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Book Review

Review of “Aeroacoustics of low Mach number flows: Fundamentals, Analysis and Measurement”, Stewart Glegg, William Devenport. Academic Press, London (2017).

Aeroacoustics, as a scientific discipline, is at the interface between acoustics and fluid mechanics. It borrows concepts from psycho-acoustics like SPL and EPNL, while the logarithmic sensitivity of our ears yields the remarkable properties that low levels in a quiet environment can be just as important as high levels in a noisy environment, and that orders of magnitude estimates are often enough to assess a noise source. Via acoustics, it borrows methods from electromagnetic wave theory. For the foundation of the models, however, we have to consider aeroacoustics as a branch of fluid mechanics. Subtle coupling between acoustics, vorticity and entropy, leading to a disturbing lack of energy conservation (at least, at the level of the acoustic perturbations), noise produced by seemingly silent turbulence, and a number of other phenomena can only be understood from the fluid mechanical basis. Necessarily, the range of problems is broad and require relatively sophisticated mathematics. For all these reasons books on aeroacoustics are rare, even if we take into account its relatively recent appearance.

We therefore welcome the present book on aeroacoustics of low Mach number flows (for the practical applications hardly a restriction). This book contains a comprehensive overview of the most important tools that have been developed in the field of aeroacoustics since it became a separate discipline in the 1950's. It starts with a survey of the theoretical fundamentals, like Lighthill's and related analogies. It continues with an overview of the most important types of facilities, hardware and processing techniques for performing measurements. In the final part, the theory is further detailed and applied to important aeroacoustic topics like blade noise and fan noise. Some applications clearly illustrate the complexity of the analysis that one needs in order to describe and understand the source mechanisms. It is the first time that such a comprehensive overview has been published.

The book has a clear structure in four parts: Part 1 on fundamentals, Part 2 on experimental approaches, Part 3 on edge and boundary layer noise, and Part 4 on rotating blades and duct acoustics. This distinction is probably motivated by the authors' backgrounds and expertise. Edges are important in many ways, but another author could have chosen a Part 3 on jet noise, musical instruments, instabilities, or maybe atmospheric effects. In total, the book consists of 18 chapters and 3 appendices spanning 537 pages. Each chapter consists of a number of sections (typically between 4 and 10) plus references.

It was a very good idea to create a website, https://aeroacoustics.net/, which includes a dynamically updated list of corrections on typo's and other errors, sample course outlines, sample Matlab codes, a problem set (including worked example solutions), experimental data, and more. A book is never really finished, never really error free, and via this supplementary website both readers and authors benefit from the corrections, new developments and new material for courses.

Part 1 has 9 chapters: 1 Introduction; 2 The equations of fluid motion; 3 Linear acoustics; 4 Lighthill's acoustic analogy; 5 The Ffowcs Williams and Hawkings equation; 6 The linearized Euler equations; 7 Vortex sound; 8 Turbulence and stochastic processes; 9 Turbulent flows. The treatment is detailed (we like the careful working out of Goldstein's equation) and look familiar, although some original and useful excursions are made, like the dynamics of vorticity (of course!), conformal mapping (for compact sources), rapid distortion theory, and other. In section 2.6 on sound power, we suggest it could have been made more explicit that acoustic energy in mean flow is conserved only in irrotational and homentropic flow, perhaps referring to Myers' [10] acoustic energy equation with its right-hand side of vortical and entropy sources. This was one of the great issues in the 60's and 70's before it was made clear by Bechert's [8] experiments and Howe's [9] explanation that sound may be absorbed or produced by vortical flow. Section 5.3 on moving sources is about a source moving uniformly along a straight line. The general solution given by the Liénard-Wiechert potential [1] is not given, but would have been useful for propellers and the like.

Part 2 has 3 chapters: 10 Aeroacoustic testing and instrumentation; 11 Measurement, signal processing, and uncertainty; 12 Phased arrays. These chapters are devoted to aeroacoustic measurements, with emphasis on measurements in wind tunnels. In chapter 10, the pros and cons of different wind tunnel set-ups (open jets, closed test sections) are highlighted. Emphasized are the benefits of the hybrid wind tunnel, featuring a closed test section in which one or more solid walls are replaced by Kevlar screens, backed by an anechoic room. Chapter 10 continues with a detailed description of the open jet

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wind tunnel corrections for level and radiation angle, needed to correctly interpret measurements with microphones outside the jet. A short section follows considering the additional attenuation due to a Kevlar screen, although without addressing the dependency on radiation angle. Further, an overview of microphone types is given, the significance of their support is discussed, and some other wind tunnel measurement techniques (hot-wire, PIV) are reviewed.

In the discussion about wind tunnels, there is no mention of the haystacking (or spectral broadening) phenomenon, which occurs in open jet wind tunnels. While propagating through the turbulence in the shear layer, initially tonal sound changes into broadband noise featuring a spectral hump around the initial tone. This severely impedes, for example, open rotor measurements, where identification of tones is paramount. Here, the authors could have highlighted another advantage of the hybrid wind tunnel, that is, the open jet shear layer is effectively replaced by a boundary layer on the Kevlar screen, which is much thinner and carries less turbulence. Furthermore, in section 16.5 the word "haystacking" is used in a completely different context. Here it is used for the creation of spectral humps around the blade-passing frequency and higher harmonics of a rotor, when it interacts with turbulent eddies that have length scales larger than the interval between the blades.

