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On the noise sources of the unsuppressed high-speed jet

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The paper describes an interpretation of jet-noise theory and scale-model experiments to highlight physical properties of jet-noise sources at very high speed. The study is prompted by current efforts to suppress the noise of supersonic transport aircraft.

The principal noise sources are shown to be very large-scale wave-like undulations of the jet flow that travel downstream at supersonic speed for a distance of several jet diameters. These motions are relatively well ordered and are probably more akin to recognizable instabilities of a laminar flow than the confused small-scale turbulence. Because of this we postulate a model of the noise generating motions as the instability products of a jet flow of low equivalent Reynolds number. This Reynolds number is based on an eddy viscosity and can be further reduced by artificially increasing the small-scale turbulence level. This step would tend to stabilize the flow and inhibit the formation of large-scale noise producing eddies.

1. Introduction

An essential prerequisite to a rational approach to the jet-noise problem is that the nature and location of the important noise sources be clearly understood. We know that the source characteristics are highly sensitive to changes in jet speed and that the relative importance of different flow régimes may well be a function of engine power. Accordingly the problem has to be tackled systematically taking one fixed operational condition at a time. The maximum take-off power condition is one of the most important problem areas for the supersonic transport aircraft. This paper describes the location and general characteristics of the noise sources in such a jet.

Several new and interesting features have come to light, some of which lead us to believe that the very high-speed noise problem may well be relatively tractable. We arrive at this view after a systematic investigation using small-scale experiments to check-out details of a theoretical model. One point we believe has particular significance. We find that the most important noise sources are clustered in the mixing region that surrounds what is loosely termed the potential core of the jet. These sources are associated with unsteady flow on a scale much larger than the main turbulence in the mixing region and indeed larger than the width of the shear layer in that region. The noise is generated by extremely

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large eddies that have not yet been distorted and stretched into the confused motion that is normally treated in studies of mixing-layer turbulence. The mechanics of turbulence remain obscure, so that it comes as a matter of some relief to find that the motions that now interest us are coherent on a large scale. They are the large eddies that arise from the instability of the primary flow. These instabilities grow, interact with one another and with the mean straining motion eventually to form conventional chaotic turbulence on a scale much smaller than the local shear layer thickness. This turbulence, however, seems to have no direct bearing on the noise-producing properties of the jet, but has a most obvious significance to the development of the mean velocity profile whose instability forms the large eddies.

This report outlines the steps that have led us to this conclusion.

2. The eddy convection speeds

The mechanical behaviour of a circular jet is influenced by fluid compressibility. This is a Mach number effect which becomes evident in two ways. First, when Mach 1 is exceeded real characteristics are possible, shock waves form and sound waves can no longer propagate against the stream.

While these features have a most obvious influence on the way sound propagates within the jet flow, they can well be considered to have minor bearing on the large-scale noise-producing structure of the jet. These large-scale eddies can be thought of as arising from the primary instabilities of the mean flow profile, a view advocated by Landahl (1967) and amplified by Lighthill (1969, 1970). The stability of the mean flow profile is of the Kelvin–Helmholtz type for compressible flow, an area studied by Miles (1958) who shows that there is no dramatic influence of compressibility on the instability until the velocity difference across the shear layer exceeds the sum of the two speeds of sound in the adjoining media. In this sense, even the 'Concorde' jets at full take-off power are 'low speed', the jet velocity (2700 ft/sec) being smaller than the sum of the two speeds of sound (3300 ft/sec).

Because of this we can expect the large-scale turbulent structure to have much in common with that of low-speed jets about which a considerable amount is known. Davis, Fisher & Barratt (1963) have measured many of the quantities determining the acoustic efficiency of jet turbulence. In particular they show that, on average, the turbulent eddies travel downstream at approximately 65 % of the free-stream velocity at the jet centre-line. This convection speed was measured by a cross-correlation technique where the time delay for maximum average correlation between turbulence conditions at two axially displaced points was determined. It is usual to interpret this result as indicating that the dominant eddies are travelling downstream with this 'convection' speed, though it must be admitted that this interpretation is not unique. The correlation data is also consistent with a model (due to N. H. Johannesen) of many eddies travelling downstream with velocities varying from zero to the full jet speed according to the mean velocity at the radial position where the particular eddy has its 'core'. The statistical average convection speed, determined by the correlation technique is then some intermediate value (65 %). This 'convection' speed is therefore ambiguous in that it corresponds to either: (*a*) eddies at this speed occurring most frequently or having high energy and appearing more significant in the averaging process; or (*b*) it is the average of the speeds with which eddies travel downstream but is a speed no more likely to occur or any more significant than any other speed that is less than the jet velocity. We must then interpret the correlation measurements with considerable caution. On the other hand, it is the convection velocity, as determined from correlation measurements, that controls convective effects on the mean-square properties of the acoustic field. This is clear from the theory relating turbulence statistics to those of the sound

