference to Structural Fatigue and Boundary Layer Noise," Douglas Aircraft Company Report SM 22795, 1957

31. Harrison, M., "Correlations and Spectra of Pressure Fluctuations on the Wall Adjacent to a Turbulent Boundary Layer," (abstract only) J. Acoust. Soc. Am. 29:1252 (1957)

32. Willmarth, W.W., "Space-time Correlations of the Fluctuating Wall Pressure in a Turbulent Boundary Layer," J. Aero. Sci. 25:335-336 (1958)

33. Trilling, L., "On Thermally Induced Sound Fields," Office of Scientific Research Tech. Note 55-47, 1954

34. Andrade, E.N. da C., "The Sensitive Flame," Proc. Phys. Soc. 53:329 (1941)

35. Brown, G.B., "On Vortex Motion in Gaseous Jets and the Origin of their Sensitivity to Sound," Proc. Phys. Soc. 47:703 (1935)

36. Brown, G.B., "The Mechanism of Edge-tone Production," Proc. Phys. Soc. 49:508 (1937)

37. Curie, N., "The Mechanics of Edge-tones," Proc. Phys. Soc. A216:412-424 (1953)

38. Powell, Alan, "On Edge-tones and Associated Phenomena," Acustica, 3:233 (1953)

39. Lenihan, J.M.A., and Richardson, E.G., "Observations on Edge-tones," Phil. Mag. 29:400-406 (1940)

40. Brown, G.B., "On the Vortex Motion Causing Edge-tones," Proc. Phys. Soc. 49:493 (1937)

41. Richardson, E.G., "Edge Tones," Proc. Phys. Soc. 43:394-404 (1931)

42. Nyborg, W.L., Burkhard, M.D., and Schilling, H.K., "Acoustical Characteristics of Jet-Edge and Jet-Edge-Resonator Systems," J. Acoust. Soc. Am. 24:293-304 (1952)

43. Garber, D.I., "The Effect of External Sound on the Vortex Shedding from Cylinders," J. Aero. Sci. 25(No. 4):275-276 (1958)

44. Bouyoucos, J.V., and Nyborg, W.L., "Oscillations of the Jet in a Jet-Edge System, II," J. Acoust. Soc. Am. 26(No. 4):511-514 (1954)

45. Nyborg, W.L., "Self-Maintained Oscillations of the Jet in a Jet-Edge System," J. Acoust. Soc. Am. 26(No. 2):174-182 (1954)

46. Nyborg, W.L., Woodbridge, C.L., and Schilling, H.K., "Characteristics of Jet-Edge-Resonator Whistles," J. Acoust. Soc. Am. 25:138-146 (1953)

47. Mercer, D.M.A., "The Voicing of Organ Flue Pipes," J. Acoust. Soc. Am. 23:45-54 (1951)

48. Anderson, A.B.C., "Metastable Jet-Tone States of Jets from Sharp-Edged Circular, Pipe-Like Orifices," J. Acoust. Soc. Am. 27(No. 1):13-21 (1955)

49. Anderson, A.B.C., "Vortex-Ring Structure-Transition in a Jet Emitting Discrete Acoustic Frequencies," J. Acoust. Soc. Am. 28(No. 5):914-921 (1956)

50. Darlington, W.H., "Air Jets for Use in Gas Turbine Combustion Chambers," University of London, Ph.D. Thesis, 1949

51. Anderson, A.B.C., "A Circular-Orifice Number Describing Dependency of Primary Pfeifenton Frequency on Differential Pressure, Gas Density and Orifice Geometry," J. Acoust. Soc. Am. 25(No. 4):626-631 (1953)

52. Anderson, A.B.C., "A Jet Tone Orifice Number for Orifices of Small Thickness-Diameter Ratio," J. Acoust. Soc. Am. 26(No. 1):21-25 (1954)

53. Anderson, A.B.C., "Dependence of Pfeifenton (Pipe Tone) Frequencies on Pipe Length, Orifice Diameter and Gas Discharge Pressure," J. Acoust. Soc. Am. 24(No. 6):675-681 (1952)

