J. Fluid Mech. (1977), *vol.* 83, *part* 2, *pp.* 396–400
Printed in Great Britain

REVIEW

Aeroacoustics. By MARVIN E. GOLDSTEIN. McGraw-Hill, 1976. 293 pp. £16.45.

Aerodynamic sound, as a scientific discipline, is now twenty-five years old. Activity in the subject has grown rapidly in the last ten years, involving large numbers of workers throughout Europe, the United States and Canada. It is a subject which makes use of ideas from an exceptionally wide range of longer-established fields, such as linear and nonlinear bulk and surface wave propagation, unsteady aerodynamics, fluid mechanics of turbomachinery, classical scattering and diffraction theory, wave propagation in inhomogeneous and random media, hydrodynamic stability and shear-flow turbulence in the aeronautical context. In addition the worker in underwater flow noise needs ideas from the theories of elastic structure response under fluid loading, and of cavitation and bubble dynamics. On the experimental side a correspondingly wide range of techniques has been deployed to examine the acoustics and aerodynamics of configurations varying from the full-scale wide-bodied airliner in flight in the real atmosphere to model jet nozzles, of 1 in. diameter or even less, in a carefully controlled laboratory environment.

Such a subject cries out for textbooks and monographs at all levels and from many points of view. Until now there has been no book at any level, though there have been a number of good review articles (among them those by M. J. Lighthill, *Proc. Roy. Soc.* vol. A 267, 1962, p. 147; *A.I.A.A. J.* vol. 1, 1963, p. 1507; H. S. Ribner, *Adv. in Appl. Mech.* vol. 8, 1969, p. 104; J. E. Ffowcs Williams, *Ann. Rev. Fluid Mech.* vol. 1, 1969, p. 197) which must have formed the basis for innumerable graduate courses. The most pressing need is for a textbook aimed at postgraduate students and beginners in the subject, a need which I think could have been met with any lasting success only at the present time (the 'sixties in particular were such a time for paradoxes and misunderstandings in the basics of noise theory that one can only be relieved that no book succeeded in emerging at that time). It is this need which I feel the book under review meets, and despite the reservations set out below I welcome Dr Goldstein's book as, above all, a work to recommend enthusiastically to students and newcomers to aeroacoustics.

In its earlier form, as *N.A.S.A. Special Publication* no. 364 (1974), the book has already been tested in the classroom. It makes no attempt at exhaustive coverage of flow-noise phenomena, even within the aeronautical context, and one can easily argue that some material excluded is at least as important as, and no more speculative than, some of that presented. In that respect the book is somewhat uneven, as it also is in respect of the degree of mathematical sophistication assumed. On the other hand, the material is presented with generally admirable style and lucidity and with a reasonably felicitous choice of notation (a matter to which insufficient attention is often devoted in papers on aeroacoustics). The subject is treated from the point of view of the applied mathematician. Though I should like to be proved wrong on this, I doubt that it will get the reception it deserves from the engineering community in this country – and which it clearly will receive in the U.S.A.

Chapter 1 gives a review of the linear acoustics of moving media. It deals with some familiar matters (plane waves, source convection and Doppler shifts, transmission across a thin shear layer, the pulsating sphere, Kirchhoff's theorem, multipole expansions) and also with less elementary topics such as the inhomogeneous equation for perturbations to a parallel shear flow, whose homogeneous Rayleigh-equation form governs the stability characteristics of the flow, and energy flux and energy density relations. This review is useful though extremely variable. I felt that a formal perturbation approach to the acoustic problem was unnecessarily elaborate here, bearing in mind that only the first approximation was sought and that only one length and one time scale were involved. In later chapters, where a formal scheme might make the validity of some approximation transparently obvious, no such scheme is attempted. A minor irritation throughout the book is the introduction of a 'very large, but finite' time T, and corresponding integrals over $[-T, +T]$; generalized functions are used in Green's function manipulations consistently in the book, and they should also have been used here in dealing with stationary random processes, avoiding the use of the large time T in favour of relations like

$$\langle f_1(\omega) f_2^*(\omega')\rangle = S_{12}(\omega)\,\delta(\omega-\omega')$$

between the Fourier coefficients of stationary processes and their cross-power spectral density. On the other hand, the consistent use of $(\mathbf{y}, \tau)$ for source variables and $(\mathbf{x}, t)$ for observer co-ordinates justifies itself in the end, despite having some unnatural aspects, and typifies the author's care for clarity of exposition. As another minor criticism it is nonsense to suggest (in one of the three appendices to chapter 1) that the method of images has any generality; transform methods of one kind or another are really the only general methods we have for finding Green's functions. I should in any case have preferred it if these appendices had been replaced by one in which the formal properties of convolution products under differential operators were set out in general; this would make redundant the tiresome manipulations of retarded time integrals which figure so prominently in aerodynamic sound work.

