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Acoustics of turbulent flows: a report on Euromech 142

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The European Mechanics Colloquium, Euromech 142, was held at the Ecole Centrale de Lyon from 23 to 25 September 1981 and was attended by 70 participants, from 9 countries, active in the fields of (i) sound production by turbulent flows and (ii) the effects of flow and turbulence on the propagation of acoustic waves. For topic (i), attention was mostly paid to shear-layer and jet instabilities and to the flow–surface interaction of flexible boundaries, vibrating blades and rigid thick airfoils. Applications were concerned in particular with propeller noise and airframe self-noise of large aircraft. Impinging shear layers were also considered for single and multiple cavities in which self-sustained oscillations can occur. Another subject discussed at the meeting was the noise from inhomogeneities, with applications to flames. For topic (ii), theoretical formulations were presented for the far field of moving multipole sources in the presence of flow and for sound propagation in ducts of variable cross section, with flow, for frequencies around the cut-off. The effect of turbulence was investigated in terms of the space–time coherence of the transmitted pressure fields. Broadband active sound control in the presence of flow was also considered, with emphasis on the progress made possible by use of digital filters. Finally, new experimental techniques, such as acoustic intensity measurements, were presented and large anechoic wind tunnels and other acoustic facilities were described.

1. Introduction

Research on aeroacoustics has been active for many years in Europe where several meetings have taken place, for example the AGARD Specialist Meetings at Brussels in 1963 and 1973 and at St Louis (France) in 1969, and the IUTAM/ICA/AIAA meeting at Göttingen in 1979. The pioneer model of the acoustic analogy of Lighthill was first used and improved in the early 1960s. Several source-location theories and experiments were then developed and debated in the 1970s. Currently, a growing interest lies in the physical mechanisms involved in noise generation. Many subtle possibilities have been pointed out, such as the instabilities of free shear layers and jets, the scattering by edges, the diffraction by surfaces, and the acceleration of inhomogeneous flows; the state of the art in these areas was reviewed in 1977 by Ffowcs Williams. Self-sustained oscillations of impinging free shear layers are also important for the acoustic control of instabilities, and numerous illustrations were given in a recent review paper by Rockwell & Naudascher (1979). At the present meeting, priority was given to new fundamental insights along the lines just mentioned, but engineering aspects, mostly issuing from the aircraft industry, were also included because they have always been an incentive to the development of aeroacoustics. More precisely, the following topics were presented and discussed:

(a) instabilities and large eddies in shear layers and subsonic jets;
(b) instabilities and shocks in supersonic jets;
(c) noise from inhomogeneities of density, and from flames;
(d) noise emitted by flexible or vibrating surfaces;
(e) aeroacoustics of unsteady shear flows over cavities;
(f) the theoretical formulation of acoustic-wave propagation in the presence of flows;
(g) propagation of acoustic waves in turbulence, and active sound control;
(h) experimental techniques;
(i) acoustic measurements in complex flows and engineering situations.

2. Instabilities and large eddies in shear layers and subsonic jets

The experimental evidence that the large eddies can be controlled has led to a wide interest in studies of excitation mechanisms. It is also known that two different modes of excitation are possible: (i) the shear-layer mode, whose acoustical effect had been recently explored by Kibens (1979), and (ii) the jet-column mode extensively studied by Moore (1977).

The first mode of excitation was considered by *D. W. Bechert & A. K. M. F. Hussain*† (D.F.V.L.R. Berlin and University of Houston). The acoustic control of a thin shear layer shed from a semi-infinite flat plate was investigated, and the results compared with the theoretical developments already published by Bechert & Michel (1975) and Orszag & Crow (1970) for the simple case where incompressibility of the fluid and symmetry of the boundary conditions on the two sides are assumed. The experimental facility provided an initially laminar shear layer whose thickness was controlled by boundary-layer suction. Predicted and measured velocity amplitudes were compared, and it was shown that the sound-pressure difference between the two sides near the trailing edge of the plate is the relevant quantity for the shear-layer excitation. Agreement appeared very good, except in the trailing-edge vicinity, where more sophisticated theories are probably needed. A written report is in preparation (Bechert & Hussain 1982).

The case of jets excited in the column mode was analysed by *J. Haertig, R. Meyer & F. Schlosser* (Institut Franco-Allemand, Saint Louis). As a first step they predicted the shear-layer instability from a model of weakly disturbed laminar flow, solving analytically the local-instability eigenvalue problem. The results for the streaklines agreed remarkably well with the data obtained by the same authors using laser-Doppler anemometry together with eduction techniques. As a second step, they used an integral formulation involving a turbulence-energy equation, a method already suggested by Chan (1974) and developed by Dahan (1976), to predict the coherent kinetic energy as a function of axial distance and pure-tone excitation level. The main result of their calculation was the prediction of a saturation effect. However, the subharmonic amplification observed by Hussain & Zaman (1980) and also by Juvé & Roland (1980) when the frequency and the level of excitation are in the specific

† In this report the names of authors whose papers were presented at the meeting are printed in italics: a full list of these papers is given in the appendix.

ranges for vortex pairing to occur (i.e. $0.5 \lesssim f_{\text{excit}} D/\overline{U}_{\text{jet}} \lesssim 1$, $u'_{\text{excit}}/\overline{U}_{\text{jet}} \gtrsim 0.01$ for $\overline{U}_{\text{jet}} D/\nu \simeq 10^5$) is not included in the analysis.

Concerning the jet noise itself, two main problems have been investigated by *A. Michalke* (Technische Universität Berlin). The first one dealt with the controversy about the influence of azimuthal source coherence on the modes existing in the radiated field. After having reviewed the previous work of Bonnet & Fischer (1979), he introduced a new model involving a variable azimuthal length scale. The results obtained for shear noise sources distributed on a ring showed that the axisymmetric sound contribution (mode 0) increased strongly with the azimuthal length scale of the source, while that of the first and second modes decreased. It seems worthwhile to recall that the prominence of modes 0, 1, 2 was also found experimentally by Juvé, Sunyach & Comte-Bellot (1979) for clean jets, and that significant increase of mode 0 appeared for excited jets (Juvé & Sunyach 1981). The second topic dealt with the influence of the axial turbulence coherence lengthscale on the directivity pattern. Michalke found that at subsonic jet Mach numbers the directivity at small angles of observation is increased by about 20 dB when the lengthscale is increased by only a factor 2. These theoretical results appear to be in good agreement with the experimental data obtained by Ronneberger & Ackermann (1979), who increased the axial lengthscale by exciting the jet. (In the latter publication it is interesting to note that the excitation was produced by a nonlinear interaction of two frequencies, which avoided contamination of the acoustic far field by the exciting sources.) It was therefore concluded that the strong coherent turbulence components do in fact contribute directly to the far-field sound.