54. Powell, Alan, "Noise of Jets," University of Southampton, Ph.D. Thesis, 1953

55. Powell, Alan, "A Schlieren Study of Small Scale Air Jets, and Some Noise Measurements on Two-inch Diameter Jets," Aero. Research Council Paper 14726, 1951

56. Powell, Alan, "The Noise of a Pulse Jet," J. Helicopter Ass'n of Great Britain, 7:32 (1953)

57. Lassiter, L.W., "Noise from Intermittent Jet Engines, and Steady Flow Engines with Rough Burning," N.A.C.A. TN 2756, 1952

58. Veneklasen, P.S., "Noise Characteristics of Pulsejet Engines," J. Acoust. Soc. Am. 25:380-383 (1953)

59. Oleson, S.K., and Ingard, V., "Acoustical Characteristics of Model Pulsed Jets," J. Acoust. Soc. Am. 20(No. 10):1145-1146 (1957)

60. Powell, Alan, "On the Noise Emanating from a Two-dimensional Jet above the Critical Pressure," Aero. Quarterly, 4:103 (1953)

61. Powell, Alan, "On the Mechanism of Choked Jet Noise," Proc. Phys. Soc. B66:1039 (1953)

62. Davies, M.G., "Acoustic Radiation of Discrete Frequency from a Choked Rectangular Jet," Aero. Research Council Paper 19016, 1957

63. Lassiter, L.W., and Hubbard, H.H., "The Near Noise Field of Static Jets and Some Model Studies of Devices for Noise Reduction," N.A.C.A. TN 3187, 1954

64. Franklin, R.E., "Noise Measurements of Cold Jets using Convergent-Divergent Nozzles," Aero. Quart., 8:346-359 (1957)

65. Lilley, G.M., "Aerodynamic Noise Work at the College of Aeronautics," Proc. International Congress on Theoretical and Applied Mechanics, Istanbul, 1952

66. Powell, Alan, "The Reduction of Choked Jet Noise," Proc. Phys. Soc. B67:313 (1954)

67. Greatrex, F.B., "Jet Noise," Fifth International Aero. Conference, I.A.S. Preprint 559, 1955

68. Cole, J.N., von Gierke, H.E., Kyrazis, D.T., Eldred, K.M., and Humphrey, A.J., "Noise Radiation from Fourteen Types of Rockets in the 1000 to 130,000 Pounds Thrust-Range," W.A.D.C. Tech. Report 57-354, 1957

69. Corrsin, S., "Investigation of Flow in an Axially Symmetrical Heated Jet of Air," N.A.C.A. ACR 3L23 (also Wartime Report W-94), 1943

70. Laurence, J.C., "Intensity, Scale and Spectra of Turbulence in Mixing Region of Free Subsonic Jet," N.A.C.A. Report 1292, 1956 (supersedes TN 3561 and TN 3576)

71. Westley, R., and Lilley, G.M., "Investigations of the Noise Field from a Small Jet, and Methods for its Reduction," College of Aeronautics, Cranfield, Report 53, 1952

72. Ribner, H.S., "On the Strength Distribution of Sources along a Jet," U. of Toronto, Inst. of Aerophysics, U.T.I.A. Report 61, 1958

73. Powell, Alan, "Similarity Considerations of Noise Production from Turbulent Jets, both Static and Moving," Douglas Aircraft Co. Report SM 23246, 1958

74. Richards, E.J., Private communication concerning work in progress at the University of Southampton

75. Dyer, Ira, "Distribution of Sound Sources in a Jet Stream," (abstract) J. Acoust. Soc. Am. 30(No. 7):676 (1958)

76. Gerrard, J.H., "An Investigation of the Noise Produced by a Subsonic Air Jet," J. Aero. Sci., 23(No. 9):855-866 (1956)

77. von Gierke, H.E., Parrack, H.O., Gannon, W.J., and Hanson, R.G., "Noise Field of a Turbojet Engine," J. Acoust. Soc. Am. 24:169 (1952) (correction 25:369 (1953))