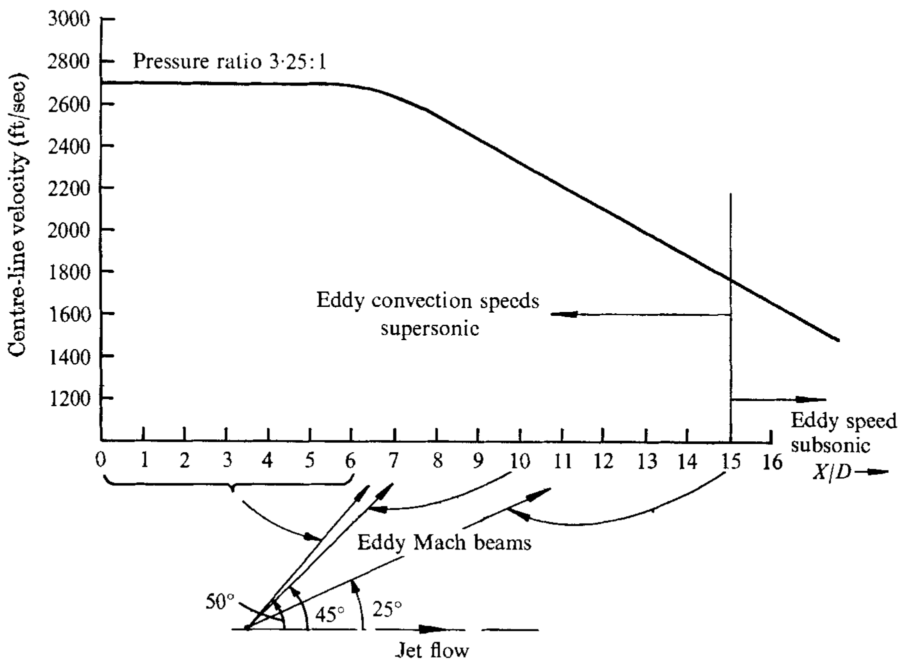

FIGURE 1. The variation of flow velocity with axial position. The jet velocity is 2700 ft/sec. In the first six diameters of the jet the eddies travel at a convection Mach number of 1·5 and radiate a Mach beam at an angle of 50°. The beam is at 45° and 25° for eddies at 10 and 15 diameters downstream of the nozzle.

(see, for example, Ffowcs Williams 1963, p. 487), so that there is no ambiguity in the convective effects as they influence the only quantitatively studied part of the noise field, the statistical mean value of the intensity.

The eddy convection matters a lot. At subsonic speeds it accounts for the Doppler shifting of observed frequencies and for the preferred forward emission of the jet turbulence. If the eddies move supersonically then the mechanism by which they radiate changes, the wave field then taking the form of ballistic shock waves on a supersonically moving eddy. This evidently is the main mechanism of sound generation in the unsuppressed 'Concorde' jets at full power because the eddy speeds appear to be supersonic in the sound-producing regions. The mean velocity is known as a function of axial position. See, for example, the report by Trevett (1968). His data is reproduced in figure 1, where it will be seen that even at 15 diameters downstream of the nozzle the axial velocity on the jet centre-line is as high as 0·7 of the fully expanded velocity which, for 'Concorde', is 2700 ft/sec. Taking the eddy convection speed as 0·65 of the maximum mean speed at the jet axis, we see that at 15 diameters downstream the eddy is moving supersonically relative to the *ambient* air at a convection Mach number, M_e, of 1·1. These eddies will radiate Mach waves at an angle, θ_m, of 25° to the jet axis. At 10 diameters downstream the eddy convection speed is 1·4 × the ambient speed of sound making the Mach wave angle 45° to the jet axis. The eddy convection Mach number of the upstream flow is 1·56 and the Mach angle 50°. This information shows that, provided the main noise-producing zones are upstream of 15 diameters then the eddies are moving supersonically. The main mode of radiation from supersonic eddies is of the Mach wave type where no conventional near field exists and where it is unimportant to recognize that the eddies are arrayed in a quadrupole array. Their acoustic behaviour is quite different from low-speed turbulence described by the usual form of Lighthill's theory which predicts the sound to increase with the eighth power of jet speed. The Mach wave radiation of supersonically moving eddies increases with the cube of jet velocity and this is the experimentally measured velocity index in the 'Concorde' jets at maximum power.