It was also the change in the scale effect which was believed by *U. Michel & A. Michalke* (D.F.V.L.R. Berlin and Technische Universität Berlin) to be the most relevant factor in the modification of sound by flight. From the static case, two changes were suggested: (i) the stretching of both the axial source length and the axial coherence lengthscale, and (ii) a Mach-number modification representing the effects of convection and of the flight velocity. Predictions of fly-over jet-noise spectra were presented at the meeting and compared with experimental data. More data related to this work could be found in Michalke & Michel (1979) and Michel & Michalke (1981). As a major reference, we also mention the work of Michalke & Hermann (1982) on the instability of a circular jet with external flow.

3. Instabilities and shocks in supersonic jets

Two experimental contributions dealt with supersonic jet noise. The first one, given by *S. L. Hall* (1) (The New South Wales Institute of Technology, Sydney), included a systematic investigation of air and helium jets operating in the 50–150 % expansion range. Schlieren photographs enabled her to visualize the different waves λ_0, λ_1, λ_2 pointed out theoretically by Tam (1972, 1975) for the ideally expanded supersonic case (λ_0 is the wavelength due to cell-like structure; λ_1 and λ_2 are the short and long wavelengths related to spiral instabilities). Results showed that the measured values of the acoustic-wave angles were within 4° of their calculated values when convection and acoustic impedance effects were used to correct the air-jet values.

The other work concerned the supersonic jet-noise simulation on shallow water. Using the technique previously described by Webster (1970), *E. Brocher & J. P.*

Gondran (IMFL, Marseille) carried out visualizations of over-expanded supersonic jet instabilities. They observed that there is a lateral flapping of the jet connected to the shedding of large vortices. This motion could become very large when the shock structure near the exit was unstable because of fluctuations in the shock wave angle. An attempt to model this type of instability was also presented, giving an estimate of the range in which the resonance phenomenon could occur. Details are given in Brocher & Gondran (1981).

4. Noise from inhomogeneities of density and from flames

Some fundamental remarks concerning the description of acoustic sources that originate from inhomogeneities of mass density were presented by *J. E. Ffowcs Williams* (Emmanuel College, Cambridge). It was in fact the importance of the term

$$\frac{1}{c^2}\frac{\partial^2}{\partial t^2}(p-c^2\rho)$$

that was analysed, and several examples illustrated that whenever inhomogeities of density occur, in or near the apparent source region, it is wrong to discard that term even when the speed of sound is a constant. In other words, it was shown that it is not reasonable to discuss the field of more obvious sources such as q (rate of mass creation per unit volume), or f_i (external force per unit volume) or $\rho u_i u_j$ (turbulence stress tensor), as if they could exist independently of that induced by the imbalance between p and $c^2\rho$. If q, for example, results from the creation of a second immiscible phase of fluid at mass density ρ_q occupying a (variable) fraction β of unit volume, and if ρ_f is the mass density of the original fluid phase, the correct source term was shown to be $\partial(\beta\rho_f)/\partial t$ and not $\partial q/\partial t$, hence depending essentially on the rate of *volume* creation β rather than on the rate of *mass* addition. Furthermore, the difficulties that can be encountered when interfaces are present were indicated. In particular it was shown that the neglect of the imbalance between p and $c^2\rho$ can lead to apparent contradictions when used with an analogy in which the effect of an interface is contained in the Green function. Two useful papers on the subject are those of Kempton (1977) and Dowling, Ffowcs Williams & Goldstein (1978).

Modelling of density fluctuations in diffusion flames is an essential step towards the prediction of combustion noise, and this topic was investigated by *J. Janicka & J. L. Lumley* (Institut für Technische Thermodynamik, Aachen; and Cornell University). The authors started their presentation by giving the general equations that govern the first-order moment (mean value of the mixture fraction) and all the second and triple moments (correlations between velocity fluctuations and mixture fraction fluctuations). Then they carried out an expansion in the relative-density fluctuations for all the terms requiring modelling, making use of the continuity equation. That led to the definition of a small parameter approximately proportional to the root mean square of the relative-density fluctuation. This procedure permitted them to cast all the non-constant density terms into correction terms, which were placed on the right-hand side of the equations, all the left-hand side terms of the equations being the normal ones for constant density. Additional comments were made about the analytical form and the order of magnitude of the correction terms (details are available in an unpublished report, Janicka & Lumley 1981). Finally, the case of a diffusion flame with fast chemistry was considered. The reaction rate was introduced into the relation between the density and the mixture fraction. Use of logarithmic derivatives enabled the authors simply to superpose the effects of the mixing and the effect of the reaction so that in practice the only new requirements were limited to a change in the value of the expansion parameter. Computations were carried out for H_2 flames. Results dealing with values of density fluctuations were obtained and the small-parameter assumption appeared justified, especially in the reaction zone where most of the density changes take place.

Concerning experimental work on combustion noise, preliminary results for gaseous hydrocarbon flames which use oxygen instead of air were presented by *S. L. Hall* (2) (The New South Wales Institute of Technology of Sydney). Experiments were carried out on a small welding torch (velocity 15–60 m/s). Details of the flame structure were obtained using schlieren photographs and a high-speed ciné camera. Among the results reported at the meeting it was interesting to note two significant changes produced when oxygen is used in place of air as oxidizer: (i) a shift of the preferred direction of acoustic emission from 60° to 75° from the flame axis; (ii) an increase of sound-pressure levels and peak frequencies. These changes could be explained if one considers the increase of the burning velocity, which both causes an increase of the maximum temperature rise and enhances refraction effects. One topic discussed was the different sound power-law dependence on velocity. The present work has produced an exponent of 3·5 while Shivashankara, Strahle & Handley (1973) obtained the third power and Smith & Kilham (1963) obtained the second power exponent. A possible explanation is that the combustion mechanism changes with the ratio of flame velocity to turbulent velocity. More careful experiments, involving turbulence control in flames, will be necessary to achieve a better understanding of the subject.