78. Lassiter, L.W., and Hubbard, H.H., "Experimental Studies from Subsonic Jets in Still Air," N.A.C.A. TN 2757, 1952

79. Coles, W.D., and Callaghan, E.E., "Investigation of Far Noise Field of Jets: II Comparison of Air Jets and Jet Engines," N.A.C.A. TN 3591, 1956

80. Rollin, V.G., "Effect of Temperature on Jet Noise Generation," N.A.C.A. TN 4217, 1958

81. Lassiter, L.W., "Turbulence in Small Air Jets at Exit Velocities up to 705 feet per Second," J. Appl. Mech. 24:349-354 (1957)

82. Morkovin, M.V., Comments upon the above paper by L.W. Lassiter, J. Appl. Mech., Vol. 25, pp. 314-315, 1958

83. Tyler, J.M., and Perry, E.C., "Jet Noise," Pratt & Whitney Aircraft Report, PWA Inst. 451, 1954

84. Lassiter, L.W., and Hubbard, H.H., "Some Results of Experiments Relating to the Generation of Noise in Jets," J. Acoust. Soc. Am. 27:431-437 (1955)

85. Mull, H.R., and Erickson, J.C., "Survey of the Acoustic Near Field of Three Nozzles at a Pressure Ratio of 30," N.A.C.A. TN 3978, 1957

86. Mayes, W.H., "Some Near- and Far-Field Noise Measurements for Rocket-Engine Operating at Different Nozzle Pressure Ratios," (abstract) J. Acoust. Soc. Am. 30(No. 7):694 (1958)

87. Westervelt, P.J., Dyer, I., and Franken, P.A., "Changes in Jet Noise by Mixing, and an Upper Limit on Jet Noise Production," (abstract) J. Acoust. Soc. Am. 29(No. 6):778 (1957)

88. Kamps, E.C., "Statistical Evaluation of Near Field Sound Pressures Generated by Exhaust of a High Performance Jet Engine," (abstract) J. Acoust. Soc. Am. 30(No. 7):692 (1958)

89. Douglas Aircraft Company, Unpublished data

90. von Gierke, H.E., Private communication concerning work in progress at Wright Air Development Center

91. Powell, Alan, "A Comparison between the Noise from Jets having 4:1 Elliptic and Circular Orifices," J. Acoust. Soc. Am. 30(No. 7):642-643 (1958) (formerly Aero. Research Council Paper 18123, 1956)

92. Powell, Alan, "The Influence of the Exit Velocity Profile on the Noise of a Jet," Aero. Quarterly, 4:341 (1954)

93. Waterhouse, R.V., and Berendt, R.D., "Reverberation Chamber Study of the Sound Output of Subsonic Air Jets," J. Acoust. Soc. Am. 30:114-121 (1958)

94. Howell, H.H., "Summary Progress Report on Jet Noise Suppression," Boeing Airplane Co. Report, February 1957

95. Tyler, J.M., and Towle, G.B., "A Jet Exhaust Silencer," Pratt and Whitney Aircraft Report, PWA Inst. 469

96. Coles, W.D., and Callaghan, E.E., "Full Scale Investigation of Several Jet Engine Noise Reduction Nozzles," N.A.C.A. TN 3974, 1957

97. Douglas Aircraft Company, Unpublished data

98. Ciepluch, C.C., North, W.J., Coles, W.D., and Antl, R.J., "Acoustic, Thrust and Drag Characteristics of Several Full Scale Noise Suppressors for Turbojet Engines," N.A.C.A. 4261, 1958

99. North, W.J., "Transonic Drag of Several Jet-noise Suppressors," N.A.C.A. TN 4269, 1958

100. Laurence, J.C., and Benninghoff, J.M., "Turbulence Measurements in Multiple Interfering Air Jets," N.A.C.A. TN 4029, 1957

101. Corcos, A.M., "Some Measurements Bearing on the Principles of Jet Silencing Devices," Douglas Aircraft Co. Report SM-23114, 1958

102. Lees, R., and Smith, E.B., "Experimental Investigation of Noise Radiated by Concentric Jets," General Electric Co., Report R 57 AGT 381, 1957

