Preface

The concepts and techniques that form the basis of the discipline known as "acoustics" are critically important in almost every field of science and engineering. This is not a chauvinistic prejudice but a consequence of that fact that most matter we encounter is in a state of stable equilibrium; matter that is disturbed from that equilibrium will behave "acoustically." The purpose of this textbook is to present those acoustical techniques and perspectives and to demonstrate their utility over a very large range of system sizes and materials.

Starting with the end of World War II, there have been at least a dozen introductory textbooks on acoustics that have been directed toward students who plan to pursue careers in fields that rely on a comprehensive technical understanding of the generation, propagation, and reception of sound in fluids and solids and/or the calculation, measurement, and control of vibration. What is the point of adding another textbook to this long list? One may ask a more direct question: what has changed in the field and what appears missing in other treatments?

The two most obvious changes that I have seen over the past 40 years are the rise in the availability and speed of digital computers and the abdication of research and teaching responsibilities in acoustics and vibration by physics departments to engineering departments in American universities. This academic realignment has resulted in less attention being paid to the linkage of acoustical theory to the fundamental physical principles and to other related fields of physics and geophysics.

Beauty is in the eye of the beholder.

The same can be said for "understanding." We all know the wonderful feeling that comes with the realization that a new phenomenon can be understood within the context of all previous education and experience. I have been extraordinarily fortunate to have been guided throughout my career by the wisdom and insights of Isadore Rudnick, Martin Greenspan, Seth Putterman, and Greg Swift. Those four gentlemen had similar prejudices regarding what constituted "understanding" in any field of science or technology. Briefly, it came down to being able to connect new ideas, observations, and apparatus to the fundamental laws of physics. The connection was always made through application of (usually) simple mathematics and was guided by a clear and intuitively satisfying narrative.

Understanding Acoustics is my attempt to perpetuate that perspective. To do so, I felt it necessary to include three chapters that are missing from any other acoustics treatments. In Part I—Vibrations, I felt this necessitated a chapter dedicated to elasticity. In my own experience, honed by teaching introductory lecture and laboratory classes at the graduate level for more than three decades, it was clear to me that most students who study acoustics do not have sufficient exposure to the relationship between various elastic moduli to be able to develop a satisfactory understanding of the vibrations of bars and plates nor the propagation of waves in solids. It was also an opportunity to provide a perspective that encompassed the design of springs that is critical to understanding vibration isolation.

In Part II—Waves in Fluids, there are two chapters that also do not appear in any other acoustics textbook. One covers thermodynamics and ideal gas laws in a way that integrates both the phenomenological perspective (thermodynamics) and the microscopic principles that are a consequence of the kinetic theory of gases. Both are necessary to provide a basis for understanding of relations that are essential to the behavior of sound waves in fluids.

I have also found that most acoustics students do not appreciate the difference between reversible and irreversible phenomena and do not have an understanding of the role of transport properties (e.g., thermal conductivity and viscosity) in the attenuation of sound. Most students have been exposed to Ohm's law in high school but do not appreciate the similarities with shear stresses in Newtonian fluids or the Fourier Diffusion Equation. Without the concept of thermal penetration depth, the reason sound propagation is nearly adiabatic will never be understood at a fundamental level.

After reading the entire manuscript for this textbook, a friend who is also a very well-known acoustician told me that this textbook did not start its treatment of acoustics until Chap. 10. Although I disagreed, I did see his point. It is not until Chap. 10 that the wave equation is introduced for sound in fluids. In most contemporary acoustics textbooks (at least those that do not initially address vibration), the wave equation appears early in Chap. 1 (e.g., Blackstock on pg. 2 or Pierce on pg. 17). Again, my postponement is a consequence of a particular prejudice regarding "understanding." From my perspective, combining three individually significant equations to produce the wave equation makes no sense if the student does not appreciate the content of those equations before they are combined to produce the wave equation.

If you learn it right the first time, there's a lot less to learn.

I will readily admit that I've included numerous digressions that I think are either interesting, culturally significant, or provide amusing extensions of the subject matter that may not be essential for the sequential development of a specific topic. For example, it is not necessary to understand the construction of musical scales in Sect. 3.3.3 to understand the dynamics of a stretched string. Such sections are annotated with an asterisk (*) and can be skipped without sacrifice of continuity of the underlying logical development.

With the availability of amazingly powerful computational tools, connecting the formalism of vibration and acoustics to fundamental physical principles is now even more essential. To paraphrase P. J. O'Rourke, "without those principles, giving students access to a computer is like giving a teenage boy a bottle of whisky and the keys to a Ferrari." The improvements in computing power and software that can execute sophisticated calculations, sometimes on large blocks of data, and display the results in tabular or graphical forms raise the need for a more sophisticated understanding of the underlying mathematical techniques whose execution previously may have been too cumbersome. More importantly, it requires that the understanding of the user be sufficient to discriminate between results that are plausible and those which cannot possibly be correct. A computer can supply the wrong result with seven-digit precision a thousand times each second.