5. Noise emitted by flexible or vibrating surfaces

A theoretical analysis of sound production in a turbulent boundary layer over a flexible surface was presented by *A. P. Dowling* (Cambridge University). The method of approach is a generalization of previous work by Dowling *et al.* (1978). The pressure perturbation, at a point on the surface whose properties are specified by a compliance relation, is obtained in terms of a Green function that takes into account the physical surface and an hypothetical vortex sheet positioned at the outer edge of the boundary layer. For the particular case of a hard surface and when the mean-flow profile is neglected, Ffowcs Williams (1965) found that the pressure spectrum is singular for spectral components whose phase speed is equal to the speed of sound. The inclusion of the mean-flow profile controls this singularity for all upstream-propagating spectral elements, but enhances the singularity for downstream-propagating elements. This singularity is due to a mode whose energy remained 'trapped' within the boundary layer and only decays slowly with distance from the source. Another interesting case is that of a bending plate with its front surface exposed to the turbulent boundary layer and backed by a void. Plates in air are generally sufficiently massive compared with the effective fluid loading to behave like a hard surface. However, in underwater applications the fluid loading is greater, so that the pressure spectrum is dominated by the surface properties, and it is found that the speed V of flexural waves in the plate plays a crucial role. If V is subsonic the pressure spectrum is singular for spectral components whose phase velocity is nearly equal to V, while for elements with sonic phase speed the pressure spectrum remains finite, controlled by the finite surface impedance. When V is supersonic the plate has a 'spring-like' response for modes with sonic phase speed, and a singularity occurs in the spectrum for sonic spectral elements. The technique can also be applied to plates with a composite structure or covered by sound absorbent material.

The significance of blade flexibility for sound radiation from fans was considered by *S. Glegg* (I.S.V.R. Southampton). In addition to the dominant source term (the aerodynamic load due to inflow distortions), Glegg estimated the role of two other mechanisms: the aerodynamic load that results from the oscillations of the blade (whose strength was found to be negligible in most cases) and the mass loading attached to the blade (whose strength may be appreciable in some cases, particularly with heavy fluids). The relative magnitude of the fluid-loading term, compared with the inflow source, was then expressed in terms of the externally induced displacement (both frequency and amplitude), the fluid density, the mass per unit length of the blade, the modal stiffness and the modal displacement of the blade (the blade was here assumed of high aspect ratio, with only flexural modes present). An experimental investigation has been also made on a fan powered by a diesel engine and hence subjected to large axial vibrations (typical displacement velocities were of the order of 0·035 m/s; the frequency range of interest was 0·1–2 kHz). Work in progress deals with the vibration characteristics of the fan assembly.

Measurements concerning the acoustic boundary layer on a rigid surface were presented by *G. Höhler* (D.F.V.L.R. Göttingen). Recall first that such a layer is created by the no-slip condition at the wall, which causes a shear wave to propagate away from the wall under viscous and turbulent shear stresses. For rigid ducts this acoustic boundary layer is relevant to sound attenuation, which is known to increase with flow when compared with that for a medium at rest (the effect being larger as the acoustic boundary layer gets thicker than the viscous sublayer; Ronneberger & Ahrens 1977). If a complex wall impedance is defined for these waves by the ratio of the complex amplitude of the shear stress and the velocity in the shear wave, then its real part determines the sound attenuation whereas its imaginary part represents changes in the phase velocity. The shear waves can be excited either by small perturbations of the mean-flow velocity (sound) or by longitudinal oscillations of the wall. Both methods were used in Ronneberger & Ahrens (1977), and additional data obtained with the latter technique were presented at the meeting. The experiments were made in a fully developed channel flow (oil tunnel) and the longitudinal velocity was obtained with a hot-film probe. A phase-average procedure permited the amplitude and the phase of the fluctuating velocity $\tilde{u}(y^+)$ of the shear wave to be obtained at different wall distances y^+. The shear stress $\tilde{\tau}(y^+)$ and the shear rate of the shear wave $\partial\tilde{u}/\partial y^+$ were also determined at different wall distances, as well as an 'effective' viscosity ν_{eff} defined by the ratio of $\tilde{\tau}$ to $\partial\tilde{u}/\partial y^+$. The reliability of the latter concept was strongly questioned, however, because of the fact that ν_{eff} was sometimes observed to be smaller than the molecular viscosity ν.

Concerning the leading- and trailing-edge noise generated by airfoils, on which a considerable amount of work has already been done (Amiet 1975, 1976, 1981; Howe 1978; Goldstein 1979; Brooks & Hodgson 1981; Arbey 1981), attention was focused at the meeting on two specific topics. First, the noise spectrum due to incident turbulence was analysed by *R. K. Amiet* (United Technologies Research Center, East

Hartford), who reminded the participants of the predictions he was able to obtain by the use of a compressible aerodynamic transfer function. Some discrepancies between predictions and measurements observed for the case of high frequencies and low mean velocities were attributed to a thickness effect. However, recent experiments by Arbey (1981) showed that the phase shift observed for the pressure field along the chord could also be a relevant parameter. Further measurements of this field close to the leading edge are certainly needed. Another topic considered was the trailing-edge noise in the case of a turbulent boundary layer along the airfoil. Using a similar analysis, Amiet obtained noise-spectrum predictions that are in good agreement with experimental data. Finally, an extension to the case of a rotating airfoil, such as that of a propeller, was made when the frequency of the sound generated is significantly greater than the rotational speed of the rotor. The case of skewed inflow to a rotor, such as would be the case for a helicopter in forward speed, was also tentatively investigated.

6. Aeroacoustics of unsteady shear flow over cavities

The unsteady nature of free shear layers that impinge upon solid boundaries has received considerable attention in recent years (Rockwell & Naudascher 1979; Rockwell & Knisely 1979; Rockwell 1982). The case of slots and wall cavities is of particular interest in aeroacoustics, as well as in marine applications, and several contributions were presented at the meeting.