3. The location of the primary noise sources in the unsuppressed high-speed jet

The following test was conducted at the Bristol Engine Division of Rolls-Royce Ltd. A high-speed hot jet was aimed through a small hole in a large sound-absorbent screen. The hole was big enough that it did not interfere with the jet structure but small enough that it did not allow any significant portion of the sound generated on one side of the screen to pass to the other side. Sound heard on any one side of the screen was therefore generated by those parts of the jet flow which were directly visible. The test is not ideal because low-speed aerodynamic quadrupoles which have an intense near field can interact with the screen to generate new sound that confuses the interpretation of the experiments. However, if the eddy convection speeds are supersonic relative to the ambient fluid then the turbulence has no conventional near field (Ffowcs Williams 1965, Ffowcs Williams & Hawkings 1969) and the interpretation of the results is far less ambiguous. The test arrangement is illustrated in figure 2, and figure 3 shows some of the results obtained. These results are the levels recorded by a distant microphone at the angle that peak noise is heard. The sound level is given as a function of frequency for several different positions of the screen. When the screen is zero diameters downstream of the nozzle exit it does not affect the flow and the spectrum is that measured on a normal jet issuing from a convergent nozzle. When the screen is 5 diameters downstream it is seen that the high frequencies are attenuated implying that the high frequencies were generated largely upstream of the screen. Similar results hold when the screen is 10, 15 and 19 diameters downstream of the nozzle. The curves for 15 diameters and 19 diameters are quite similar, implying that the important source activity lies upstream of the 15-diameter position. We have already seen that upstream of 15 diameters the eddy speeds are supersonic so that we may deduce from this result that the main noise is Mach wave radiation and that the source location experiments are readily interpretable because there is no quadrupole near field. Mach wave radiation from any one eddy takes the form of a fairly directional beam radiating at the Mach angle of that eddy (e.g. see figure 8,

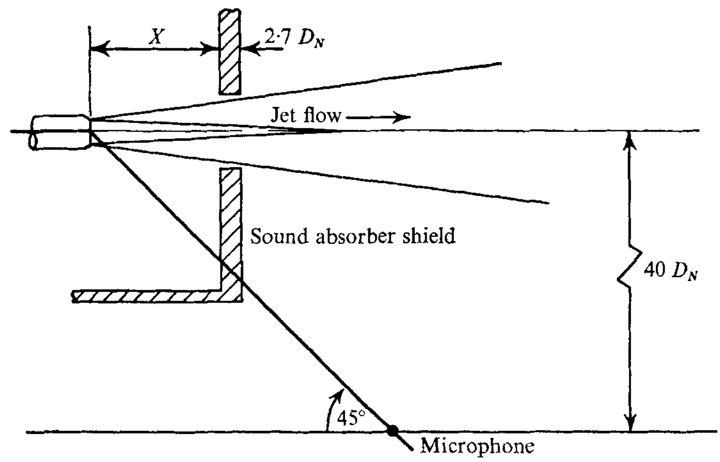

FIGURE 2. Plan of the microphone and shield arrangement in the source location tests. D_N is the nozzle diameter.