In the second chapter Dr Goldstein gives a careful, conventional exposition of Lighthill's theory of aerodynamic sound from a boundary-free turbulent region. Eddy convection effects are emphasized, though fluid shielding and refraction effects are at this stage omitted. On this basis only a limited range of predictions bears direct comparison with experiment; the author makes these comparisons, where possible, for subsonic clean exit flow model jets. No attempt is made to draw more than rather general qualitative conclusions from the theory in respect of flows with supersonic eddy convection velocities. The chapter ends with brief discussions of a number of less well understood features of jet noise: imperfectly expanded jets, location of acoustic sources, edge tones and orderly jet structure. I have to call attention to the altogether too sketchy treatment of the latter, beginning as it does with a plate (figure 2.27) taken from the article by Crow & Champagne (this journal, vol. 48, 1971, p. 547) and showing 'roll-up of a low Reynolds number jet' with a statement in the text to the effect that such behaviour is found only for $160 < Re_D < 1200$. In fact the minimum value of Re_D used by Crow & Champagne was $1{\cdot}05 \times 10^4$, and the persistence of the orderly structure to much higher Re_D was clearly postulated by Crow & Champagne and observed by Crow (*APS Meeting, Univ. Colorado*, 1972, paper IE6). Admittedly, the acoustic significance of the orderly structure has only recently begun to be appreciated (cf. Crow *op. cit.* 1972; D. Bechert & E. Pfizenmaier, *J. Sound Vib.* vol. 43, 1975, p. 581; and most recently the paper in this journal, vol. 80, 1977, p. 321, by

C. J. Moore), but one might have expected a more discriminating appraisal from Dr Goldstein. I also find the very brief remarks (one paragraph of p. 110) on the relevance of the theory of pure jet mixing noise to real aircraft engines quite inadequate; it is, indeed, arguable that an understanding of subsonic mixing noise, as it is found in clean static unheated model jet rigs, is utterly irrelevant to the problem of the noise of a full-scale engine on an aircraft in flight.

Chapter 3 gives an admirably thorough and wide-ranging treatment of the effects of solid boundaries in flow noise. It starts with an efficient derivation of the Ffowcs Williams–Hawkings extensions of Kirchhoff's theorem to include arbitrary convection of volume and surface source distributions; Curle's theory, which is still widely believed to have a universal applicability which it does not, is given as a particular case of this general formulation. In order to implement any of these formal results in an unambiguous way it is necessary to calculate, among other things, the pointwise distribution of unsteady aerodynamic loading over the surface of a rotor, for example, and the author therefore includes a description of the formulation, though not the method of solution, of the well-known Sears problem for airfoil response to a harmonic gust. The Sears function is then used to predict the sound from a thin, chordwise-compact airfoil in a turbulent flow. This section will no doubt appeal to many because it is not content with mere dimensional analysis, but pushes the calculation through to a formula which is favourably compared – in absolute level, not just in parametric variation – with measurements. Actually, however, this comparison does not test the variation of the sound with (airfoil chord)/(eddy size), which the formula gives in an awkward function arising from a specific correlation coefficient form. Thus all that is actually tested is the $U^6 \sin^2\theta$ dipole variation of Curle's theory together with a coefficient which can be estimated with acceptable accuracy, for the circumstances of the experiment cited, without going through the Sears problem and with no need to postulate any specific turbulence correlation function.

Aeolian tones are also discussed in similar numerical detail, much of which I believe is illusory, though I do not underrate the future importance of unsteady aerodynamics calculations in aeroacoustics and think Dr Goldstein is right to try to integrate them with the acoustic side wherever possible.

In the remainder of this long chapter 3 there are good discussions of discrete tone rotor noise (in which, however, I was not convinced of the case for retaining only the blade force dipole and omitting the thickness monopole and the flow quadrupole) and of broadband rotor noise, and a section in which the exact Green's function for the infinite plane and semi-infinite plane are used to derive the U^8 reflexion principle (A. Powell, *J. Acoust. Soc. Am.* vol. 32, 1960, p. 982) for the former and the U^5 edge-scattering law (J. E. Ffowcs Williams & L. H. Hall, this journal, vol. 40, 1970, p. 657) for the latter. Any final remnants of controversy on either of these situations must be dispelled by the decisive experimental evidence quoted.

Generation of duct modes in the presence of uniform mean flow by fans and compressors is treated in chapter 4. The analysis is tedious, but the discussion is enlivened by the sections on rotor–stator interaction, the effect of inlet flow distortion, 'buzz-saw', and the effect of finite duct length. The latter section is actually confined to propagation of rotor noise out of the engine inlet, with the same uniform flow inside the duct and outside it; transmission across the nozzle exit, with differential flow inside and outside the duct, is a much more difficult problem whose solution will shortly appear in a paper by R. M. Munt in this journal. The discussion throughout chapter 4 keeps the rotor noise features of real engines firmly in mind, in the way I hoped for, but did not find, in the treatment of jet exhaust noise.

