

# Acoustics, An Introduction to Its Physical Principles and Applications

Allan D. Pierce

Originally published in 1981; Reprinted in 1989

## Table of Contents

List of Symbols

Chapters

### 1. The Wave Theory of Sound

- 1-1 A Little History
  - 1-2 The Conservation of Mass
  - 1-3 Euler's Equation of Motion for a Fluid
  - 1-4 Pressure-Density Relations
  - 1-5 Equations of Linear Acoustics
  - 1-6 The Wave Equation
  - 1-7 Plane Traveling Waves
  - 1-8 Waves of Constant Frequency
  - 1-9 Speed of Sound and Ambient Density
  - 1-10 Adiabatic versus Isothermal Sound Speeds
  - 1-11 Acoustic Energy, Intensity, and Source Power
  - 1-12 Spherical Waves
- Problems

### 2. Quantitative Measures of Sound

- 2-1 Frequency Content of Sound
  - 2-2 Proportional Frequency Bands
  - 2-3 Levels and the Decibel
  - 2-4 Frequency Weighting and Filters
  - 2-5 Combining of Levels
  - 2-6 Mutually Incoherent Sound Sources
  - 2-7 Fourier Series and Long-Duration Sounds
  - 2-8 Transient Waveforms
  - 2-9 Transfer Functions
  - 2-10 Stationary Ergodic Processes
  - 2-11 Bias and Variance
- Problems

### 3. Reflection, Transmission, and Excitation of Plane Waves

- 3-1 Boundary Conditions at Impenetrable Surfaces
  - 3-2 Plane-Wave Reflection at a Flat Rigid Surface
  - 3-3 Specific Acoustic Impedance
  - 3-4 Radiation of Sound by a Vibrating Piston within a Tube
  
  - 3-5 Sound Radiation by Traveling Flexural Waves
  - 3-6 Reflection and Transmission at an Interface between Two Fluids
  - 3-7 Multilayer Transmission and Reflection
  - 3-8 Transmission through Thin Solid Slabs, Plates, and Blankets
- Problems

### 4. Radiation from Vibrating Bodies

- 4-1 Radially Oscillating Sphere
- 4-2 Transversely Oscillating Rigid Sphere
- 4-3 Monopoles and Green's Functions
- 4-4 Dipoles and Quadrupoles
- 4-5 Uniqueness of Solutions of Acoustic Boundary-Value Problems
- 4-6 The Kirchhoff-Helmholtz Integral Theorem
- 4-7 Sound Radiation from Small Vibrating Bodies
- 4-8 Radiation from a Circular Disk
- 4-9 Reciprocity in Acoustics
- 4-10 Transducers and Reciprocity Problems

### 5. Radiation from Sources Near and on Solid Surfaces

- 5-1 Sources near Plane Rigid Boundaries
  - 5-2 Sources Mounted on Walls: The Rayleigh Integral; Fresnel-Kirchhoff Theory of Diffraction by an Aperture
  - 5-3 Low-Frequency Radiation from Sources Mounted on Walls
  - 5-4 Radiation Impedance of Baffled-Piston Radiators
  - 5-5 Far-Field Radiation from Localized Wall Vibrations
  - 5-6 Transient Solution for Baffled Circular Piston
  - 5-7 Field on and near the Symmetry Axis
  - 5-8 Transition to the Far Field
- Problems

### 6. Room Acoustics

- 6-1 The Sabine-Franklin-Jaeger Theory of Reverberant Rooms
  - 6-2 Some Modifications
  - 6-3 Applications of the Sabine-Franklin-Jaeger Theory
  - 6-4 Coupled Rooms and Large Enclosures
  - 6-5 The Modal Theory of Room Acoustics
  - 6-6 High-Frequency Approximations
  - 6-7 Statistical Aspects of Room Acoustics
  - 6-8 Spatial Correlations in Diffuse Sound Fields
- Problems