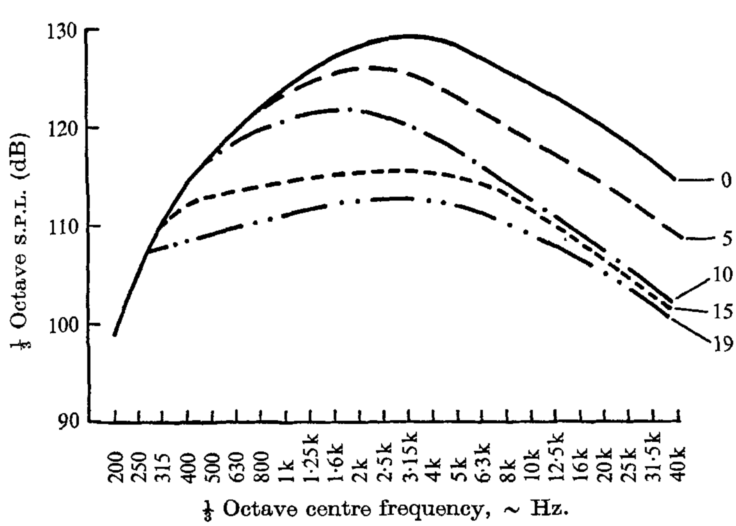

FIGURE 3. Spectra measured by the microphone for various shield positions. The length of jet (in diameters) that is obscured by the shield is indicated on each curve.

Ffowcs Williams, 1963). By observing the zone of maximum intensity at two radial positions from the jet one can locate this beam and trace it backwards to find its origin. This has been done at several different frequencies and the results are illustrated in figure 4. In this figure it will be seen that the experimental points fall approximately on two distinct curves. One refers unambiguously to

Mach wave radiation; that is the set of data points for frequencies in excess of 1 kilohertz where the source frequency is proportional to the inverse of distance from the nozzle exit, as it should be in the initial supersonic linearly growing shear layer (Ffowcs Williams 1969). The second set of points seems to be associated with the distant jet radiating to higher angles than the Mach angle, because the observation point at 40 diameters from the jet axis makes an angle of 80° or so to those downstream portions of the jet. In this region the source location experiment is not so clearly interpreted though the results seem to accord with

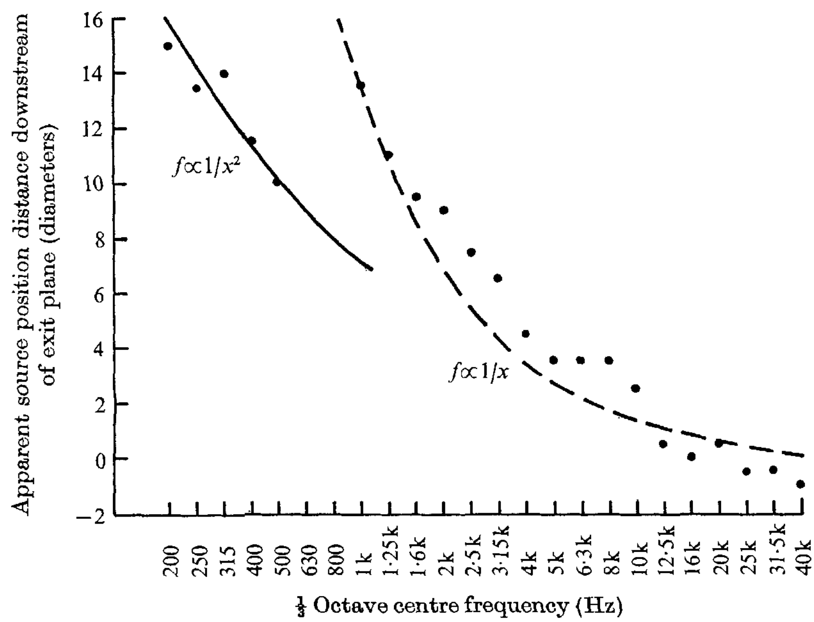

FIGURE 4. Curves indicating the location of the primary noise sources as a function of frequency. Nozzle diameter is 3 in., jet velocity is 2700 ft/sec.

theoretical prediction for the fully developed jet (Ribner 1958; Lilley 1958). In this region source frequencies scale on Strouhal number based on the linearly increasing jet width and the centre-line velocity that is inversely proportional to axial distance. The frequencies therefore scale on the inverse square of axial position. But this range is only of academic importance since the frequencies are too low to be subjectively significant in any full-scale application. The frequencies are higher by a factor of about 10 than those of a typical full-scale engine because of the scale effect. The most critical frequency at a full-scale condition is approximately 400 hertz which is 4 kilohertz on the model experiment. It is this frequency that is subjectively most important for this category of jet flow. The primary sources of this frequency are seen to be positioned about 4 diameters downstream of the exit plane. The maximum spectral level occurs at about 2 kilohertz and these sources are evidently positioned near the end of the potential core at 8 diameters downstream. At full-scale conditions these frequencies also are too low to be of subjective significance. We can also say how extensive is the source region at any one frequency by comparing the Mach wave levels measured at the near and distant field points. The source region is in fact very extensive, any one source contributing to the peak of the noise spectrum (2 kilohertz) appearing to occupy an axial range of about 5 diameters. This point we deduce as follows: Let X be the distance travelled by the Mach wave source during its coherent lifetime. In the near field not all the source is seen due to the finite beam width of the Mach waves, a beam that we approximate as a sharply defined cone diverging at an angle of 20°–30°. If we define the beam width as