There are many fundamental principles, independent of the algorithms used to obtain results, which can be applied to computer-generated outputs to test their validity. That written, there is no substitute for physical insight and a clear specification of the problem. One goal of this textbook is to illuminate the required insight both by providing many solved example problems and by starting the analysis of such problem from the minimum number of fundamental definitions and relations while clearly stating the assumptions made in the formulation.

Unfortunately, some very fundamental physical principles that can be used to examine a seemingly plausible solution have vanished from the existing textbook treatments as the teaching of acoustics has transitioned from physics departments to engineering departments. In some sense, it is the improvement in mathematical techniques and notation as well as rise of digital computers that have made scientists and engineers less reliant on principles like adiabatic invariance, dimensional analysis (i.e., similitude or the Buckingham Π-Theorem), the Fluctuation-Dissipation Theorem, the Virial Theorem, the Kramers–Kronig relations, and the Equipartition Theorem. These still appear in the research literature because they are necessary to produce or constrain solutions to problems that do not yield to the current suite of analytical or numerical techniques. This textbook applies these approaches to very elementary problems that can be solved by other techniques in the hope that the reader starts to develop confidence in their utility. When solving a new problem, such principles can be applied to either check results obtained by other means or extract useful results when other techniques are inadequate to the task.

For example, the Kramers–Kronig relations can be applied to a common analogy for the behavior of elastomeric springs (consisting of a series spring-dashpot combination in parallel with another spring). The limiting values of the overall stiffness of this combination at high and low frequencies dictate the maximum dissipation per cycle in the dashpot. Although for springs and dashpots these results can be obtained by simple algebraic methods, when measuring the frequency dependence of sound speed and attenuation in some biological specimen or other complex medium, the Kramers–Kronig relations can expose experimental disagreement between those two measurements that might call the results into question.

Traditionally, the analysis of the free decay of a damped simple harmonic oscillator generates an exponential amplitude decay that results in the mass eventually coming to rest. Since energy is conserved, the energy that is removed from the oscillator appears as heating of the resistive element which exits "the system" to the environment. It is important to recognize that the route to thermal equilibrium is a two-way street. It also allows energy from the environment to excite the oscillator in a way that ensures a minimum (nonzero!) oscillation amplitude for any oscillator in thermal equilibrium with its environment. Simple application of the Equipartition Theorem provides the statistical variance in the position of the oscillating mass and can elucidate the role of the resistance in spreading the spectral distribution of that energy, leading to an appreciation of the ubiquity of noise introduced by all dissipative mechanisms. The origin of fluctuations produced by dissipation is known in physics as "Onsager Reciprocity." In acoustics, it is much more likely that our "uncertainty principle" is dominated by Boltzmann's constant, rather than by Planck's constant. In an era of expanding application of micromachined sensors, thermal fluctuations in those tiny oscillators can be the dominant consideration that determines their minimum detectable signal.

The calculation of the modal frequencies of a fluid within an enclosure whose boundaries cannot be expressed in terms of the 11 separable coordinate systems for the wave equation is another example. These days, the normal approach is to apply a finite-element computer algorithm. Most enclosure shapes are not too different from one of the separable geometries that allow the mode shapes and their corresponding frequencies to be determined analytically. Adiabatic invariance guarantees that if one can deform the boundary of the separable solution into the desired shape, while conserving the enclosure's volume, the modal frequencies will remain unchanged, and, although the mode shape will be distorted, it will still be possible to classify each mode in accordance with the separable solutions. (Adiabatic invariance assumes that "mode hopping" does not occur during the transformation.) Needless to say, this provides valuable insight into the computer-generated solutions while also checking the validity of the predicted frequencies. In this textbook, adiabatic invariance is first introduced in a trivial application to the work done when shortening the length of a pendulum.

Another motivation for taking a new approach to teaching about waves in fluids is fundamentally pedagogical. It comes from an observation of the way other textbooks introduce vibrational concepts that are focused on Hooke's law (a primitive constitutive relation) and Newton's Second Law of Motion. These are first combined to analyze the behavior of a simple harmonic oscillator. This is always done before analyzing waves on strings and in more complicated (i.e., three-dimensional) solid objects. This is not the approach used in other textbooks when examining the behavior of waves in fluids. Typically, the fundamental equations of thermodynamics and hydrodynamics (i.e., the equation of state, the continuity equation, and Euler's equation) are linearized and combined to produce the wave equation and much later the subject of "lumped element" systems (e.g., Helmholtz resonators, bubbles) that are the fluidic analog to masses and springs is addressed.

