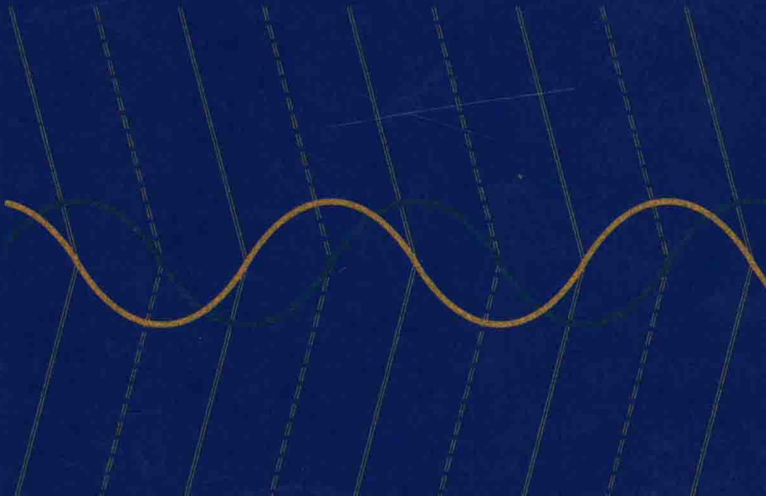
SECOND EDITION

SOUND AND STRUCTURAL VIBRATION

Radiation, Transmission and Response



FRANK FAHY • PAOLO GARDONIO

Sound and Structural Vibration

Radiation, Transmission and Response

FRANK FAHY
Institute of Sound and Vibration Research
University of Southampton
Southampton, UK

PAOLO GARDONIO
Institute of Sound and Vibration Research
University of Southampton
Southampton, UK

ELSEVIER

AMSTERDAM BOSTON HEIDELBERG LONDON NEW YORK OXFORD
PARIS SAN DIEGO SAN FRANCISCO SINGAPORE SYDNEY TOKYO

Academic Press in an imprint of Elsevier

Academic Press is an imprint of Elsevier
Linacre House, Jordan Hill, Oxford OX2 8DP, UK
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, UK
30 Corporate Drive, Suite 400, Burlington, MA 01803, USA

First edition 1987
Second edition 2007

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress

For information on all Academic Press publications
visit our web site at books.elsevier.com

ISBN 13: 978-0-12-373633-8

Transferred to Digital Printing in 2008

Sound and Structural Vibration

Radiation, Transmission and Response

In thanksgiving for the love and support given to us by our parents, Amalia, Meg, Riccardo and Frank.

Preface to the First Edition

In writing this book my aim has been to present a unified qualitative and quantitative account of the physical mechanisms and characteristics of linear interaction between audio-frequency vibrational motion in compressible fluids and structures with which they are in contact. The primary purpose is to instruct the reader in theoretical approaches to the modelling and analysis of interactions, whilst simultaneously providing physical explanations of their dependence upon the parameters of the coupled systems. It is primarily to the engineering student that the book is addressed, in the firm belief that a good engineer remains a student throughout his professional life. A preoccupation with the relevance and validity of theoretical analyses in relation to practical problems is a hallmark of the engineer. For this reason there is a strong emphasis on the relationship of results obtained from theoretical analysis of idealised models and the behaviour of the less than ideal realities from which they are abstracted.

The teacher of analysis in any sphere of applied science is faced with a central dilemma: systems which can be modelled and analysed in a manner sufficiently explicit and direct to illustrate a principle are usually gross oversimplifications of the real world and are hence, to some extent, trivial; systems which are of practical concern are usually much too complex to offer suitable examples for didactic purposes. In attempting to grasp this nettle I hope I may be forgiven by any physicists and applied mathematicians who may pick up this book for sacrificing a certain amount of mathematical rigour for the sake of qualitative clarity.