The first one, given by *M. S. Howe* (B.B.N., Cambridge, Massachusetts, now at the Mathematics Department, University of Southampton) outlined a linearized theory of unsteady shearing flow of a weakly compressible fluid over a two-dimensional slot in a thin rigid wall. The interaction of the shear flow with the trailing edge of the slot results in the ejection of vorticity, which is subsequently swept downstream. The motion induced by the vorticity can be characterized asymptotically (at large distances from the slot) in terms of boundary-layer 'displacement-thickness waves' on the downstream wall, following a suggestion due to Liepmann (1954). In a first step, the real and the imaginary parts of the mass flux through the slot were determined. This flux consists of the fluid displaced by the vortex sheet together with the flux through the trailing edge, the latter being associated with the formation of the displacement-thickness waves. In a second step, an expression was provided for the power extracted from the mean flow. It permitted the author to analyse the self-sustained wall-cavity oscillations. More precisely, the velocity range within which the cavity modes were excited could be predicted for the experiments of De Metz & Farabee (1977), and good agreement was found. The present theory was applied with and without allowance for vorticity ejection. In the first case, the velocity range is larger than the second one, but the predicted velocity minima are the same in both cases. Recent papers on the subject are Howe (1981*a*, *b*).

Experiments on a cavity shaped as a Helmholtz resonator and embedded in the wall of a water tunnel were reported by *D. Leducq* (Société Bertin, Paris). Several parameters were adjustable, in particular the incident velocity of the water flow, the thickness of the bottom wall of the cavity, the geometry of the cavity opening and the shape of the upstream edge of the cavity (either sharp, or with a ramp to move slightly away from the wall the shear layer shed by the edge). An additional phenomenon was also pointed out. It is the eventual coupling between the modes of the cavity and the modes of the whole tunnel itself. An attempt to predict the relevant frequencies was made for the different situations investigated.

Finally, a complex case involving a system of periodic open cavities was presented by *J. Delcambre, J. M. Parot & H. Arbey* (Electricité de France, Paris; Société Métravib, Lyon; Ecole Centrale de Lyon). Such a system is found in practice on the large electric insulators that support high-voltage lines. Two coupled mechanisms explain the intense pure-tone frequency noise observed for specific wind magnitudes and directions: (i) a standing acoustic wave along the shell stack, similar to that described by Parker (1967) for a periodic arrangement of plates; (ii) a self-sustained shear-layer oscillation over the cavities that exist between the reinforcing ribs of the shells themselves. Coincidence of the frequencies associated with these two mechanisms can then generate intense pure-tone noise. In particular, the frequency jumps occurring as the velocity is increased could be accurately predicted. More details are available in a recent paper (Arbey *et al.* 1981).

The work presented by *P. O. A. L. Davies* (I.S.V.R. Southampton) dealt mainly with the acoustics of ducts in situations where plane-wave propagation dominates (Helmholtz number below 1·5). After a review of the knowledge required for prediction of sound transmission and radiation from flow ducts, attention was paid to the modelling of the energy transport and to flow–acoustic coupling mechanisms. First, it was emphasized that, although many of the processes observed at discontinuities exhibit a nonlinear behaviour, the energy transport can be reliably predicted by linear models that include a proper allowance for losses. The subject of flow–acoustic coupling was then discussed. Two basic mechanisms were analysed: (i) the excitation of a resonator by the vortices developed in the shear layer of a free jet flowing into it, and (ii) the direct excitation of a cavity resonator by a train of vortices flowing across its neck (Davies 1981). A parametric study of both types of flow-excited acoustic source was provided. In the special case of an expansion chamber inserted in a duct interesting results for the design of improved acoustic silencers were given, concerning the prediction of the velocity dependence of the sound level (M^5 law), the peak frequencies, and the acoustic-energy transmission at high levels of excitation ($\simeq$ 140 dB). In addition, the use of perforated bridging tubes across the expansion chamber was shown to be an efficient way of suppressing the acoustic coupling. However, the absolute levels of the acoustic quantities of interest are not included in the present analysis.

Additional information about the mechanism, previously described by Davies, of the oscillation induced by a free jet flowing into a cavity was given in the experimental work of *W. M. Jungowski & G. E. A. Meier* (Max-Planck-Institut für Strömungsforschung, Göttingen). It was demonstrated that the frequency of oscillation depends mainly on the resonator, even if the oscillation is caused by the shear-layer instability (subsonic jet) or shock-wave instability (supersonic jet). Pressure-spectrum measurements and a film recorded with a high-speed camera were presented for different configurations.

7. The theoretical formulation of acoustic-wave propagation in the presence of flows

The first paper, given by *H. Levine* (Stanford University), dealt with the asymptotic (far-field) estimate of multiple Fourier integrals of the type $\int F(\mathbf{k}, \omega)\, e^{i\mathbf{k}\cdot\mathbf{r}}\, d\mathbf{k}$, such as those encountered in numerous source representations (as usual, ω is the frequency, $\mathbf{k}$ the wavevector and $\mathbf{r}$ the observer location). The method is based on a plane-spherical equivalence of $e^{i\mathbf{k}\cdot\mathbf{r}}$ for $|\mathbf{r}| \rightarrow \infty$ that involves a delta function that peaks when the wavevector points toward the observer. The integration with respect to the direction of the wavevector is then immediate, and only a single integral with respect to the modulus of $\mathbf{k}$ remains. This technique seems to be a direct and broadly applicable means of ascertaining far-field behaviour in aero- or hydro-acoustics, where sources can possess a multipolar nature, execute various types of motion, and also manifest variable strength. In particular, the technique is believed to be an alternative operational procedure for the conventional 'stationary-phase method' (e.g. Lighthill 1978).

The propagation of acoustic waves in nozzles of non-uniform or even variable cross-section, in the presence of flow, is an important topic for aircraft design, for which the jet-engine characteristics have to be matched to different atmospheric conditions or flight demands. Yet much of the literature available (e.g. Candel 1975; Howe 1975) applies only to either abrupt changes (its effect on waves being described by means of impedances and reflection and transmission coefficients, hence a low-frequency limit) or gradual changes of the cross-section (so that waves may be assimilated to rays at high frequency, as in the WKB approximation). Substantial improvements were therefore proposed by *L. M. B. C. Campos* (Instituto Superior Técnico, Lisbon). The theory developed is exact in the sense that it applies to all frequencies, allows substantial continuous changes of cross-section and the associated variation in mean-flow velocity, and accounts for propagation over any distances from a few to many wavelengths. The restriction of low-Mach-number flow was, however, assumed in the present work in order to permit analytical solutions to be developed. The method of approach involved a 'nozzle wave operator', which generalizes both the convected and the horn-wave operators. Several important acoustic properties of the nozzle were then pointed out in terms of amplitude changes, phase shifts and cut-off frequency predictions. The case of an exponential nozzle was developed for a large range of conditions of propagation, $0{\cdot}3 \lesssim \lambda/L \lesssim 6$, $0{\cdot}8 \lesssim x/\lambda \lesssim 16$ (λ is the acoustic wavelength, L the characteristic length of variation of the cross-section, and x the length of the nozzle). This solution was expressed in terms of confluent hypergeometric functions. Comparisons with previous simplified theories were made. In particular, cut-off properties that were not included in the WKB limit could be predicted. Extension to high-speed nozzle flows are in progress; for that case the treatment would be largely numerical. A recent reference is Campos (1982).