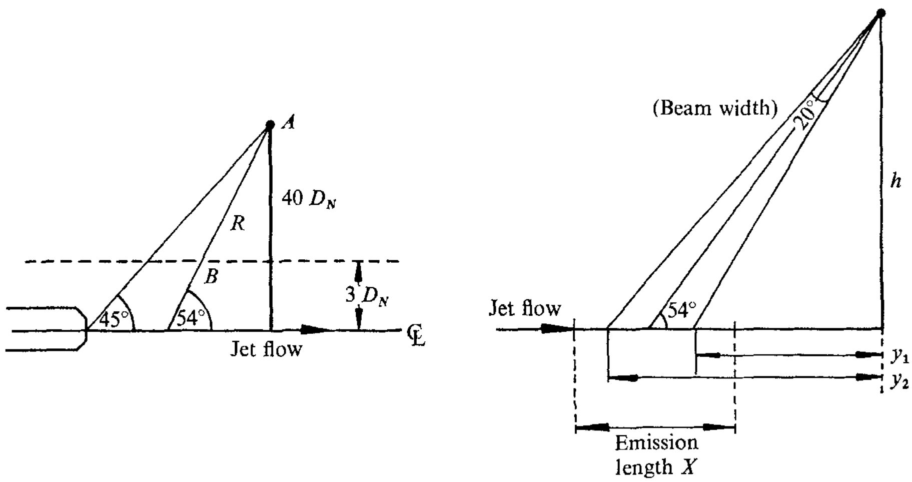

FIGURE 5. Plan indicating the detailed geometry of the measuring positions and Mach wave beam width. A, far-field measurement point; B, near-field point. $R = 35D_N$.

the 'peak − 3 dB' then, by measurement, the beam is 20° wide. If the beam is defined as the 'peak − 6 dB', then the beam width is 30°, again by measurement. Given this definition of beam width, we compute the variation of field strength with distance. If the source strength per unit length is a constant, q, then the pressure at distance h from the jet axis for a 20° beam (cf. figure 5) is

$$p = \int_{y_1}^{y_2} \frac{q\,dy}{(h^2+y^2)^{\frac{1}{2}}},$$

where
$$\left.\begin{aligned} y_1 &= h\cot 54^\circ - \tfrac{1}{2}X \\ y_2 &= h\cot 54^\circ + \tfrac{1}{2}X \end{aligned}\right\} h > \tfrac{1}{2}X(\cot 54^\circ - \cot 64^\circ)^{-1};$$

and
$$\left.\begin{aligned} y_1 &= h\cot 64^\circ \\ y_2 &= h\cot 44^\circ \end{aligned}\right\} h < \tfrac{1}{2}X(\cot 54^\circ - \cot 64^\circ)^{-1}.$$

This level, relative to a datum, which is actually the pressure level at 35 nozzle diameters from the source, that being the experimental point, is plotted in figure 6 for three values of X and for the two values of beam width. From these figures, on which are also plotted the experimental near-field measurement, we see that the source travels a coherent distance, X, of $5D$ or $8D$ dependent on the exact definition of beam width. The interesting and significant point is that the distance is large compared with source size, but shorter than the mixing region.