## **7. Low-Frequency Models of Sound**

### **Transmission**

- 7-1 Guided Waves
  - 7-2 Lumped-Parameter Models
  - 7-3 Guidelines for Selecting Lumped-Parameter Models
  - 7-4 Helmholtz Resonators and Other Examples
  - 7-5 Orifices
  - 7-6 Estimation of Acoustic Inertances and End Corrections
  - 7-7 Mufflers and Acoustic Filters
  - 7-8 Horns
- Problems

## **8. Ray Acoustics**

- 8-1 Wavefronts, Rays, and Fermat's Principle
  - 8-2 Rectilinear Sound Propagation
  - 8-3 Refraction in Inhomogeneous Media
  - 8-4 Rays in Stratified Media
  - 8-5 Amplitude Variation along Rays
  - 8-6 Wave Amplitudes in Moving Media
  - 8-7 Source above an Interface
  - 8-8 Reflection from Curved Surfaces
- Problems

## **9. Scattering and Diffraction**

- 9-1 Basic Scattering and Concepts
- 9-2 Monostatic and Bistatic Scattering-Measurement Configurations
- 9-3 The Doppler Effect
- 9-4 Acoustic Fields near Caustics
- 9-5 Shadow Zones and Creeping Waves
- 9-6 Source or Listener on the Edge of a Wedge
- 9-7 Contour Integral Solution for Diffraction by a Wedge
- 9-8 Geometrical-Acoustic and Diffracted-Wave Contributions for the Wedge Problem

- 9-9 Applications of Wedge-Diffraction Theory Problems

## **10. Effects of Viscosity and Other Dissipative Processes**

- 10-1 The Navier-Stokes-Fourier Model
  - 10-2 Linear Acoustic Equations and Energy Dissipation
  - 10-3 Vorticity, Entropy, and Acoustic Modes
  - 10-4 Acoustic Boundary-Layer Theory
  - 10-5 Attenuation and Dispersion in Ducts and Thin Tubes
  - 10-6 Viscosity Effects on Sound Radiation
  - 10-7 Relaxation Processes
  - 10-8 Absorption of Sound
- Problems

## **11. Nonlinear Effects in Sound Propagation**

- 11-1 Nonlinear Steepening
  - 11-2 Generation of Harmonics
  - 11-3 Weak-Shock Theory
  - 11-4 N Waves and Anomalous Energy Dissipation
  - 11-5 Evolution of Sawtooth Waveforms
  - 11-6 Nonlinear Dissipative Waves
  - 11-7 Transition to Old Age
  - 11-8 Nonlinear Effects in Converging and Diverging Waves
  - 11-9 N Waves in Inhomogeneous Media: Spherical Waves
  - 11-10 Ballistic Shocks; Sonic Booms
- Problems

Appendix  
Answers and Hints to Problems

Indexes  
Name Index  
Subject Index

---

## **Preface to the Reprint Edition**

This edition, with minor corrections and with the addition of a section of hints and answers to exercises, is the same as the first edition published by McGraw-Hill in 1981. An errata of obvious misprints and subtle mistakes accumulated over the intervening years, and I am grateful for the opportunity to incorporate the required changes into a new printing of the text. It is difficult to remember all the colleagues who contributed to the compilation of the errata, but those I do remember include David Blackstock, Stephen Crandall, Wayne Wright, Martin Almgren, Robert Waag, Peter Rogers, Michael Meyers, and Vic Sparrow.

The appended section, giving answers to problems that request answers and giving hints for problems that request one to fill in missing steps, was written with the encouragement of William Hartmann, the present chairman of the Acoustical Society's Committee on Books. It is my hope that readers who are studying acoustics will find this new section helpful.

Allan D. Pierce  
State College, PA  
January 1989

## **Preface to Original Edition**

This book introduces the physical principles of acoustics. The predominant objective is to develop those concepts and points of view that have proven most useful in traditional realms of application such as noise control, underwater acoustics, architectural acoustics, audio engineering, nondestructive testing, remote sensing, and medical ultrasonics. The book is suitable as a text or as supplementary reading for senior and first-year graduate students in engineering, physics, and mathematics.