The distribution of sound power among the propagating modes in ducts has been considered by *S. M. Baxter & C. L. Morfey* (I.S.V.R. Southampton). This research was motivated by the need for prediction of sound attenuation in lined ducts. The technique is specially designed to work at high frequencies where attempts to resolve individual modes are impracticable. A statistical approach, derived from previous work in architectural acoustics, is therefore used. The central idea is that with increasing frequency the many-mode sound field in an enclosure can approach an asymptotic form, known as a free-wave sound field, which is spatially homogeneous and composed of uncorrelated plane waves. Conditions for such an approach have been investigated. The key function expresses the angular dependence of the sound intensity in the field. Experimental estimation of this function is possible from the spatial cross-spectral density measured by two microphones, the duct being excited by an inlet from a reverberant chamber within which Hartmann sound generators are placed. Preliminary experiments (performed at the N.G.T.E., Pyestock) showed that as few as 12 microphone positions may yield a useful estimate. Data and further details are available in Baxter & Morfey (1981).

8. Propagation of acoustive waves in turbulence; and active sound control

The propagation of acoustic waves in random media has already generated a large interest (e.g. Tatarski 1971; Ishimaru 1978), but experimental investigations have often been made directly in the atmosphere, where different fluctuations co-exist (e.g. velocity, temperature, humidity), and not in well-controlled laboratory conditions. The latter case was recently considered by *Ph. Blanc-Benon & D. Juvé* (Ecole Centrale de Lyon) for velocity fluctuations in a jet, but with conditions representative of the propagation of sound in the atmosphere with large distances of propagation compared with the integral lengthscale of turbulence and with small acoustic wavelength (again compared with the integral lengthscale of turbulence). The results concerning the attenuation of the coherent wave, the acoustic intensity and the spectral broadening have been already published (Blanc-Benon & Juvé 1981*a*, *b*). The new data reported dealt with the space and space–time coherence of the transmitted pressure field. For the former, a useful expression was given for the transverse integral lengthscale of the pressure field. For the latter, a convective velocity U_c of the acoustic diffraction pattern was pointed out. It is of the order of 1·8 times the mean speed U of the turbulent flow, a value which could be justified by numerical estimates based on the parabolic approximation for an acoustic beam of Gaussian shape. For the limiting cases of plane and spherical waves, U_c would be equal to U and $2U$ respectively (Ishimaru 1978). Recent references are Blanc-Benon & Juvé (1982*a*, *b*).

Active sound systems require several improvements if they have to tackle cases in which complex geometry, flow velocities and temperature changes are present. We recall that this technique involves three main components: the detector, the controller and the cancelling source whose effect is to absorb or to reflect the sound back to the noise source.

The work presented by *C. F. Ross* (Cambridge University and Topexpress Ltd) dealt with an improved design of the controller by use of a digital filtering technique. An algorithm was provided that enabled an optimal controller to be produced. This algorithm involved three random-noise tests on the system with a loudspeaker driven by filtered white noise in place of the noise source. It led to two time series related to the theoretical transfer function needed by the controller. This transfer function is then approximated in terms of weighting coefficients obtained by system identification, introducing an error sequence and its minimization by the least-squares method. Details of this algorithm can be found in Ross (1982). The resulting filters were actually tried on a square duct (between 15 to 20 dB of reduction was achieved from 25 to 350 Hz) and also in the entrance lobby of the R.S.R.E. Malvern anechoic chamber (10 dB of reduction around 47 Hz).

Phase differences due to turbulence can exist between the detector and the controller, and this topic was investigated by *A. Roure & M. Sunyach* (L.M.A. Marseille and Ecole Centrale de Lyon) for a fully turbulent pipe flow. The simple case of plane waves was considered, as in previous contributions, the source being a loudspeaker driven at 1·2 kHz and mounted in the plenum chamber at the entrance of the pipe. Two flush-mounted wall-pressure transducers were used, at the detector and the controller locations. (Pulse trains of ten periods were emitted at convenient intervals to avoid reflections at the end of the duct.) Signals were digitized simultaneously at 100 kHz, and fed into a computer by blocks of ten pulse trains. The phase lag was investigated from the zero-crossings of the signal within an accuracy of 0·2°. The results showed that the time lag measured at each consecutive period was rapidly varying, depending strongly on the flow velocity and on the signal-to-noise ratio (here defined as the acoustic- to the turbulent-pressure level). For high values of this ratio (e.g. 30 dB in a third octave band), and a mean velocity around 20 m/s, the r.m.s. value of the phase change was about 0·5°, a value that can be roughly estimated from known values of turbulent velocity and length scales. For lower signal-to-noise ratios, larger phase lags were observed, for example 2° for a ratio of 15 dB. These results are useful in the design of the phase loop of the controller and for the prediction of its optimal performance. Future developments are aimed at improving the acoustic-signal detection within the turbulence; preliminary work on this topic has been done by Chamant (1981) and Benarrous & Chamant (1981). The effect of turbulence on the radiative impedance of the cancelling source should also be analysed, as pointed out by Roebuck at the meeting.

