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Aerodynamic noise

By M. J. FISHER
Institute of Sound and Vibration Research, The University, Southampton

AND M. V. LOWSON
Department of Transport Technology, Loughborough University

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A symposium on aerodynamic noise was held at Loughborough University from 14 to 17 September 1970 under the sponsorship of the Royal Aeronautical Society and the British Acoustical Society. The objective of the meeting was to focus attention on unsolved theoretical and experimental problems which will require attention over the next few years. Areas which were covered included jet noise, non-linear acoustics, rotor noise, and diffraction theory. The symposium was successful in bringing together several new themes in aerodynamic noise research. The most significant of these were the existence of a degree of order in turbulent jet flows, and the dominant effect of inflow conditions on rotor noise radiation. In addition an improved and unified basis for jet noise theory seems to be evolving.

Jet noise

The first of two conference sessions on the subject of jet noise was initiated, most appropriately, by a review paper presented by Professor M. J. Lighthill. His paper was further augmented during an additional evening session by the showing of the film, by Lighthill & Ffowcs Williams (1967), demonstrating the fundamentals of the subject. These contributions were valuable in setting the stage for the subsequent presentations.

The remainder of the first session was occupied with papers on the structure and mechanism of jet flows. L. J. Poldervaart showed his impressive Schlieren movie demonstrating the feedback mechanisms which lead to the production of discrete tone (screech) noise in jet flows containing shocks. This exhibited the phenomena for a two-dimensional jet. A second film, due to Westley (1968), for an axisymmetric jet was also shown. The comparison indicates that a number of additional oscillatory modes occur in the axisymmetric case, making interpretation more difficult there. It would appear that a useful purpose can be served by subsequent quantification of the phenomena demonstrated qualitatively by these films, particularly in view of the recent paper by Hay & Rose (1970), regarding practical manifestation of these phenomena on the V.C. 10 aircraft. This latter work does suggest that while 'screech' is seldom encountered on full-scale engines at ground level it can occur significantly at altitude providing a potential structural fatigue problem. In spite of the fact that the general mechanism of screech production has been understood for nearly twenty years (e.g. Powell 1953) the conditions under which it may or may not be significant (i.e. its amplitude dependence) seem to have received relatively little attention.

Turning to the subsonic jet structure, two complementary papers were presented by Lau, Fisher & Fuchs, and by Crow & Champagne, regarding the existence of an orderly structure in these flows. The former presented measurements of fluctuating pressures and velocities in both the potential core and entrainment regions of the flow. It was shown that these fluctuations have a relatively narrow band spectral content when compared to those measured in the jet mixing region. Furthermore, a high degree of statistical interdependence (correlation) exists between fluctuations in core and entrainment regions. The paper concluded with a demonstration that all results were consistent with the concept of a series of equally spaced toroidal vortices contained in the jet mixing region and being swept downstream at a speed 0·6 times the jet efflux velocity. The paper by Crow & Champagne described an experiment in which the stagnation pressure of a very low-speed jet ($\sim$ 20 ft/sec) had been pulsed at various frequencies with the aid of a pressure transducer, located in the jet settling chamber. Their studies combined visual and hot-wire investigations of jets from Reynolds numbers of 2000 to 100000. They showed how an initial series of ripples developed into a series of vortex puffs, which could be detected even at the higher Reynolds numbers. Crow showed how the initial growth of the disturbances agreed with linear theory with a greater growth rate at high frequencies. But these disturbances rapidly reached 'saturation' with the final growth rate being a maximum at a Strouhal number, based on jet diameter and efflux velocity, of 0·3. The final vortex puff form of these disturbances was very similar to that of the toroidal vortices postulated by Lau *et al.* from their pressure/velocity measurements. Thus it appears that the existence of a significant degree of order in jet turbulence is confirmed. It seems likely that this will persist to the practical Reynold numbers. On the other hand, the practical significance is less clear. Delegates to the conference were evenly divided on this. Active workers in turbulence generally felt that understanding of the structure must give possibilities for control, but others felt that the turbulence had a strong tendency to adopt a 'normal' configuration, comparatively insensitive to input conditions or possible control measures.