In teaching mechanical engineering and engineering acoustics over a number of years it has struck me forcibly that an appreciation of structural vibration as a form of wave motion, a concept readily grasped by the student of physics, is often lacking in those reared on a diet of lumped elements and normal modes. One unfortunate effect is that the associated wave phenomena such as interference, scattering and diffraction are often believed to be the preserve of water and air, and the link between natural modes and frequencies of structures, and the component waves intrinsic to these phenomena, is not readily perceived. The subject of this book appeared to be the ideal vehicle for persuading students of the advantage to be gained by taking a dual view of vibrational motion in distributed elastic systems. Hence I have emphasised the wave 'viewpoint' right from the start, in the hope of encouraging the reader to 'think waves'.

The three main categories of practical problems to which the material of this book is relevant are sound radiation from vibrating structures, sound transmission between adjacent regions of fluid media separated by an intervening solid partition, and the response of structures to excitation by incident sound fields. Much of the source material is only available (in English at least) in articles scattered throughout the learned journals of the world. In particular, fundamental analyses in acoustics textbooks of sound transmission through partitions tend to be restricted to highly idealised cases, and the complicating effects of finite panel size, non-homogeneous structures, cavity absorption and frames, and panel curvature are at best briefly and only qualitatively described. This is why Chapter 4 is the longest in the book.

Although the aim of the book is instructional, it is different from many other textbooks in that it is not divided into neat, self-contained sections of analysis, which can be concluded with Q.E.D.; it also contains a large amount of descriptive text. The first feature is connected with the 'dilemma' previously mentioned; the second stems from a desire to provide a text from which the reader can learn in the absence of a formal lecture course, although it is hoped that my prolixity will not deter a lecturer from using the book to complement his course.

The arrangement of questions in the book does not generally follow the conventional pattern of formalised quantitative examples at the ends of chapters. The reader is challenged at various places within the text to think about the material which he is currently reading, while it is fresh in his mind. I hope, in this way, to solicit more active cooperation in the learning process, and to stimulate a questioning approach to the material, rather than passive acceptance. The questions at the ends of chapters are linked to specific sections in the text and range from straightforward numerical evaluation of quantities, intended to encourage a 'physical feel' for their orders of magnitude, to rather open-ended questions, which can only be answered in qualitative terms. The absence of a large number of formal calculation exercises reflects both the nature of the subject and the fact that the readership is expected to have developed previously the facility for performing formal analyses of fundamental vibrational and acoustical problems.

Numerous references to other books, research publications and reports are provided in the text. The list is clearly not comprehensive, but it is hoped that it will provide the reader with jumping-off points for further and deeper study. The omission of any particular relevant reference in no way constitutes reflection of its value, any more than inclusion of a reference implies that it is considered to be uniformly meritorious and correct.

It is my hope that this book, for all its faults which will no doubt emerge, will help at least a few people to understand more fully the fascinating interplay between sound and structural vibration, and thereby serve to increase their ability to control whatever aspect of the subject commands their attention.

Frank Fahy
Southampton
November 1983

Preface to the Second Edition

The first edition of 'Sound and Structural Vibration' was written in the early 1980s. Since then, two major developments have taken place in the field of vibroacoustics. Powerful computational methods and procedures for the numerical analysis of structural vibration, acoustical fields and acoustical interactions between fluids and structures have been developed and these are now universally employed by researchers, consultants and industrial organisations. Advances in signal processing systems and algorithms, in transducers, and in structural materials and forms of construction, have facilitated the development of practical means of applying active and adaptive control systems to structures for the purposes of reducing or modifying structural vibration and the associated sound radiation and transmission.

In this greatly expanded and extensively revised edition, we have retained most of the analytically based material that forms the pedagogical content of the first edition, and have expanded it to present the theoretical foundations of modern numerical analysis. Application of the latter is illustrated by examples that have been chosen to complement the analytical approaches to solving fairly simple problems of sound radiation, transmission and fluid–structural coupling that are presented in the first edition. The number of examples of experimental data that relate to the theoretical content, and illustrate important features of vibroacoustic interaction, has been augmented by the inclusion of a selection from the vast amount of material published during the past twenty five years. The final chapter on the active control of sound and vibration has no precursor in the first edition.

