Acoustics of Fluid–Structure Interactions

M. S. Howe, Cambridge University Press, Cambridge, England, United Kingdom, 1998, 560 pp., $85.00

The subject of acoustics of fluid–structure interactions is a very complex one. Perhaps this complexity, together with the importance of the subject in many different areas of acoustics, fluid mechanics, and aero/hydroacoustics, accounts for the many alternative formulations and interpretations of the solutions and experiments found in the literature. Making sense of these various treatments and results can be perplexing. This book provides a very important contribution to this field by presenting the equations and solutions for an extremely broad range of fluid–structure interaction problems, all carefully derived from first principles. Clarity and rigor are the trademarks of each section. The book follows in the strong analytical tradition of the other 16 monographs in the Cambridge Monographs on Mechanics Series: monographs authored by such notables as Lighthill, Saffman, Lumley, and Holmes. (The series is edited by Batchelor, Freund, Leibovich, and Tvergaard.) Rigor and detail would surely be greater in this book had there not been a page limit set by the general editors.

Howe, who is an applied mathematician and theorist, does a marvelous job of setting real-world problems in a mathematical framework while, in most cases, offering concise physical interpretations and insights based on the derived solutions. He does this in a way that allows, in many examples, the incorporation of the mean properties of fluid–structure interactions determined from numerical codes such as Reynolds-averaged Navier–Stokes codes. The result is that detailed aero- and hydrodynamic calculations for complicated structures can be coupled with the analytical solutions of the wave and/or structural vibration equations presented here to arrive at reasonable, and usually quite accurate, predictions of both time- and frequency-dependent sound radiation and/or surface vibration properties. It should be noted that Howe sets the stage for true fluid–flexible structure interaction in the first half of the book by analyzing the radiation and scattering of aerodynamic sources by rigid bodies of varying geometrical complexity. The effect of flow-induced structural vibration on the radiation and absorption of sound is then treated rigorously in the second half of the book.

The first chapter, the introduction, covers the fundamental equations governing Newtonian fluid mechanics and the structural dynamics of elastic solids, with emphasis on vibrating membranes, plates, and shells. The author covers quite thoroughly the Green's function method of solution of the inhomogeneous wave equation, which is the primary method of solution used throughout the book. His treatment of the compact Green's function, which permits calculation of the leading monopole and dipole terms of the sound produced by low-Mach-number hydroacoustic sources near solid bodies, is particularly clear. He shows that this function can be computed from elementary potential theory. If the Laplace equation can be solved (either analytically or numerically) for the steady, incompressible, uniform flow of unit velocity in the i direction about the particular rigid body of interest, then the i component of the vector Green's function can be specified using the formulations given. The chapter concludes with a detailed discussion of the vorticity formulation for aeroacoustic sources, which is particularly useful in the prediction of many kinds of fluid–structure interaction problems. These include direct sound radiation from vortex shedding and problems requiring calculation of vortex-induced unsteady forces. A concise method is presented for calculating the time-dependent circulation of vortices shed from a rigid half-plane.

Chapter 2 covers the fundamental equations of the acoustic analogy method of aeroacoustic analyses. In particular, the author mathematically develops the Lighthill and Ffowcs Williams–Hawkings equations. The former equation is well known, of course, but Howe emphasizes that the expected quadrupole sources in free-space turbulence can be augmented by additional dipole and monopole "hot-spot" sources when density variations are included. This theory has application to hot jets and emphasizes the role of entropy inhomogeneities in sound production. The latter equation is particularly important in the aeroacoustics associated with non-stationary-flow noise sources on and near solid structures in motion, such as a rotating lifting surface attached to a craft in forward flight. The equation and its solution are valid for either flexible or rigid structures and with or without fluid aspiration. Its solutions form a major part of Chapter 3.

After convincing arguments that it is primarily vorticity and entropy fluctuations that are the dominant sources of flow noise at low Mach numbers, Howe develops an acoustic analogy based on fluctuations of the total enthalpy. He goes on to apply the theory to a variety of practical problems, including the radiation from spinning vortices, laser-excited heat sources, and two-phase flow. Damping, absorption, and scattering of sound by turbulence are analyzed, and the chapter concludes with the mechanisms of mixing, screech, and forward-flight-affected jet noise. The latter topic is based more on experimental findings in the literature than on rigorous analysis.