W. J. Hiller presented the other paper in this session by Hiller, Jaeschke & Meier on the influence of air humidity on pressure and density fluctuations in free transonic jets. Their paper was motivated by the finding that the laboratory data recorded were a function of the weather conditions. Perhaps all experimenters find such effects, but the Gottingen team showed that in this case the effect was real, and due to air humidity. Noise levels were reduced by 10 dB on increasing air humidity from 5 to 60 %. Their data were taken from wall-pressure measurements in the separating shear layer of a Laval nozzle. No explanation for the effect is forthcoming at present, although it seems due to some type of condensation-shock phenomenon. No equivalent measurements for far-field radiation are available, but it is likely that similar effects could be found.

The second session on jet noise began rather disappointingly with the cancellation of the scheduled review lecture by Ffowcs Williams due to illness. This provided rather more time for Meecham, to expound his ideas on 'A fluid mechanics view of aerodynamic sound theory'. This paper again raised the old question of the relative merits of regarding noise production by a turbulent flow as being due to a set of convected simple source or due to an equivalent stationary array of stresses (quadrupoles) as in the original Lighthill formulation. Meecham began by expanding field variables about their incompressible value to include both hydrodynamic (non-propagating components) and the remaining acoustic component. Substituting these definitions into the continuity and Navier–Stokes equations, recognizing (apparently) that the incompressible flow variables satisfy these equations independently and neglecting some high-order terms, resulted in the appearance of two types of convected acoustic source, a monopole from the continuity equation and a dipole source from the Navier–Stokes equation. A physical explanation of the appearance of the two sources was then reviewed in terms of mass fluctuations within and force fluctuations on a control volume of fluid as it convects with the local flow speed. In spite of such an attractive physical explanation, it appears that the appearance of two sources, as opposed to one for the Lighthill formulation, and the necessity of adopting approximations in the course of the derivation, not during application of the analysis, leaves little of major appeal. It is further claimed by Meecham that an advantage of the approach adopted is to separate noise production from subsequent refraction. There seems no reason why modification should not be adopted to obtain the same end in the exact Lighthill formulation as indicated by Csanady (1966). The question as to the procedure to be adopted in the region where sound wavelengths are comparable to flow dimensions, is, however, equally unclear. This point, as we shall see in a subsequent paper by Lush, is of considerable significance in the practical situation.

Turning from the theoretical to the highly practical, the paper by Bushell offered an excellent empirical correlation of a large range of data for various jet configurations. His figure 1 showed a convincing collapse of data (peak OASPL *vs.* Mach number) for both model and full scale configurations above a jet efflux velocity of 1000 ft/sec. Below this velocity the measurements deviate increasingly from the V^8 line until at 400 ft/sec typical experimental results are 20 dB above the anticipated values. By way of explanation Bushell shows a comparison of measurements on the same (model) rig with and without an unlit combustion can obstructing the flow upstream of the nozzle. The presence of the obstruction raised the noise levels by as much as 20 dB at 400 ft/sec, while the typical engine results are in closer agreement with the 'obstructed flow' case. The message seems clear. At these lower jet efflux velocities the predominant noise is not the jet mixing process, but is created by unsteady flow upstream of the nozzle exit plane as suggested by Ffowcs-Williams & Gordon (1965). Indeed this conclusion is encouraging for the future since such noise sources, at least in principle, are considerably more accessible to treatment than the more remote jet mixing process. Present results would indicate that very appreciable noise reductions are available for low-speed jets if such sources can be eliminated.

The paper then continued to develop the basis for an empirical prediction technique for co-axial jet configurations. The significant fact was noted that the bypass or fan stream follows a lower noise correlation curve than the hot centre core stream if they are considered separately. Thus in many practical configurations a useful prediction can be made by considering the centre core stream alone. The paper concludes with a plea for more *basic* data on noise production by coaxial streams. This plea is echoed by these authors with the additional proviso that considerable care must be taken to ensure that erroneous noise sources upstream of the nozzle are eliminated. Without such precautions the data will not be *basic* but typical only of the rig on which it is measured.