Chapter 5 has the title 'Theories based on solution of linearised vorticity–acoustic field equations'. What the chapter actually does, out of all the things that might be subsumed under this title, is to work out the interaction field, including the propagated acoustic modes, arising from the incidence of a vorticity wave on a linear blade cascade between parallel plates. The mean flow is completely subsonic, but all the analytical intricacies of complex transform theory for this kind of geometry are encountered. The solution is obtained from the numerical inversion of an integral equation with a single degree of freedom to enable a trailing-edge Kutta condition to be met. Mutual interference effects between blades are found to be critical in leading to a finite radiated power near the cut-off condition, a case that would be difficult to deal with by the acoustic-analogy formalism used in the preceding chapters. Apart from this feature I doubted whether this topic should have been given such prominence, as it is rather specialized for beginners and cannot, on the other hand, be expected to lead to much more work on the same lines (in fact the only significant extension seems to be the mixed supersonic–subsonic problem, with shocks in the passages between the cascade blades, to be published shortly by Dr Goldstein, W. H. Braun & J. J. Adamczyk in this journal, vol. 83, 1977, p. 569).

Finally we come to the all-important issue of mean-flow shielding and refraction effects upon jet mixing noise sources. The author first derives Phillips' inhomogeneous convected wave equation and then eliminates the linear part of the forcing term to give the third-order equation now known as the Lilley equation. In an interesting section he then shows how the Lilley equation can be transformed back into an equation of Phillips' form, but with the most important linear propagation terms now eliminated from the source term. This does not altogether reinstate the Phillips' form, however, for the forcing function now involves the vector potential, which is not locally determined and perhaps not susceptible to unambiguous estimation. Asymptotic expressions for the Lilley and Phillips Green's functions are next derived by WKB-type methods for high frequencies and matched expansions for low. Surprisingly, the Lilley Green's function is equal to that for the Phillips operator multiplied by one inverse power of the Doppler factor $1-M(r_0)\cos\theta$ at high frequencies and by two inverse powers at low frequencies, $M(r_0)$ being the mean-flow Mach number at the source point r_0. Further, the Phillips Green's function is equal to the free-space Green's function in the low frequency limit, whereas the Lilley formulation predicts, astonishingly, that mean-flow shrouding effects persist, through the $(1-M(r_0)\cos\theta)^{-2}$ factor, even in the fully compact limit. This is not brought out too clearly here, though there is no doubt as to the correctness of the result, which has now also been obtained by Dr Goldstein in collaboration with J. E. Ffowcs Williams & A. Dowling from the Lighthill analogy (this journal, to appear). I also did not feel that fluid shielding or shrouding (i.e. the inhibition of the Lighthill-type of convective amplification, a source effect) was sufficiently well differentiated from refraction (a propagation effect leaving the total power unchanged). Otherwise this is a thoroughly up-to-date account in which it is legitimately claimed that much of the important role of flow–acoustic interaction is indeed well described by the Lilley approach. One could hardly expect Dr Goldstein to do any better than he does – or anyone else does, for that matter – on the issue of the possible instabilities associated with the Lilley operator for free shear layers. Are they just a mathematical nuisance to be dismissed as irrelevant, are they the source of much of the excess noise found in aeroengines, or are they in fact the very essence of the natural mixing process itself? Of the three possibilities, Dr Goldstein appears to favour the first, though there is mounting evidence that in almost all practical (i.e. non-laboratory) situations the second and even the third may be nearer the truth (cf. S. C. Crow; D. Bechert & E. Pfizenmaier; C. J. Moore *loc. cit.*).

In summary I have two main criticisms, to some extent related, of this book. First, even in the aeronautical context, it concentrates too much on a highly idealized model situation whose relevance to the real aircraft noise problem is no longer altogether clear. The real problem in any case exposes the need for a study of all sorts of interesting basic mechanisms in aeroacoustics, and these are hardly mentioned here. Second, I was sorry that the book did not embrace wider aspects of flow noise. Underwater flow noise in particular is a field which is useful to aeronautics in both a didactic sense, offering really low values of reduced frequency and Mach number at which the consequences of failure to appreciate the principles of multipole structure, for example, can lead to vast errors, and also because it highlights a great variety of new source mechanisms, some of which most certainly have direct relevance to aeronautical noise (cf. O. J. Whitfield & M. S. Howe, this journal, vol. 75, 1976, p. 553). Having said that, I must say that this is an important book which I read with pleasure, from which I learned a great deal, and which, on behalf of the acoustics and aeronautical communities, I welcome very warmly indeed.

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