Indeed, some important remarks about the effect of turbulence in active noise control were formulated by *I. Roebuck* (Admiralty Underwater Weapons Establishment, Portland), with particular reference to the discussion of the acoustic-energy balance. First, it was pointed out that the mutual-impedance terms must be taken into account to analyse correctly the total energy radiated by two or more sources. This total output power is therefore expressed in terms of a matrix product $\mathbf{V}^{\mathrm{T}}\,\mathbf{Z}\mathbf{V}$, where $\mathbf{V}$ is the vector of the imposed normal velocities at the sources, and $\mathbf{Z}$ the mutual impedance matrix whose general term Z_{ij} is defined as the ratio of the pressure induced at the ith source to the normal velocity at the jth source acting alone. The active sound control is then achieved when this product is zero. In practice one has to look for a vector $\mathbf{V}$ that will minimize it. Two bounds are then given for the performances of real systems: (i) the enhancement of matrix coefficients by noise, and (ii) the time limitations encountered in the deduction of the impedance matrix. In addition it was suggested that in turbulent flows, apart from the practical difficulty of accurate acoustic measurements, the impedance change at the controller due to turbulence also introduces a fundamental limitation.

9. Experimental techniques

The mean acoustic intensity vector $\mathbf{I}$, with components $I_i = \langle pu_i \rangle$ (p is the acoustic pressure and u_i are the particle-velocity components), has recently received increasing attention because it permits the investigation of the acoustic near fields, despite their complexity, to find out which part of energy is really radiated as sound. A great effort has already been made to study the first component I_1 by the 'two-microphone technique', in which p and u_1 are approximated by

$$p = \tfrac{1}{2}(p'+p''), \quad u_1 = -\frac{1}{\rho_0}\int \frac{p''-p'}{\Delta r_1}\,dt,$$

where Δr_1 denotes the microphone separation and p' and p'' are the two microphone signals (Pavic 1977). Substantial improvements were made in the technique by digital processing and fast Fourier transforms so that I_1 could be obtained from the imaginary part of the cross-spectra between p' and p''(Fahy 1977):

$$I_1 = \frac{1}{2\pi\rho_0 \Delta r_1}\int_0^\infty \frac{\mathscr{I}[\phi_{p'p''}(\omega)]}{\omega}\,d\omega.$$

In addition, phase and amplitude responses of the microphones could be conveniently matched (Krishnappa 1981). Furthermore, errors due to the microphone separation Δr_1 could be estimated for typical sources, such as monopoles, dipoles or quadrupoles, and corrections were applied when necessary (Thompson & Tree 1981; Elliott & Thompson 1981). There was, however, a need for the simultaneous measurement of several components of **I** simply because the direction of **I** is not known *a priori*. A three-microphone probe was therefore designed to obtain two components of **I** in the frequency range 1–6 kHz, and it was presented at the meeting by *D. Juvé & Ph. Esparcieux* (Ecole Centrale de Lyon). Three small 'electret' transducers were used, with their sensitive surfaces located in the same plane to reduce diffraction effects. An iterative procedure was elaborated to correct for the gradient approximation and the differences between the microphones. The technique was applied to the acoustic near field of a circular jet, clean or excited (column mode). Preliminary results were in agreement with those obtained with the polar-correlation technique (Juvé & Sunyach 1979). The noise emission is more intense, and concentrated closer to the nozzle, when the jet is excited. A still more elaborate probe, with four microphones to obtain simultaneously the three components of the acoustic-intensity vector, is under development.

Great attention was also paid at the meeting to the causality technique used for high subsonic jets and *M. Schaffar* (Institut Franco-Allemand de Recherches, Saint Louis) reported several improvements and extensions to this technique. Extensive use was made, for example, of laser-Doppler anemometry, a non-perturbing technique, to obtain the turbulent velocity in the jet. Radiated pressure was also isolated from the background noise with the help of an acoustic mirror, and the associated diffraction pattern was carefully analysed. However, a very unusual development that was presented concerned the newly designed 'Dalembertometer'. This optical set-up permitted the obtaining of the Dalembertian of the density

$$\Box\rho = \frac{\partial^2}{\partial t^2}\rho - c_0^2\frac{\partial^2}{\partial x_i^2}\rho,$$

integrated along a jet diameter. It consists of a Mach–Zehnder interferometer (whose output signal was differentiated twice with respect to time) and of two schlieren devices (whose outputs were combined to give the second spatial derivatives). Technical details, including the calibration tests, are available in Sava & Smigielski (1976). The additional data obtained with this technique were in good agreement with previous findings, in particular for the location along the jet axis of the equivalent acoustic sources. A paper on that subject is Schaffar & Hancy (1982).

Concerning the acoustic facilities, recent improvements brought to the large anechoic wind tunnel Cepra 19, built jointly by ONERA and the Centre d'Essais des Propulseurs, were presented by *P. Rebuffet & A. Guedel* (ONERA, Paris). We recall that the open test section of this tunnel is 2 or 3 m in diameter for a maximum speed of 100 or 70 m/s respectively, about 10 m long, and surrounded by an anechoic room shaped like a quadrant of a sphere (radius $\simeq$ 8·5 m). Since the fan is located downstream of the open test section, the collector receiving the jet has to be carefully designed and positioned with respect to the jet. Some tests were therefore made on an 8:100 scale model that permitted aerodynamic as well as acoustic measurements to be taken. It was thus found that, due to an edge-tone mechanism added to a coincidence of the self-sustained frequency with a mode of the room, an important and damaging resonance phenomenon might take place around 10–16 Hz in real scale, if the length L of the open section was too short compared with the jet diameter D (i.e. L/D between 3 and 4). A longer test section was therefore designed and realized at full scale ($L/D = 5{\cdot}42$ for $D = 2$ m and $U_0 = 100$ m/s). The background noise and the recirculation flows did not seem to have been significantly increased by the unusually large L/D value chosen for the test section. Details are available in Rebuffet & Guedel (1981).

To measure acoustic impedance and the attenuation produced by different linings as a function of the wave incidence angle, *C. Saulpic & J. M. Ville* (U.T.C. Compiègne) used a spinning mode generator. This system, described in Ville (1977), consists of sources equally spaced around a circle and powered with suitable phase and amplitude signals to induce a single propagating mode in the duct; the number of sources is chosen equal to the number of propagating modes at the driving frequency. Four cases were considered, the plane wave and the three first azimuthal modes. The velocity inside the duct varied from 0 to 30 m/s. Pressure measurements along the duct axis gave the axial complex wavenumber and therefore the attenuation per unit length. The acoustic impedance of the lining was then computed by solving numerically the second-order differential equation governing the radially dependent part of the pressure. This procedure permitted the actual velocity profile to be taken into account. Very careful experiments were conducted for two different linings (honeycomb or glass wool) covered by a perforated steel sheet. Among the results reported, it is interesting to note that the acoustic impedance of honeycomb and, to a lesser extent, of glass wool is practically independent of the azimuthal wavenumber and also of the shape of the mean velocity profile.