103. Dryburgh, W.W., "Noise Tests on an Avon R.A.7 Engine on the Open Air Test Bed — 1st Report," Rolls Royce Report Gtx/WWD.i/JB., Jan. 1, 1954

* * * * *

A. Powell

DISCUSSION

R. H. Kraichnan (New York University)

I'd like to say a few words about why the maximum frequency doesn't seem to go up with Mach number as fast as one might expect. I have done some work recently on predicting quantitatively the amount of noise from isotropic turbulence, which is a very idealized approach to the jet problem but it does seem to indicate some qualitative features. One of the results is that at high Reynolds numbers the radiation is principally at high frequencies coming from small eddies and, in fact, the spectrum at high frequencies falls off inversely with frequency.

The radiated power is proportional to the rate of dissipation of power in the jet itself, and to the fifth power of the Mach number. For Mach numbers of the order of unity the acoustic damping of the turbulence becomes very strong. This indicates a strong coupling between the acoustical and vortical modes at high frequencies. In the region of appreciable Mach numbers, because of the strong damping at the relatively high frequencies, one would expect that these frequencies could no longer increase in power and, therefore, that the maximum in the acoustic radiation curve would not go up as fast.

This doesn't solve Lighthill's paradox in a neat form because it doesn't answer why one begins and ends with the eighth power law. Aside from any specific investigation for nonlinear phenomena, one would certainly expect things not to increase as fast, so certainly the power law is going to drop off.

There is a slight increase in efficiency if the Reynolds number is separated from Mach number dependence. This increase would give a decrease in the power law. The turbulence itself is damped.

We will accept the experimental evidence. I have no competence to do otherwise, and I would like to point out what seems to be the great danger in all of this. The theoretical explanations are very simple and it is not too difficult to find a theoretical effect which agrees with any given experimental effect. Whether you are happy in doing this depends on how strongly you want to support a particular theory.

A. Regier (National Advisory Committee for Aeronautics)

In our earlier experiments we soon became aware of the fact that the frequency in the far field did not increase as rapidly as the velocity. However, in the near field we found that both the turbulence in the jet and the pressures close to the jet did agree nicely with the velocity increase. I wondered if Dr. Kraichnan or Dr. Powell would accept this as an experimental fact and explain it, or is there anything further to be said on that, whether the near field does follow the velocity but the far field does not?

E. Mollo-Christensen (California Institute of Technology)

From the dimensional analysis in the near field I think there is no doubt that things should scale with velocity, but in the far field one has radiation and there feels something quite different. In the far field, as I show in my paper, we find that certain frequency ranges scale with velocity very precisely. We also find in other parts of the far field that we do have scaling with the velocity of sound, suggesting an acoustic mechanism of sound radiation. There are apparently two mechanisms involved. This is speculation now, but it agrees with our experimental results.

I think that one can get more out of narrow band measurements. The measurements to which Mr. Regier refers are octave-band measurements on the decibel scale.

J. H. Gerrard (University of Manchester)

I should like to comment on Dr. Powell's question, "would the placing of an edge in the vortex street behind a cylinder result in a flow analogous to edge tones?"

Edge tones have been produced by placing a circular cylinder in a jet. One might expect the similarity suggested by Powell to be detected, therefore, when two cylinders were placed one behind the other in an air flow. I have made some exploratory observations of the pressure fluctuations on the surface of a one-inch-diameter cylinder when a second cylinder was placed parallel to it a short distance, 2 in. to 6 in., upstream and downstream (also to port and starboard). Increased amplitude of pressure fluctuation at the surface corresponds to increased Aeolian tone intensity radiated from that cylinder. If the flow assumed the character of an edge tone one would expect: (a) the surface pressure fluctuation would increase when a second cylinder was placed upstream or downstream, and (b) the character of the fluctuation would change from that characteristic of Aeolian tones to the pure-tone form associated with edge tones. No change in intensity was detected when the second cylinder was interposed in the fore or aft position. When, however, the cylinders were separated across the stream the signal intensity increased about twofold. In neither case did the appearance of the signal change from that of a narrow band of noise. The Reynolds number of this experiment was about 5×10^4.

* * * * *