The paper by Lush presented an exhaustive comparison of model air jet noise measurements with the Lighthill theory over a Mach number range from 0·3 to unity. It is worth mentioning here that considerable precautions were taken in the development of the rig for these experiments to eliminate the upstream noise sources alluded to by Bushell. These included the provision of acoustic treatment between the final flow control valve and the jet settling chamber and the use of a large (36:1) nozzle contraction ratio to keep down flow velocities upstream of the nozzle. With these precautions it is found that for measurements at 90° to the jet axis the Lighthill V^8 law is obeyed over the entire velocity range. It might be noted here that certain early measurements (see, for example, Lighthill 1954), showed lower indices for this position and this was explained on the basis of a reduction of turbulent intensity with increasing Mach number, a contention which has persisted to the present day. It would now appear probable that these lower indices were due to rig noise raising the measured noise levels at lower jet speeds, or to other errors.

Further comparison of the data with theory at smaller angles to the jet axis, however, indicated noticeable discrepancies. This led Lush to a comparison of experiment with theory as a function of frequency, specifically, as a function of a Strouhal number, $f_S D/U_0$ where f_S is the source frequency, related to the observed noise frequency by a Doppler factor, namely

$$f_S = f_{\text{obs}}(1 - M_c \cos\theta).$$

It was found that at low 'reduced frequencies' (i.e. low values of $f_S D/U_0$) the predictions of the Lighthill theory, with due allowance for convective amplification as corrected by Ffowcs Williams (1963), were borne out with very acceptable accuracy. This refers both to the variation of filtered sound pressure level with jet velocity at a given angle as well as to the total acoustic power radiated at that chosen 'frequency.' However, as the 'reduced frequency' was increased the results, particularly at small angles to the jet axis, deviated from the theory showing an increasing lack of convective amplification with both increasing speed and decreasing angle of observation. At high speeds the higher frequency noise showed an almost complete lack of directionality. This is, of course, not a new result, it has been attributed to refraction of the higher frequencies by the jet shear layer. However, Lush's measurements of acoustic power at these high frequencies also indicate the complete lack of convective amplification. Thus the process is not entirely one of redistribution of the acoustic energy by refraction, but a fundamental difference in the noise production process, as suggested some years ago by Powell (1960). Lush also presented evidence to suggest that these anomalous phenomena begin to occur when the path lengths of the sound in the shear layer become comparable with the acoustic wavelength. This is in agreement with the work of Csanady (1966) who shows, by solution of the convected wave equation for the high-frequency situation where wavelengths are small compared with the shear layer dimensions, that only refraction and no convective amplification is to be anticipated for this situation. The practical significance of this phenomenon is clearly demonstrated by acoustic spectra presented in Lush's paper. At 90° where no convective amplification is expected the spectra for various speeds scale satisfactorily on a Strouhal number $f_S D/U_0$ as predicted. However, at 15° to the jet axis the lack of convective amplification at the higher frequencies is sufficient that the peak noise frequency has a constant value over the entire speed range investigated. It seems clear, therefore, that a considerable development of our knowledge of noise production under circumstances where acoustic wavelengths are comparable to shear layer dimensions is needed before detailed prediction of jet noise can be placed on a firm theoretical basis. Since this condition covers a large portion of the acoustic spectrum at all practical jet operating speeds, the matter is one of considerable practical, as well as theoretical, interest.

During discussion Lowson presented an analysis of noise data by K. Ahuja which closely supported Lush's findings, and P. O. A. L. Davies stated that his measurements showed no effect of Mach number on turbulence intensity. Thus it does seem that several of the previously accepted features of jet noise must now be revised, and this new data offers the basis for improvements in understanding.

The final paper of this session by S. P. Pao was a theoretical study of the generation of sound by a source in a shear layer. Unfortunately he was not able to present his paper in person and his written text was rather too brief to allow a full analysis. He has apparently solved the problem of jet radiation in shear layer via a solution of Phillips's (1960) equation. This was Fourier transformed into a Sturm-Liouville equation and solved by the WKBJ method. His results are of interest since they show a significant difference between the behaviour of high- and low-frequency sound. The high-frequency sound is predicted to be attenuated by the action of the shear layer. The work justifies close study, especially since the conclusions qualitatively support Lush's data.