Chapter 11 gives a useful summary of the signal processing essentials that are needed to understand spectral data. The following topics are addressed: bit range in A/D conversion, sampling and aliasing, uncertainty, averaging and convergence, discrete Fourier transform (DFT) and windowing, averaging over DFT records and obtaining wave number spectra. As usual in signal processing text books, a heuristic approach is followed to discuss DFT features like the convolution theorem and the Poisson summation formula for Dirac-delta comb functions.

In chapter 12, a brief summary of phased array beamforming is given. It is explained how acoustic images (source maps) are obtained through Delay-and-Sum beamforming. Important effects of array shading, array design and incoherence of broadband noise sources are well explained. The concept of deconvolution (correction for point spread functions) is explained, including the well-known DAMAS algorithm. Also, the idea of source integration (obtaining absolute levels radiating from non-compact source regions) is introduced. Not much is said about the effects of removing the diagonal of the cross-spectral matrix, except that it should be avoided.

Part 3 has 3 chapters: 13 The theory of edge scattering; 14 Leading edge noise; 15 Trailing edge and roughness noise. Of these are 14 and 15 about the interaction between moving gusts and blades and turbulent boundary layers along a trailing edge and rough surfaces. The approach follows the usual Lighthill-type of argument for turbulent sources, but with the complication of close proximity to the scattering edge geometry. Chapter 13 considers the canonical problem[1] of sound waves scattering at the edge of a semi-infinite plane, and is apparently preparatory to the other chapters. This problem with mean flow involves vortex shedding from the trailing edge and has therefore a role for the (unsteady) Kutta condition. The approach presented in chapter 13 is by means of the Wiener-Hopf technique.[2] An alternative approach [2–4] would be to Prandtl-Glauert transform the no-flow solution into a solution with mean flow. This can be done directly for the pressure, in which case we obtain the Kutta condition solution (good for a trailing edge), or for the potential (and derive the pressure afterwards), in which case we obtain the singular, no-Kutta condition solution (good for a leading edge). Their difference is the eigensolution of shed vorticity.

Part 4 has 3 chapters: 16 Open rotor noise; 17 Duct acoustics; 18 Fan noise. Open rotor noise is an important and classic [5] area of aeroacoustics. It is the flow around the rotor blade that causes the noise. In fact, it is one of the most successful and celebrated applications of the Ffowcs Williams and Hawkings equation, which is rightfully taken as the backbone of the survey in chapter 16, both in time and in frequency domain. Also duct acoustics is important - in aeronautical applications in the context of turbofan aircraft engines — although in its simplest form (straight duct with uniform mean flow) it borrows much from classical acoustics. From non-classical duct acoustics a non-uniform mean flow with (assumed) irrotational perturbations is considered (section 17.6), but not the effects of mean flow on the lining (Brambley's ill-posedness of the Ingard and Myers' boundary condition in the time domain), nor hydrodynamical instabilities or vortex shedding from a duct exit (Munt's problem [11]). It is true (section 17.3) that some insight can be obtained from the behaviour of soft-wall acoustic modes by approximate solutions, but this is not the case for surface waves-type modes. The modal energy given in 17.5 states correctly that modal energy is uncoupled so that a noise control problem can be treated mode by mode, but the conclusion that only cut-on modes carry energy is not exactly true. This is only the case for a unidirectional mode field. Left and right running cut-off modes may couple, leading to (for example) energy transfer through a duct section with only cut-off modes (also known as tunnelling). In 17.4 the Green's function in a cylindrical hard-walled duct with uniform mean flow is derived by the classical method of eigenfunction expansion for Sturm-Liouville problems. This is very useful, but since the construction is based on the orthogonality of the eigenfunctions, it is for hard walled ducts only. Application of Fourier transformation in the axial coordinate yields the same result for hard walls, but would allow lined walls, and seems therefore more versatile. Highly relevant for aircraft engines is chapter 18 on fan noise. Indeed, whereas in the pre-high-bypass era the jet dominated the radiated noise, it is now the fan with interaction tones, buzz saw noise, distortion tones, multiple pure tones, etc. Thickness and loading noise (again the ubiquitous Ffowcs Williams and Hawkings!), rotor-stator interaction noise (Tyler and Sofrin [12], unmentioned however), the effects of cascades, gusts, wakes in swirling flow, broadband (turbulence) noise and more are all briefly introduced in a well-illustrated way.

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[1] Here called "Schwarzschild problem", after Karl Schwarzschild [6]. It is a generalization of "Sommerfeld's problem" for plane waves [7].

[2] Not "Weiner Hopf".

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Three appendices finish the book. Appendix A is on nomenclature and some notation conventions, which is always useful, and *vital* in case one co-operates in (transnational and transdisciplinary) projects. Appendix B is on branch cuts of complex square roots (or better: the logarithm of complex functions). We greatly appreciate the attention paid to this subtle issue, but it is a pity that it is necessary in the first place. Apparently, too many courses on complex functions for technical students have been diluted such that a function as important as the square root has been trivialized to an extent that it is no longer useful. One remark on this section: all examples of branch cuts considered are straight lines, but this is not necessary. For example, the important square root $(1\text{-}z^2)^{½}$ with sign-fixed imaginary part has two L-shaped branch cuts. Finally, in appendix C some technical details for section 18.3 are given.

In conclusion, this is a broad and varied book with an enormous amount of information. It is useful for both the starting student in the form of a course, and for the aeroacoustic expert in the form of self-study. The supplementary website will undoubtedly be very useful.

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