The fact that the continuity equation leads directly to the definition of fluid compliance (e.g., the stiffness of a gas spring) and the Euler equation defines fluid inertance should be introduced before these equations are combined (along with the equation of state) to produce the wave equation. In my experience, the wave equation is of rather limited utility since it describes the space–time evolution of a particular fluid parameter (e.g., pressure, density, or particle velocity) but does not relate the amplitudes and phases of those parameters to each other. The "lumped element first" approach is adopted in Greg Swift's *Thermoacoustics* textbook, but that book is intended for specialists.

Having mentioned Greg Swift's name, I gladly admit that much of the content of this textbook has been based on an approach that was taught to me by my Ph.D. thesis advisors, Isadore Rudnick and Seth Putterman, at UCLA, in the 1970s. Their perspective has served me so well over the past four decades, in a variety of applications, as well as in teaching, that I feel an obligation to future generations to record their insights. Unfortunately, neither Rudnick nor Putterman have written acoustics textbooks, but as a student, I had the foresight to make detailed notes during their lectures in courses on acoustics and on continuum dynamics.

In addition to the traditional vibrational and acoustical topics covered in this textbook, I intended to write three chapters to illustrate the extension of these principles to more contemporary applications: nonlinear acoustics, sound waves in superfluid helium, and thermoacoustic engines and refrigerators. Entire textbooks have been dedicated to each of these areas, so these treatments were only intended to demonstrate some of the simpler but fascinating results. The purpose of including these topics was to explore consequences of going beyond the standard introductory topics. I have always felt that a real understanding of linear acoustics is only accessible to someone who has looked at the consequences of nonlinearity. Similarly, an understanding of sound in single-component fluids is much more comprehensive after sound in a two-component fluid is analyzed. This can be achieved by examining fully ionized plasmas, as well as looking at superfluid helium, but my choice was dictated by my long-term interest in quantum fluids. Finally, a thermoacoustics chapter would have introduced some interesting and unanticipated acoustical phenomena that are only exhibited when sound is generated or absorbed in the presence of nonzero time-averaged temperature gradients. Personal and professional circumstances prevented me from completing the chapters on acoustics in quantum fluids and on thermoacoustic engines, refrigerators, and mixture separation in time for the first edition.

As I hope I have expressed above, this textbook is an attempt to synthesize a view of acoustics and vibration that is based on fundamental physics while also providing the engineering perspectives that provide the indispensable tools of an experimentalist. This preface closes with a table of quotations that have guided my efforts. Unfortunately, I must take full responsibility for both the errors and the ambiguities in this treatment, though hopefully they will be both minor and rare.

"If you learn it right the first time, there's a lot less to learn."

R. W. M. Smith

"One measure of our understanding is the number of different ways we can get to the same result."

R. P. Feynman

"An acoustician is merely a timid hydrodynamicist."

A. Larraza

"Thermodynamics is the true testing ground of physical theory because its results are model independent."

A. Einstein

"Superposition is the compensation we receive for enduring the limitations of linearity"

Blair Kinsman

"A computer can provide the wrong result with seven-digit precision."

Dr. Nice Guy

"I have often been impressed by the scanty attention paid even by original workers in physics to the great principle of similitude. It happens not infrequently those results in the form of 'laws' are put forward as novelties on the basis of elaborate experiments, which might have been predicted *a priori* after a few minutes of consideration."

J. W. Strutt (Lord Rayleigh)

"Given today's imperfect foundations, additional approximations are useful whenever they improve computational ease dramatically while only slightly reducing accuracy".

G. W. Swift

"Each problem I solved became a rule which served afterward to solve other problems."

R. Descartes

"The industrial revolution owes its success to the fact that the computer hadn't been invented yet. If it had, we would still be modeling and simulating the cotton gin, the telegraph, the steam engine, and the railroad."

D. Phillips

"The best science doesn't consist of mathematical models and experiments. Those come later. It springs fresh from a more primitive mode of thought, wherein the hunter's mind weaves ideas from old facts and fresh metaphors and the scrambled crazy images of things recently seen. To move forward is to concoct new patterns of thought, which in turn dictate the design of models and experiments. Easy to say, difficult to achieve."

E. O. Wilson

"In no other branch of physics are the fundamental measurements so hard to perform and the theory relatively so simple; and in few other branches are the experimental methods so dependent on a thorough knowledge of theory."

P. M. Morse

Pine Grove Mills, PA Steven L. Garrett

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