The principal additions to the material of the first edition are as follows. Chapter One has been expanded to illustrate the relation between waves and modes in a more explicit, analytical manner. The section on waves in thin-walled, circular, cylindrical structures, originally presented in the chapter on sound transmission, has been relocated in this chapter. Statistical parameters such as modal density and overlap are introduced. The brief introduction to impedances and mobilities of structures that originally closed Chapter One has been replaced by an extensive treatment of the topic in Chapter Two, which also introduces the energy based model of coupling between structural elements. Chapter Three, on sound radiation by vibrating structures, concludes with a presentation of the Kirchhoff–Helmholtz integral formulation and also introduces radiation modes. Chapter Five, on sound transmission through partitions, has been expanded to cover a wider range of non-uniform structures, amplifies the original treatment of sound transmission through thin-walled, circular cylindrical shells, and presents a theoretical analysis of sound transmission through pipe walls. The original analytical models of acoustic coupling between structures and enclosed volumes of fluid are complemented in Chapter Seven by sections that present the Kirchhoff–Helmholtz integral formulation for the interior problem, and briefly analyse the waveguide behaviour of fluid-filled pipes at low frequency. The original brief introduction to Statistical Energy Analysis has been modestly expanded. Chapter Eight presents a comprehensive introduction to numerical analyses of vibroacoustic coupling. Finite Element Analysis is illustrated by application to the problem of acoustic coupling between an elastic plate and fluid in a rigid rectangular box and Boundary Element Analysis is illustrated by the associated problem of sound radiation from the plate. Chapter Nine introduces the fundamental principles, theory, devices, and implementations of active control and illustrates the benefits and shortcomings of various strategies by theoretical examples.

Notes on notation:

1. Because there is inconsistency between the symbols conventionally used in analytical treatments of fluid dynamics, acoustics and vibroacoustics, and those conventionally used in numerical analysis of structural vibration, the notation for displacements and velocities employed in Chapter Eight,

which is defined in a footnote on p. 456, differs from that in the rest of the book.
2. The tilde over a symbol indicates 'complex number'.
3. An overbar denotes time average and angle brackets denote space average.

Frank Fahy and Paolo Gardonio
Southampton
May 2006

Acknowledgements

The authors wish to acknowledge contributions to the preparation of this book made by the following colleagues. Special thanks are due to Emanuele Bianchi for scanning the first edition, of which there existed no electronic version, and Silvia Rossetti for retyping most of the mathematical content of the parts included in this edition. Advice with regard to the presentation of some of the more challenging technical material was provided by Steve Elliott, Brian Mace, Mike Brennan and Chris Jones. The work of PhD students Cristoph Paulitsch, Cristobal Gonzalez Diaz and Damien Emo formed the basis of some of the material of Chapter Nine. Advice on matters of grammar and vocabulary was sought by the second author of Joyce Shotter and Maureen Strickland and graciously given.

Lynne Honigmann and Vicki Wetherell at Elsevier waited patiently as many deadlines came and went and were always ready to offer helpful advice. We also wish to acknowledge the contribution of CEPHA Imaging Pvt. Ltd, Bangalore, India.

The first author wishes to thank his wife Beryl for accepting the deprivation of shared social activities caused by the regular and prolonged physical and mental absences of her husband on book business. Assistance with the proof reading of the mathematical content was generously provided by Thomas Fahy.

List of Permissions

Figures 1.2, 1.7, 1.13, 5.4, 5.13, 5.18 and 5.27 Reproduced with permission from Fahy, F. J. (2001) *Foundations of Engineering Acoustics*. Academic Press, London.