In jet noise theory two principal schools of thought have developed. There is now no major disagreement between the two approaches. Nevertheless, the British school, led by Lighthill and Ffowcs Williams has tended to concentrate on the convective amplification effects, while the American school represented by Ribner, Powell and Csanady, has emphasized the refractive effects of the flow. It is now clear that results from both schools must be combined to give the complete picture. Lush's experiments give a good idea of the basic effects, and Pao's work appears to be a first step towards a unified theory embracing both approaches. Work by Ribner & McGregor (1968) has already shown how the two approaches can be combined empirically.

Non-linear acoustics

The third session was devoted to non-linear acoustics which is assuming increasing importance in present day aerodynamic noise phenomena. D. T. Blackstock gave an entertaining historical review which went back 200 years, and which also pointed out that theoreticians had the solution in their grasp repeatedly, but repeatedly turned aside. There must be a moral for today in this observation. He also discussed weak-shock theory and the Burgers equation and emphasized that weak-shock theory would not in fact apply if the shock were sufficiently weak. The simplicity of weak-shock theory is, however, a major attraction.

D. F. Pernet presented theoretical and experimental considerations of harmonic distortion of bands of noise due to high amplitude non-linear effects. The effects of such spectral cascading on the apparent attenuation rates of aircraft noise were briefly reviewed. Order of magnitude calculations indicate that at frequencies above 4 kHz distortion effects produce signal levels quite comparable to those of the original signal. It was, however, emphasized that such conclusions are tentative requiring further analysis and experimental verification. It is also appropriate to mention here the paper by D. L. Hawkings on 'Multiple tone generation by transonic compressors'. He showed this to be a natural result of non-linear phenomena, which preferentially reduce the regular part of the signal, leaving the irregular signal, due to blading imperfections, as the principal contributor to the observed sound. Hawkings gave an analytic solution of wide applicability to weak-shock processes. Blackstock pointed out the significance of Hawkings's work for underwater acoustics and also that Berktay (1965) had given an entirely different type of analysis of a similar phenomenon in that field, recently confirmed experimentally by Moffett *et al.* (1970).

W. Möhring gave a thorough theoretical study of the sound propagation in the duct flow, explicitly demonstrating the significance of the shear. Finally M. Howe presented an analysis of sound propagation in turbulent flow. His very attractive analysis resulted in a type of Burgers equation with a dissipation factor depending on turbulence intensity. This would appear to have wide application. Howe used this equation to predict shock wave thickening and obtained results in agreement with experiment. However, Crow pointed out that although the results would be valid for an ensemble average any single realization would not give the same thickening result. Nevertheless, the underlying physical basis for this work does seem sound, and it seems that the result must be at least qualitatively, correct.

Rotor noise

The papers on rotor noise were opened by a review written by Hubbard, Lansing & Ruynan. Their review was far ranging and several interesting results were presented. Their data showed an increase in helicopter rotor noise of about 5 dB due to the addition of sand roughness. The data was taken on a full-scale tower test. This result may be compared with the results from 'owl wing' tests where the addition of multiple miniature strakes on the leading edge of a propeller reduced noise levels by 5 dB. Undoubtedly the reasons for this variation lie in the Reynolds number effects, probably related to transition and separation phenomena, but this does indicate that surface details could be a significant factor on noise generation. The paper also discussed the theoretical work of Lansing (1969). He has solved the full open duct diffraction problem for higher-order modes, and his results show some significant effects. The one figure shown demonstrated especially good agreement with experiment, but further correlation and comparison with other similar theories is required.

M. V. Lowson discussed the effects of non-uniform inflow on rotor noise. His paper included a simple model for the spectrum produced by non-uniform input to a full rotor, giving peaks at the blade passing frequencies from turbulent input. The results are apparently in general agreement with experiment. He also showed how the presence of a duct reduced the side line level of rotor noise. This point is in agreement with the more exact theory of Lansing.