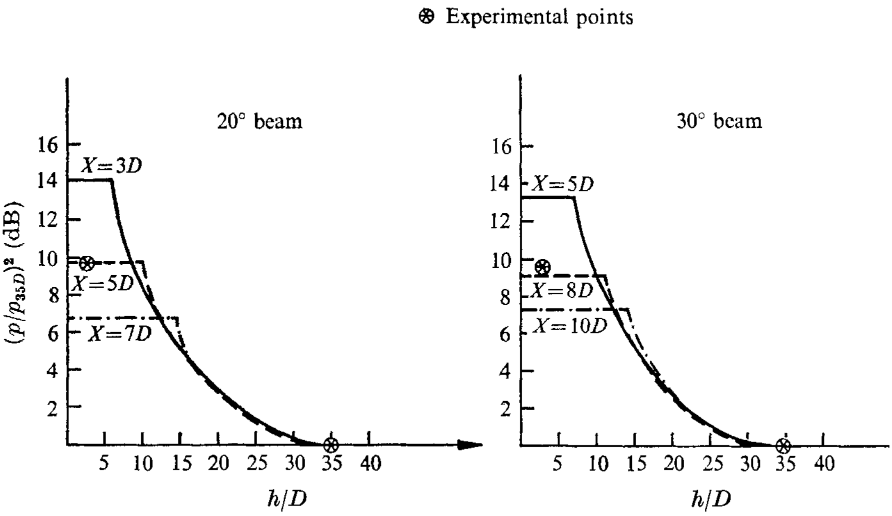

FIGURE 6. Curves showing the variation in sound level as a function of distance for the source model considered. The experimental points are superimposed on the curves to indicate that an eddy radiation length of approximately 5 jet diameters is consistent with the experimental data.

4. The scale of the noise-producing eddies

Figure 4 indicates the frequencies at which eddies radiate at different positions downstream of the nozzle exit. Associated with each frequency is a definite wavelength and in the Mach wave régime the length of the eddy that generated the sound is the same as the wavelength of that sound. The conversion factor is straightforward; 1 kilohertz corresponds to a wavelength of 1 ft. We are inferring this equivalence of length scale because we know that the Fourier inverse, the wave-number, of both sound and source field are equal (Ffowcs Williams 1963). There should be no ambiguity in this step because the spectrum is relatively peaked at a frequency of 2 kilohertz, which corresponds to a space correlation of the sound field, and hence of the source field (for Mach wave radiation), which undulates at a length scale of 6 in. Figure 4 describes tests on a nozzle of 3 in. diameter, e.g. the 2 kilohertz sound corresponds to a wavelength and hence a generating eddy of 6 in. dimension. That eddy was situated about 7 diameters downstream of the nozzle where the thickness of the mixing layer is about 3 in. All the data on figure 4 correspond to eddies on a scale greater than twice the local shear layer scale. These scales are extremely large when compared to the size of the energy-bearing eddies which are much smaller than the shear layer thickness (Bradshaw, Ferris & Johnson 1964). An eddy on this large scale implies that the motion is coherent on this scale and such large eddies might be readily recognizable as a coherent transverse motion more in the category of a complicated laminar flow than chaotic turbulence. In any event the eddies generating the noise seem to be much bigger than those eddies which have been the subject of intensive turbulence study. They are very likely those large eddies which derive their energy from an instability of the mean motion and which eventually give up their energy on being distorted and strained in the cascading process where smaller eddies are evolved with the increased chaos of fully developed turbulent flow. The large eddies are a breed apart and should be regarded as such. One possible approach is described below.

5. A model of the large sound-producing eddy structure

The principal effect of turbulence on the mean flow is that the effective Reynolds number is drastically reduced. The mean flow profiles are very similar to those of viscous laminar flow, the coefficient of viscosity being the effective eddy viscosity rather than the molecular viscosity. The analogy is not perfect but from it one can get a good quantitative feel for the effect of turbulence as far as mean flow is concerned. This analogy leads us to postulate that the effect of small-scale turbulence can be similarly represented by an effective eddy viscosity on the mean flow. The flow will again be regarded as one of relatively low Reynolds number, the Reynolds number having been reduced by the replacement of the molecular coefficient of viscosity by an effective eddy viscosity. However, the Reynolds number is not low enough that the flow is rendered stable; in fact we shall regard the instabilities of this model flow as generating the large-scale eddy structure which we now know generates the noise. These instabilities would be expected to have many features in common with instabilities of laminar flows at low Reynolds numbers. Let us summarize briefly some of these properties (see, for example, Lighthill 1970). When the Reynolds number is low enough, all perturbations are damped and the flow is stable. At slightly higher Reynolds numbers, disturbances in a narrow range of frequencies, with scale of the order of the shear layer width, can grow with a small growth rate. These are the instabilities visible in the singing flame where the motion is seen to be regular at a scale of about the jet diameter. At higher Reynolds numbers still, disturbances in a broader band of frequencies are unstable and the growth rate is increased. Instabilities then appear more chaotic and the flow more turbulent. At the very high Reynolds numbers of engineering practice, the growth rates are very large and the instability band very wide. Turbulence quickly results.