Figures 1.5, 1.14, 1.16, 3.8, 5.1, 5.2, 5.5–5.8, 5.14, 5.17 and 5.26 Reproduced with permission from Fahy, F. J. (1987) *Sound and Structural Vibration*. Academic Press, London.

Figure 3.5 Reproduced with permission from Fahy, F. J. (1995) *Sound Intensity* (2^{nd} Ed.). E & FN Spon, London.

Figure 3.37 Reproduced with permission from Mead, D. J. (1990) *Journal of the Acoustical Society of America*, 88:391 © 1990 Acoustical Society of America.

Figure 3.50 Data supplied under license by ESDU International plc, its affiliated and parent companies © 1995, all rights reserved.

Figure 3.32 Reproduced with permission from Cremer, L. and Heckl, M. (1973) *Structure-borne Sound*. Springer-Verlag, Heidelberg.

Figures 4.8 and 4.9 Reproduced with permission from Stepanishen, P. R. (1982) *Model Coupling in the Vibration of Fluid-loaded Cylindrical Shells*. © 1982 American Institute of Physics.

Figure 5.3 Reproduced with permission from Fahy, F. J. (1998) *Fundamentals of Noise and Vibration*. E & FN Spon, London.

Figure 5.4 Reproduced with permission from Norton, M. P. and Karczub, D. G. (2003) *Fundamentals of Noise and Vibration Analysis for Engineers 2nd Edn*. Cambridge University Press, Cambridge.

Figure 5.9 Reproduced with permission from Quirt, J. D. (1982) *Journal of the Acoustical Society of America*, 72:834–844 © 1982 Acoustical Society of America.

Copyright on Figures from the first edition as acknowledged therein.

Introduction

I think I shall never undertake to write a book again. If one were a scamp, the work would be easy enough, but for an honest man it is dreadful.

John Tyndall, 1859

Tyndall went on to write another eighteen books!

As you read these words you are almost certainly experiencing various manifestations of the process of vibrational interaction between fluids and solid structures. Traffic noise may be heard through the windows of the room; the plumbing system may be announcing its operation; or perhaps the radio or the iPod is providing background music for your pleasure. The first two examples represent the undesirable aspect of this phenomenon and suggest that study of its mechanism is of importance to those concerned with the control and reduction of noise. The third example shows that the process may be put to good use: vibrations of musical instruments, microphone diaphragms and loudspeakers act as intermediaries in the generation and reproduction of sound which, at least for some listeners, is the very antithesis of noise. The principal function of this book is to explain the physical process of interaction and to introduce the reader to various mathematical models and theoretical analyses of the behaviour of coupled fluid–structural systems. Many examples of experimental data are presented to illustrate the theory. This field of study is known as 'vibroacoustics' or, in the USA, 'structural acoustics'.

Acoustic vibrations in fluids and solid structures essentially involve the propagation of wave motion throughout the supporting media, although explicit recognition of this fact is not always apparent in textbooks on mechanical vibration. Indeed, an emphasis on the work–energy approach to vibration analysis, which is based upon the representation of the vibrational state of a system in terms of a finite number of degrees of freedom and is fundamental to many modern forms of computer-based numerical analysis, tends to obscure the wave nature of the processes under analysis. In dealing with audio-frequency vibrations of systems involving the coupling of compressible fluids with plate and shell structures, it is important to possess an appreciation of the 'wave view' of vibration. There are three main reasons for this requirement. The first concerns the three-dimensional nature, and often very great extent, of fluid volumes that are in contact with elastic structures, which effectively rule out analytical limitation on the number of degrees of freedom describing the vibrational state of the fluid. The second relates to the interaction of sound waves in fluids with structural boundaries of diverse geometric form and dynamic properties, which is best understood in terms of the wave phenomena of reflection, diffraction and scattering. The third reason is associated with the fact that the frequency ranges of practical concern in the field of vibroacoustics usually embrace a very large number of natural frequencies and high order modes of the components involved; discrete models are not necessarily appropriate because of uncertainties in the modelling of detail such as structural joints and the large number of degrees of freedom involved. Hence, vibrational wavefield models, analogous to those employed in the modelling of room acoustics, are often more practicable and effective.