Preliminary versions of the book in the form of class notes have been used in a three-term (one academic year) introductory course in acoustics taken by graduate students in electrical engineering, aerospace engineering, mechanical engineering, engineering mechanics, and physics at the Georgia Institute of Technology. Portions of the presentation evolved from a graduate course on wave propagation previously taught at MIT to students from the departments of mechanical engineering, ocean engineering, and earth and planetary sciences. The mathematical developments and the assumptions concerning the prior academic experiences of the readers are such that no one with any of the backgrounds just mentioned should be precluded from taking a course in which this book is used as a text or as principal outside reading. The text, however, is intended to be at a level of mathematical sophistication and intellectual challenge comparable to distinguished graduate texts in the basic engineering sciences (such as fluid dynamics, solid mechanics, thermodynamics, and electromagnetic theory); a deep understanding of acoustical principles is not acquired by superficial efforts.

Graduate courses rarely follow a text closely; the instructor is invariably deeply involved in research or in the applications of the subject, and shapes the course content to conform with what appears timely, with the research programs at the institution, and with the common interests of the students. This book is intended to facilitate such flexibility. The common ground of introductory acoustics courses is covered thoroughly, so the student can fill in whatever gaps result because of the pace of the lecture. Since the text derives almost all of the equations frequently used in acoustics, the instructor can relegate to outside reading whatever derivations seem too time consuming for the lectures and can thereby concentrate on the physical implications and on the applications of the results without sacrificing the course's level of rigor.

Portions of the text's material have also been used in senior elective courses for engineering and physics students. This book is suitable for such a course, provided the instructor exercises good judgment in the selection of topics and the course does not cater to the handbook-oriented student. A possible path through the text for a one-term undergraduate course begins with Chapter 1, but omits Section 1-10; the course then continues with Chapter 2 through Section 2-6, with an extraction of results from Sections 2-7 and 2-8. Section 3-1 is terminated with the derivation of Eq. (3-2.1). Sections 3-2 and 3-3 are then covered, with a subsequent jump to Sections 4-1 through 4-4. Then, a possibility is the discussion of reciprocity and transducers in Sections 4-9 and 4-10; Section 5-1 on sources near walls should always be included. If the students are interested in noise control or architectural acoustics, the first half of Chapter 6, through Section 6-4, possibly without 6-2, should be covered. Sections 7-2, 7-3, 7-4, 7-6, 7-7, and 7-8 should be palatable with careful circumnavigation of the more mathematical paragraphs. Students oriented toward underwater sound, remote sensing, or medical ultrasonics may be guided through Sections 8-1 through 8-5, followed by Sections 9-1 through 9-3. Other possibilities should be evident to an astute instructor.

Many of the exercises at the ends of the individual chapters come from examinations the author has given in either graduate or undergraduate courses and can be briefly carried through, once the pertinent concepts are understood. Others are more challenging and, in some cases, will require hints from the instructor if they are to be solved in a reasonable period of time by the average student. None of the

problems are of the "plug-in" variety, but there should be a sufficient quantity at various levels of difficulty that the instructor can tailor homework assignments to the abilities of the students.

The footnotes scattered throughout the book embody the author's opinion that a textbook at this level should accurately cite the original sources of the basic concepts and principles. Many citations lead us back to Rayleigh and earlier, but this does not mean that the principles are any less applicable today. Few readers will have the time to browse through the early archival literature on the subject. Indeed, one reason why textbooks are written is to obviate doing such a thing--although often (especially so with Rayleigh) the person who conceived an idea and who said it first said it best. Eloquent defenses of the value to the practicing professional of the history of the profession's current stock of knowledge may be found within the works cited in Section 1-1 by Hunt and by Lindsay. In any event, the citations in the footnotes should be harmless to the recalcitrant pragmatic reader. The book is intended to be self-contained; whatever omissions in background material the reader encounters can be filled by consulting contemporary textbooks on mathematics and basic physics.