We now propose to view the main turbulence as the debris of upstream instabilities that is convected with the stream. This turbulence is of small scale and produces an eddy viscosity, which lowers the effective local Reynolds number of the shear layer to a slightly supercritical condition where instabilities in a fairly narrow band of frequencies can grow, and grow relatively slowly. These will be at large scale and will appear rather coherent. The only available analytical evidence for this idea is to be found in the visco-elastic theory of fine-scale turbulence given by Crow (1968). According to this theory, turbulence offers viscous resistance to a large-scale slowly varying, and suitably weak, mean field. The interaction between turbulence and the mean flow which *drives* the turbulence could not be represented in eddy viscosity terms in the present form of the theory, but the action of the turbulence is suppressing the growth rate of a weak long wave instability is probably very well described in this way. It is the big eddies that generate sound. Figure 7 (plate 1) shows a photograph of the surface ripples produced on shallow water by a turbulent jet generating waves that radiate from the source. This phenomenon bears a close analogy with the jet noise problem (Ffowcs Williams & Hawkings 1968; Webster 1970). This particular photograph was taken by R. B. Webster and is of a jet simulating the 'Concorde' situation in that the velocity is properly scaled though the effective Reynolds number is not. In the simulation one can clearly see waves generated by a large eddy structure that originates in an instability of the primary flow. We suggest that this is a good modelling of the important sources of high-speed jet noise. From this point of view the bulk of the turbulence has no direct bearing on the noise producing ability of the jet, though it does control the velocity profile whose instability gives rise to the large eddies. The eddy viscosity generated by upstream events, is unable to completely neutralize the inertial instability. However, one can imagine the balance to be temporarily tilted in the stable direction by either an artificial stimulation of the viscosity-producing turbulence or a lowering of the unstable vorticity concentration by external control of the mean velocity profile. This view point allows us to suggest that the bulk of the turbulence, on a scale much smaller than the noise-producing scale, should be increased to change the velocity profile and hence alter the stability of the flow and the large eddy formation. Indeed, it could be argued that many sound suppression schemes, of a type where fingers or spades are introduced into the flow, do just this – they create new small-scale turbulence although this was by no means their primary objective.

A further way of exploiting the basic idea that it is the large-scale eddies that generate sound is the provision of secondary flows that 'stiffen' the motion. This might be done by positioning strong axial vortices which would resist strain and thereby impede the undulating motion of the large eddy structure.

6. Conclusions

Arguments have been presented that identify the main sound sources in a highly supersonic jet flow. The jet conditions studied model closely the unsuppressed 'Concorde' situation at full take-off thrust. The dominant noise is radiated at an angle of 45° to the jet axis and is generated as the Mach wave sound of supersonically moving eddies in the neighbourhood of the end of the primary jet mixing region 8 diameters downstream of the nozzle exit. The sound is generated by large eddies that move supersonically relative to the ambient fluid. They travel coherently for a distance of about 5 nozzle diameters. The scale of these eddies seems to be about 2 diameters.

The sound that is subjectively most important at full-scale conditions is at a rather higher frequency. This is identified as originating in supersonically moving eddies whose scale is about twice the shear layer thickness at approximately 5 nozzle diameters downstream of the jet exit.

The very large size of the noise-producing jet motions implies that noise generation might be a process recognizable as a distinct coherent undulation of the primary jet flow arising from an inertial instability. Viewed in this way the process is subject to a certain measure of control by devices that modify the mean velocity profile. This can certainly be done by an ordered secondary flow, such as a system of axial vortices. Changes can also be accomplished by devices that generate turbulent wakes that again modify the jet velocity profile. The object of the modification would be to delay the formation of the very large eddies, the instability products of the mean shear layer, until such time as the flow had lost more of its momentum by turbulent mixing caused by a smaller group of eddies. Ensuing instabilities would then be less violent and quieter.

This work was initiated by the Rolls-Royce Bristol Engine Division's noise panel in support of their investigations into the high-speed jet noise problem. Dr S. G. Hooker chairs that panel whose members include Professors G. M. Lilley, N. H. Johannesen and P. E. Doak. The authors acknowledge the guidance of the panel. They also acknowledge the encouragement given by the directors of Rolls-Royce for the pursuit of this work and publication of the results.

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FIGURE 7. A shallow water-table simulation of the noise field, generated by the jet at 'supersonic' eddy convection speeds.