For these reasons, Chapter 1 introduces the reader to a unified mathematical description of temporal and spatial distributions of wavefield variables and illustrates the forms of vibrational waves that travel in various ideal forms of structure such as uniform beams, flat plates and thin-walled, circular cylindrical shells. The phenomenon of wave dispersion that relates wave speed and frequency is shown to form the basis for categorising the regimes of wave interaction at interfaces between different media and different forms of structure. The phenomena of natural frequencies and modes of bounded elastic systems, and the related phenomenon of resonance, are illustrated and explained in terms of wave reflection and interference. The chapter closes with a brief introduction to probabilistic modelling of natural frequency distributions and related quantities that are employed in Statistical Energy Analysis (see Chapter 7).

Chapter 2 principally concerns the concepts of structural impedance and mobility that characterise the response of beams, flat plates and circular cylindrical shells to excitation by harmonic point forces and are also central to the modelling of networks of structural elements connected at discrete points. It is shown how mathematical expressions for the mobilities of uniform beams in bending may be derived either in terms of interference between bending waves reflected from boundaries or in terms of summations of modes that individually behave as single-degree-of-freedom systems consisting of lumped masses, springs and dampers. This reinforces the duality of wave and mode models introduced in Chapter 1. A simple model of singly connected structures is used to show how the effectiveness of a vibration isolator may be expressed in terms of mobilities. More complex networks of point-connected structural components may be represented by matrix models that incorporate the impedances or mobilities of the components at the connection points. Their application is illustrated by an analysis of the flow of vibrational energy through a beam network. The chapter closes with a brief analysis of wave energy propagation in beams and plates.

The mechanics of sound radiation by vibrating surfaces is explained in Chapter 3 in terms of the spatial distribution of vibrational acceleration normal to the interface with a fluid. The phenomenon of radiation cancellation is illustrated by a model of two simple sources. Analyses of sound radiation from planar surfaces by means of far-field evaluation of the Rayleigh integral, and in terms of travelling wave Fourier component (wavenumber) synthesis, are presented in such a way that the equivalence of these two models can be appreciated. It is shown that flexural waves travelling in an unbounded flat plate radiate sound power only if they travel supersonically. By means of wavenumber spectrum analysis of the modes of finite baffled plates, this crucial result is exploited to categorise the modes into four classes of radiator. Expressions for the radiation efficiencies of vibrating plates are derived in terms of natural modes and arrays of elementary radiators. The concept of frequency-dependent radiation modes that radiate sound power independently is explained and their derivation is presented. The utility of the Fourier approach is further illustrated by application to the evaluation of the contributions to sound power radiation by a flat plate made by concentrated applied forces and imposed velocities and from forces arising from the presence of local constraints. The radiation characteristics of stiffened, corrugated, sandwich and composite plates are illustrated. The radiation characteristics of thin-walled circular cylindrical shells are then analysed in some detail. The chapter closes with a derivation of the Kirchhoff–Helmholtz integral that expresses the sound pressure anywhere in a fluid in terms of the distributions of sound pressure and normal particle acceleration on any surface that bounds the fluid. This integral provides the basis for the numerical evaluation of sound radiated by vibrating bodies and for the influence on incident sound of bodies situated in a fluid as presented in Chapter 8.

The problem of evaluating the reaction forces (fluid loading) applied by a fluid to a vibrating body is addressed in Chapter 4. The concept of complex acoustic radiation impedance is illustrated by some simple examples. The value of the concept of wave impedance in analysing wave propagation in coupled fluid–structural systems is demonstrated in cases of bounded and unbounded flat plates. The effects of fluid loading on the natural frequencies and sound radiation by point-excited plates and circular cylindrical shells are then described and illustrated.