B. Barry and C. J. Moore presented the results of an extensive experimental study of a low-speed fan ($M \sim 0{\cdot}5$). Their results showed several features of considerable interest. They utilized on-axis measurements of acoustic spectrum as a method for inferring force spectrum. This appears to be a most useful technique. Using this they found an inverse first power law (inverse second for force squared) based on 5 % of the steady load. This was in broad agreement with aerodynamic data previously presented by Lowson. Further evidence in support of this law was the spherical radiation patterns for this type of sound shown theoretically both by Lowson and by Morfey & Tanna, and found experimentally in many investigations including that of Chandrasekhara reported at the meeting. Barry & Moore also used a wave-form 'eduction' technique to separate out the steady 'phase-locked' and randomly phased contributions to the discrete frequency sound. They found that about half came from each source. In response to a question they also showed how the Tyler & Sofrin (1962) circular duct decay rates were found very accurately for the various rotor noise harmonics (due to steady loading). This was in a region close to the rotor where the individual blade pressure signatures could clearly be recognized.

J. S. B. Mather presented an interesting analysis of noise from transonic fans. He showed how the introduction of outlet guide vanes increased the noise levels. Much of this was due to the introduction of discrete frequencies at high engine order harmonics, presumably due to blading non-uniformities. Mather was able to show that the directional and cut-off characteristics of these frequencies were consistent with an extended version of the Tyler & Sofrin (1962) duct mode theory.

C. L. Morfey was responsible for two significant theoretical papers at the symposium. In his first he made explicit calculation of the quadrupole strength associated with an array of line forces moving through a non-uniform velocity field. Ffowcs Williams and Hawkings (1969) were the first to point out the possible significance of quadrupole phenomena in rotor noise. Morfey's calculation showed that the quadrupole contribution might well exceed the dipole contribution even for Mach numbers as low as $0{\cdot}5$. Morfey took an essentially two-dimensional model, and several further questions remain to be answered, but the result is obviously of considerable significance to rotor noise in general. A later paper by Chandrasekhara confirmed the general conclusion of Morfey's argument, although his model gave a slightly different numerical result. However, Barry & Moore showed good agreement between theory and experiment for fan noise, using the dipole free field theory of Lowson & Ollerhead (1969). Barry & Moore used fluctuation data acquired from on-axis measurement partially supported by aerodynamic data. Thus conclusions on the principal source of rotor noise are not obvious at the present time. A paper by Tanna & Morfey showed how explicit algebraic results could be given for sound pressure and sound power radiation by a rotor. They based their theory on the work of Lowson (1965) on accelerated sources. Their results were of obvious value because other modal approaches give results as infinite series of Bessel functions. Unfortunately these more cumbersome formulae must be used for discrete frequency radiation, but broad band radiation can certainly be studied in more detail. It is interesting to note that the numerical results of Tanna & Morfey were apparently very similar to some of Lowson based on the Bessel function sum presented earlier at the meeting, so that a generalization to the discrete frequency case may be possible under suitable assumptions.

S. N. Smith & D. S. Whitehead presented a comprehensive two-dimensional theory covering simultaneously the compressible aerodynamics, flutter and noise generation of the rotor. Several other workers, e.g. Kaji & Okazaki (1970*a*, *b*) and Mani & Horvay (1970), have produced similar types of theories, and these seem to be of distinct potential design value. The principal problems appear to be computational.

Diffraction theory

The final session was on diffraction theory. Professor D. S. Jones presented a masterly review of the fundamentals which made diffraction theory appear elementary. He also pointed out the wide variety of problems which were accessible via existing solutions. He discussed diffraction by an edge, pointing out that a sharp edge produced a less defined shadow than a curved one. (The radius of curvature criterion separating these régimes is apparently around half a wavelength.) This point does raise questions on the validity of modelling jet engine inlets via a sharp edge mathematical model—although Lansing has had some success in this approach.

F. G. Leppington discussed the effect of a sharp trailing edge on radiation by turbulence and indicated an M^5 law rather than the M^8 or M^6 characteristic of a quadrupole or dipole. Several delegates raised the question of viscous effects on this model. It seems these should be small acoustically, but that the turbulence in the vicinity of the trailing edge could well be substantially altered. D. S. Whitehead felt that the Kutta condition would alter the model significantly. Leppington's results indicated that the radiation from the turbulence in the immediate vicinity of the trailing edge dominated the sound field. This of course tends to counter the arguments of Morfey and Chandrasekhara that direct quadrupole rotor sources were significant. This surrounds the dipole-quadrupole controversy for rotor noise with still further theoretical hurdles.