Finally, a ciné film using the schlieren technique was presented by *B. Rybak* (Institut d'Etudes Linguistiques et Phonétiques, Paris) to visualize the motion of the air during speech. The exhaling of the breath was made visible for the 'breath sounds', i.e. those which are produced without use of the vocal cords. Specific patterns could be detected for the fricative consonants, such as f and s, and the stop consonants p, t and k. Superposed randomness due to the numerous irregularities along the vocal tract and the modulation of the airstream by means of the lips, teeth and tongue also exists. The ciné film can be borrowed on request. More details are given in Rybak (1980). The recent spectral measurements by Blumstein & Stevens (1979) also confirmed the acoustic invariants associated with the stop consonants.

10. Acoustic measurements in complex flows and engineering situations

At present most civil aircraft meet the current noise certification limits. However, it is expected that more stringent future regulations will make it mandatory to reduce the noise level further. On this topic, the first contribution was given by *S. R. Sarin* (Fokker Schiphol, The Netherlands) who was concerned with jet-noise suppression for low-bypass-ratio engines, such as the Rolls Royce RB 183, which power the Fokker F 28. Extensive laboratory experiments, on a $\frac{1}{10}$th simulation model engine placed in an anechoic wind tunnel were conducted in addition to real flight measurements. At first, various nozzle–ejector combinations (conical, five-chuted, eight-lobed plus lined ejector) were tested for their acoustic and aerodynamic characteristics. It was found, however, that the noise reduction was possible only at the price of thrust. The best configuration tested indicated a 0·5 % gross thrust loss for every 1 EPNdB level reduction at take-off power and flight velocity of 75 m/s. Subsequent studies indicated that a more efficient internal mixing of the core flow with the bypass flow could also result in a substantial noise reduction. A new ten-lobed nozzle with five protruders was designed. Laboratory tests on unmixed and mixed jets, and analysis of the mixing loss, were promising. It was therefore decided to completely replace the aft part of the hushkit fitted in the F 28's production (i.e. five-chuted silencer combined with intake and tailpipe acoustic liners). In real flight, reduction of over 3 dBA or 2 EPNdB in fly-over noise were observed without any noticeable thrust penalty. Savings in weight and reduction in fuel consumption were also observed. Some of the work has been published (Sarin & de Wolf 1981). The investigation is being continued.

Airframe self-noise has become a matter of concern for large subsonic aircraft on landing approach because the noise levels are only 8–10 EPNdB below the actual certification levels (Hardin 1976). At this Euromech meeting, data were made available for the European A-300B Airbus and also for the SN 601 Corvette by *J. L. Parant* (Aérospatiale, Toulouse). Preliminary correlation of noise levels with gross aircraft characteristics (speed, drag coefficient) was proposed, but other characteristics, such as the lift, have to be included to obtain a dependence in agreement with the fifth power of velocity as previously observed for other airplanes (B 747 or CV 990, White, Lasagna & Putnam 1976). Spectral analysis revealed that the noise of the A-300 B Airbus is almost free of discrete frequencies, but some appear around 400–500 Hz for the SN 601 Corvette when the flaps are extended at 35°. In this domain work in progress has to include the understanding of the numerous physical mechanisms involved (boundary-layer separation, trailing-edge conditions at the flaps, wings and fin, surface diffraction, panel vibration, etc.).

Another topic that has recently gained renewed interest is propeller noise, and it was considered at the meeting by *F. R. Grosche & H. Stiewitt* (D.F.V.L.R., Göttingen). The main objective was to investigate the effect of the forward speed of the rotor, and this was achieved by simulation in a wind-tunnel flow. The experimental set-up and its main aerodynamic and acoustic characteristics have already been made available (Grosche & Stiewitt 1978). At the meeting the additional results presented were obtained by an elegant use of the acoustic-mirror technique. Because of the focusing effect of the mirror it was possible to listen to different parts of the propeller disk simultaneously, e.g. to the upper part moving toward the mirror, and to the lower part moving in the opposite direction. The corresponding spectra differed considerably ($\simeq$ 15 dB) for high frequency ($\gtrsim$ 2 kHz). This effect could be explained by convective amplification of the noise emission of moving sources.

Concerning jet noise, two industrial cases involving high subsonic velocities and multiple nozzles were considered. *J. Kompenhans & F. R. Grosche* (D.F.V.L.R. Göttingen) investigated the noise radiation by jets issuing from perforated plates, such as those needed to exhaust a compressed gas into the atmosphere. Different plate thicknesses, orifice diameters, number of orifices, with sharp or round edges, were tested; the open-area ratio was in the range 0·025–0·30. It was found that tone radiation may occur in some cases, and otherwise that estimates can be conveniently obtained from the Lighthill law. The acoustic-shielding effect of a jet by its neighbours has been investigated and did not seem important. The second paper on multiple jets dealt with the glass industry, where containers just blown into shape have to be cooled. *W. M. Schuller & M. Louwers* (Peutz Ltd, Paris) presented systematic noise tests made on jets with very small inner diameters and relatively thick walls and various locations of the mould. They were finally able to reduce by 10–15 dBA the noise level of the cooling system.

Finally, the case of the transmission of large volume rates of liquids or heavy gases across high pressure drops through complex piping systems was considered in two papers. *G. Regis, J. P. Allioud, J. B. Nicolet & M. Roulin* (Commissariat Energie Atomique, Saclay, and Société Bertin, Paris) were mostly concerned with self-sustained vibrations and noise occurring due to side branches. Flow visualizations in a water tunnel and hot-wire measurements in an air model gave evidence of either a pulsation of the stagnant regions at the branch entrance, or vortex shedding at the branch edge, depending on the branch-pipe configuration. As expected, resonance was then found to occur when this frequency coincided with the acoustic mode of the total system, pipe and branches. Segmented baffles placed at the entrance of the branches suppressed the feedback mechanism very efficiently. The second paper, by *L. Paulsen & K. O. Felsch* (Institut für Strömungslehre und Strömungsmachinen, Karlsruhe), dealt with the noise of control valves. Attention was paid to the aerodynamic-noise production by turbulent mixing, which was believed to be the next-dominant noise source after shock waves. Experiments were made within the connected pipe, and separation of sound and pseudosound was attempted by a space–time correlation technique with wall-mounted microphones. Difficulties were encountered due to the turbulent boundary layer along the wall, and large-scale pressure inhomogeneities. Results were, however, obtained for the pressure levels (which increased as the fourth power of the velocity in the slot) and for the spectra (which peaked at a Strouhal number of unity, based on the slot width and the velocity in the slot). For these problems, just briefly mentioned, a very useful reference is Reethof (1978).