The more recent citations include most of the author's favorite references on acoustics; these are recommended reading for anyone who desires further elaboration on the subject matter. The author regrets that the pedagogical objectives of the book and the constraint that the book be of manageable length precluded the inclusion of some of the more important topics in modern acoustics (such as, for example, jet noise, acoustic emissions, cavitation, streaming, radiation pressure and levitation, combustion noise, parametric arrays, propagation through turbulence, sound-structural interaction, surface waves, and acoustical imaging). A consequence is that many works that the author esteems highly are not mentioned here. An introductory text with the objective of inculcating a deep understanding of the basic principles cannot, however, be encyclopedic and some hard decisions had to be made. The student should be able to proceed rapidly, once these basic principles are understood, toward any of the current frontiers of acoustics.

Along with the writings of Rayleigh and other past contributors to the field, the style and content of this book have been influenced by the author's early teachers, Richard H. Duncan and Laszlo Tisza, and by his past associations with Albert Latter, Elisabeth Iliff, Charles A. Moo, S.H. Crandall, J.P. Den Hartog, Huw G. Davies, Y.K. Lin, T.-Y. Toong, Patrick Leehey, Richard Lyon, P.P. Lele, Joe W. Posey, Wayne A. Kinney, Warren Strahle, W. James Hadden, Jr., E.-A. Müller, W. Möhring, and F. Obermeier. The writing of the book has also been affected by conversations or correspondence with John Snowdon, Herbert S. Ribner, Dominic Maglieri, Lucio Maestrello, Richard K. Cook, R. Bruce Lindsay, Geoffrey Main, David T. Blackstock, K. Uno Ingard, David G. Crighton, Hugh G. Flynn, T.F.W. Embleton, Robert Waag, Robert E. Apfel, Robert W. Young, Jiri Tichy, Donald Lansing, M.C. Junger, H.M. Überall, C.-H. Chew, Edmund H. Brown, Prateen Desai, T.J. Lardner, Preston W. Smith, Jr., Michael Howe, Phillip A. Thompson, Joseph E. Piercy, Walter Soroka, Sigalia Dostrovsky, Wesley Cobb, Lawrence A. Crum, Henry E. Bass, Bill D. Cook, and Stephen D. Pettyjohn. Thanks must also be expressed to the many students who pointed out weaknesses in the earlier class notes and who suggested improvements.

Although the writing of this book has extended over many years, the author's ideas concerning its substance crystallized during a year's sojourn (1976-1977) with the Max-Planck-Institut für Strömungsforschung in Göttingen. The Institute's research objectives and atmosphere were conducive to a sustained contemplation of the principles of acoustics, of their interconnections, and of their mechanical, thermodynamic, and mathematical foundations. The author is grateful to Professor E.-A. Möller and his colleagues for their hospitality and rapport and to the Alexander von Humboldt Foundation for the generous award that made the stay in Göttingen possible.

The author thanks the staff of the School of Mechanical Engineering at Georgia Tech for their forbearance throughout this long, seemingly interminable, project. The empathy and encouragement of S. Peter Kezios, the school's Director, is very much appreciated.

The author is also grateful to the library personnel who helped him in this endeavor; he especially thanks Robert Perrault for advice and for facilitating the procurement of rare bibliographic materials.

It was the author's extreme good fortune to have the collaboration of Rosie Atkins, an outstanding technical typist and manuscript stylist. Throughout several generations of manuscripts, Mrs. Atkins patiently and accurately interpreted and translated heavily scored, barely legible manuscripts, laden with equations and symbols, into attractive and readable typescripts.

The author's largest debt of thanks is owed to his wife Penny and to his children, Jennifer and Bradford. Their loyalty, encouragement, cheerfulness, and willingness to sacrifice have contributed immeasurably to the successful completion of this book.

Allan D. Pierce

© Acoustical Society of America