The symposium closed with an extremely lively discussion chaired by E. J. Richards. One of the principal points to emerge was the comparative stagnation of jet noise research in the last twenty years. Delegates were divided on the ultimate possibility of reducing jet noise, but it seemed to be generally considered that understanding the underlying order in the turbulence would probably be the most fruitful path for jet noise control.

The principal conclusions on the rotor noise side was the extreme significance of inlet conditions. The variability of measured engine rotor noise from day to day, engine to engine, and especially from engine to model was emphasized by J. S. B. Mather. Most delegates seemed to feel the role of the duct was generally quite minor compared with the role of the inflow distortion. Thus it appears that research in this area would be most profitably achieved in inlet dynamics and noise from aircraft flyovers.

Papers presented*

M. J. Lighthill (University of Cambridge). Aerodynamic noise theory.

L. J. Poldervaart & F. H. M. Jomgsma (Technische Hogeschool, Eindhoven). Jet observation at 1–3 $\times 10^6$ frames/second (Film).

†W. J. Hillier, M. Jaeschke & G. E. A. Meier (Max-Planck Institut, Gottingen). The influence of air humidity on pressure and density fluctuations and free transonic jets.

J. C. Lau, M. J. Fisher, & H. V. Fuchs (University of Southampton). A study of pressure fluctuations in the vicinity of a jet shear layer.

S. Crow & F. H. Champagne (Boeing Scientific Research Laboratories). Orderly structure in jet turbulence.

W. C. Meecham (U.C.L.A.). A fluid mechanics view of aerodynamic sound theory.

S. P. Pao (Wyle Laboratories, Huntsville). A generalized theory on the noise generation from supersonic shear layers. (Abstract only).

†K. W. Bushell (Rolls-Royce, Hucknall). A survey of low velocity and co-axial jet noise with application to prediction.

P. A. Lush (University of Southampton). Comparison of jet noise theory with experimental results.

H. H. Heller, G. D. Holmes & E. E. Covert (Bolt Beranek and Newman, Cambridge Mass.). Flow induced pressure oscillations in shallow cavities.

†D. T. Blackstock (University of Texas, Austin). A comparison between weak-shock theory and Burgers' equation in non-linear acoustics.

†D. F. Pernet (National Physical Laboratory). Propagation of non-linear signals in air.

P. E. Doak (University of Southampton). On the interdependence between acoustic and turbulent fluctuating motions in a fluid.

* Most papers will be published in the open literature, generally in *Journal of Fluid Mechanics* or *Journal of Sound and Vibration*. Copies of the preprinted papers (marked †) are also available from the Department of Transport Technology, Loughborough University, at an inclusive price of £5 ($12.00).

W. Möhring (Max-Planck Institut, Gottingen). Energy flux in duct flow.

M. S. Howe (Imperial College, London). Sound propagation in turbulent flow.

†H. H. Hubbard, D. L. Lansing & H. L. Runyan (N.A.S.A. Langley). Review of rotor noise technology.

†M. V. Lowson (Loughborough University of Technology). Rotor noise generation in non-uniform flow.

†C. L. Morfey (University of Southampton). Tone radiation from an isolated subsonic rotor.

†B. Barry & C. J. Moore (Rolls-Royce, Derby). Subsonic fan noise.

S. N. Smith & D. S. Whitehead (University of Cambridge). Discrete tone generation by a cascade of flat plates in subsonic flow due to incident wakes.

M. J. Fisher, P. Yardley & T. Grevle (University of Southampton). The wakes of rotating compressor blades.

J. S. B. Mather, M. J. Fisher & J. Savidge (Rolls-Royce, Hucknall). New observations on tone generation in fans.

D. L. Hawkings (Rolls-Royce, Derby). Multiple tone generation by transonic compressors.

†H. K. Tanna & C. L. Morfey (University of Southampton). Sound radiation from broadband forces in circular motion.

†N. Chandrasekhara (University of Southampton). Sound radiation from random quadrupole source distributions in axial flow fans.

D. S. Jones (University of Dundee). Diffraction theory.

F. G. Leppington (Imperial College, London). Diffraction effects on sound radiation by turbulence.

Concluding discussion. Future research on aerodynamic noise. Chairman: Dr E. J. Richards (Loughborough University of Technology).

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