11. Concluding remarks

This meeting had a large participation from abroad; 9 countries were represented and three-fifths of the contributions were from outside France. A general discussion took place at the end, and permitted, first, several participants to comment on the shift of interest away from the general studies on jets that have dominated the past decade. Current preoccupation indeed concerns propellers, prop fans, rotor- and stator-blade flows, so that in addition to the new developments based on the Lighthill acoustic analogy, there was great attention paid to the fundamental analysis techniques and to the physical mechanisms involved in noise generation. Some important topics for future research were then specified.

The role played by flow instabilities was pointed out in numerous cases for free flows (shear layers, clean and excited jets, flames) and for flow/surface interactions (cavities, acoustic linings, exhaust silencers). Prediction of the preferred frequencies of noise emission is then obtained relatively easily, but the corresponding power levels are still almost beyond reach.

In many circumstances, the Kutta condition is a crucial element in the theoretical estimates. Illustrations were given at the meeting for vortex-sheet development from the trailing edge of plates and from the upstream edge of cavities. This problem has an important application in airfoil noise for incident turbulent flows, and needs further work.

For medium-sized aircraft using propellers, a crucial topic is cabin noise: it has to be kept down, despite the highly unsteady loading of the panels close to the propeller. The modelling of these unusual pressure fields, on rigid or flexible walls, with intermittent and three-dimensional features, should also be developed in the future.

Concerning experimental techniques, the need to extract, in a reliable way, the acoustic signal within a uniform or even turbulent incident flow, was indicated. Accurate measurements of acoustic attenuation in ducts encounter this problem, and so do the detectors in the active sound systems. This topic is also of importance for marine applications, since most of the laboratory tests are made inside closed water tunnels.

Finally, concerning the propagation of acoustic waves in turbulence, very few contributions are available for well-defined laboratory conditions. Multipoint statistics would be worth obtaining in relation to the development of remote acoustic techniques for source localization or identification.

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Appendix. Papers presented at the meeting

Amiet, R. K. Leading and trailing edge noise of an airfoil.

Baxter, S. M. & Morfey, C. L. Modal power distribution in ducts at high frequencies.

Bechert, D. W. & Hussain, A. K. M. F. Acoustic control of a free shear layer: theory versus experiment.

Blanc-Benon, Ph. & Juvé, D. Corrélations spatiotemporelles pour une onde acoustique ayant traversé un jet turbulent.

Brocher, E. & Gondran, J. P. On the instability and acoustic emission of supersonic overexpanded jets.

Campos, L. M. B. C. On the propagation of sound in non-uniform, low Mach number nozzle flows.

Davies, P. O. A. L. Sound generation, propagation and radiation from flow ducts.

Delcambre, J., Parot, J. M. & Arbey, H. Pure tone noise generation by a system of open periodic cavities exposed to a flow.

Dowling, A. P. Sound production in a turbulent boundary layer over a flexible surface.

Ffowcs Williams, J. E. Sound generation by sources near the interface of different media.

Glegg, S. Sound radiation from flexible blades.

Grosche, F. R. & Stiewitt, H. Experiments on propeller noise.

Haertig, J., Meyer, R. & Schlosser, F. Contribution à l'étude des structures cohérentes d'un jet rond excité.

Hall, S. L. (1) Acoustic emission from free jets.

Hall, S. L. (2) Characteristics of gaseous flames using oxygen instead of air.

Höhler, G. Interaction of the acoustical boundary layer with turbulent flow.

Howe, M. S. The aeroacoustics of unsteady shearing flows over cavities and slots.

Janicka, J. & Lumley, J. L. Computation of density fluctuations in diffusion flames (with implications for combustion noise).

Jungowski, W. M. & Meier, G. E. A. Discrete frequency noise generation by a quasi two-dimensional air jet impinging on various obstacles.

Juvé, D. & Esparcieux, Ph. Mesure du flux d'énergie acoustique dans le champ proche d'un jet subsonique.

Kompenhans, J. & Grosche, F. R. Noise radiation of multiple jets.

Leducq, D. Comportement d'un résonateur d'Helmholtz à parois déformables en présence d'écoulement hydrodynamique en tunnel.

Levine, H. A far field estimate for source integrals.

Michalke, A. Some remarks on source coherence affecting jet noise.

Michel, U. & Michalke, A. Prediction of flyover jet noise spectra from static tests.

Parant, J. L. Bruit aérodynamique des avions en approche.

Paulsen, L. & Felsch, K. O. Experimental investigation of aerodynamic noise production of valves by measurements within the connected pipe.

Rebuffet, P. & Guedel, A. Définition du convergent et de la reprise de la soufflerie anéchoïque CEPRA 19 à partir d'essais sur une maquette au 8/100.

Regis, G., Allioud, J. P., Nicolet, J. B. & Roulin, M. Excitation aérodynamique et aéroacoustique dans les réseaux de tuyauteries avec piquages angulaires.

Roebuck, I. Mutual impedance effects in active noise control and the possibility of 'extracting energy' from turbulence.

Ross, C. F. An adaptive digital filter for broadband active sound control.

Roure, A. & Sunyach, M. Absorption acoustique active dans les conduits avec écoulement turbulent.

Rybak, B. Turbulence phonatoire externe (ciné film).

Sarin, S. L. On the internal mixer and its application in controlling the in-flight jet noise.

Saulpic, C. & Ville, J. M. Mesure d'impédance acoustique en fonction de l'angle d'incidence et en présence d'écoulement.

Schaffar, M. Etude des sources de bruit équivalentes dans les jets froids au moyen de la méthode de causalité.

Schuller, W. M. & Louwers, M. Réduction du bruit de systèmes de refroidissement de machines à souffler le verre.

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