Chapter 3 sets the stage for many practical fluid–surface interaction problems by developing the state-of-the-art methods of noise generation by moving rigid surfaces. These are particular areas in which Howe made major contributions over the years. He demonstrates the ways in which the compact Green's function can be used to compute the radiation from turbulence moving through nozzles and over semi-infinite planar edges and wedges. The interaction of freestream turbulence and vorticity with leading edges, which has application in turbulence ingestion rotor noise and in blade–vortex interaction noise, is also addressed. The chapter continues with well-explained noise theories for turbulent boundary layers over smooth and rough surfaces and for trailing edges of practical shape. Again, recognizing that, if a solution to Laplace's equation exists for the flow over a particular shaped trailing edge, then the sound due to a turbulent boundary layer passing over this edge can be readily computed. He demonstrates this for rounded edges, blunt edges, serrated edges, and porous edges. The chapter concludes with analytical examples of noise generated by sources moving at very high speed. They include rotor blades that support local shocks or have cross-sectional profiles that result in thickness noise. The time-dependent pressure pulse created in a tunnel due to the entering of a high-speed train is also discussed. The analysis is detailed enough to show the effect of tunnel portal shape on the magnitude of the induced pressure pulse. In general, these first three chapters do a good job of preparing the reader to take on the topics suggested by the book's title.

Chapter 4 starts with the analysis of sound sources in the near vicinity of an elastic plate. This is the first description of a fluid–flexible structure interaction. The presentation includes the excitation of a plate by the evanescent (subsonic) pressure components of, e.g., a grazing turbulent flow. Also included are the effects of coating the plate with a compliant material of local reactance. Structural energy flow within the plate is considered, and the effects of structural discontinuities on the scattering of this internal, as well as the external, acoustic energy are detailed with rigor. Howe solves the flexible-trailing-edge-noise problem in the concluding sections of this chapter.

Chapter 5 provides the analysis of fluid–structure interactions in which the compliance of the surface contributes to the damping of the radiated noise. This is followed by a relatively thorough discussion of attenuation of sound by vorticity production at edges and by interactions with perforated screens. Initially, flows normal to the screens are considered and then grazing flows, as might be encountered with acoustic liners installed for the purpose of sound attenuation in a duct. Discussion of jetting flow in rigid and elastic tube banks, along with the various kinds of nonlinear interactions that occur, e.g., in ducts with acoustic streaming or within the vena contracta that occurs in normal flow through an aperture, concludes this chapter.

Chapter 6 covers the analysis of several resonant and unstable systems, including cavity resonance and edge tones. Elasticity of the flow boundaries is not considered in this section. Flow-excited shallow and deep cavities, situated in walls or pipes (side branches), are treated in much detail. Explicit expressions are derived for the frequencies of instability, the vorticity fluctuations, the radiated sound, or the absorption of sound. The theory of edge tones is given equal treatment in this chapter. Howe uses a vortex model of the jet and then derives the interactions of these vortices with the edge geometry of interest. Applications include devices such as the hole whistle, flue organ pipe, and flute. The topics that round out this final chapter of the book, flame and combustion instabilities and thermoacoustic engines and heat pumps, are interesting but not closely related to the title of the book. The reference section of the book is very complete, having 486 entries.

A few general comments are in order about this book. The first two objectives as stated by the author in the preface are accomplished: 1) a reference for analytical aeroacoustic methods and 2) a repository for known results and methods. It remains to be seen how well the book serves as a graduate-level textbook (the author's third objective). Howe is such an excellent mathematician that he moves quite quickly through the developments. We suspect that only the most accomplished graduate students (and instructors!) will be able to follow the mathematics of this material. The readers should not expect much in the way of "tutorials" or simple examples to elucidate the discussion. In many of the examples presented, the details are left to the reader. However, when used in conjunction with other more elementary works, this book will provide a complete offering to any graduate course on flow–structure interactions.

If a revision of the book were to be issued, we would recommend that the sections on thermoacoustics and combustion noise be dropped in favor of more complete derivations in the examples. A brief introductory section on the mathematical techniques used might also be of value to readers who are less mathematically inclined. The author should also include a more thorough physical interpretation of the multipole sources that occur in aeroacoustics analyses and analogies. These are taken for granted, or perhaps treated superficially, by the experienced aeroacoustician, but the concept of turbulence creating a quadrupole, e.g., is generally difficult to comprehend or to visualize for the first-time reader.

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