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Steven L. Garrett

Understanding Acoustics

An Experimentalist's View of Acoustics and Vibration

ASA Press

Springer

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The Acoustical Society of America

On 27 December 1928 a group of scientists and engineers met at Bell Telephone Laboratories in New York City to discuss organizing a society dedicated to the field of acoustics. Plans developed rapidly and the Acoustical Society of America (ASA) held its first meeting on 10–11 May 1929 with a charter membership of about 450. Today ASA has a worldwide membership of 7000.

The scope of this new society incorporated a broad range of technical areas that continues to be reflected in ASA's present-day endeavors. Today, ASA serves the interests of its members and the acoustics community in all branches of acoustics, both theoretical and applied. To achieve this goal, ASA has established technical committees charged with keeping abreast of the developments and needs of membership in specialized fields as well as identifying new ones as they develop.

The Technical Committees include acoustical oceanography, animal bioacoustics, architectural acoustics, biomedical acoustics, engineering acoustics, musical acoustics, noise, physical acoustics, psychological and physiological acoustics, signal processing in acoustics, speech communication, structural acoustics and vibration, and underwater acoustics. This diversity is one of the Society's unique and strongest assets since it so strongly fosters and encourages cross-disciplinary learning, collaboration, and interactions.

ASA publications and meetings incorporate the diversity of these Technical Committees. In particular, publications play a major role in the Society. *The Journal of the Acoustical Society of America* (JASA) includes contributed papers and patent reviews. *JASA Express Letters* (JASA-EL) and *Proceedings of Meetings on Acoustics* (POMA) are online, open-access publications, offering rapid publication. *Acoustics Today*, published quarterly, is a popular open-access magazine. Other key features of ASA's publishing program include books, reprints of classic acoustics texts, and videos.

ASA's biannual meetings offer opportunities for attendees to share information, with strong support throughout the career continuum, from students to retirees. Meetings incorporate many opportunities for professional and social interactions and attendees find the personal contacts a rewarding experience. These experiences result in building a robust network of fellow scientists and engineers, many of whom became lifelong friends and colleagues.

From the Society's inception, members recognized the importance of developing acoustical standards with a focus on terminology, measurement procedures, and criteria for determining the effects of noise and vibration. The ASA Standards Program serves as the Secretariat for four American National Standards Institute Committees and provides administrative support for several international standards committees.

Throughout its history to present day, ASA's strength resides in attracting the interest and commitment of scholars devoted to promoting the knowledge and practical applications of acoustics. The unselfish activity of these individuals in the development of the Society is largely responsible for ASA's growth and present stature.

Graduate Texts in Physics

Graduate Texts in Physics publishes core learning/teaching material for graduate and advanced-level undergraduate courses on topics of current and emerging fields within physics, both pure and applied. These textbooks serve students at the MS- or PhD-level and their instructors as comprehensive sources of principles, definitions, derivations, experiments and applications (as relevant) for their mastery and teaching, respectively. International in scope and relevance, the textbooks correspond to course syllabi sufficiently to serve as required reading. Their didactic style, comprehensiveness and coverage of fundamental material also make them suitable as introductions or references for scientists entering, or requiring timely knowledge of, a research field.

For Izzy, Moe,

Seth, and Greg

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

Acknowledgements

As mentioned in both the Dedication and the Preface, this textbook is my attempt to repay the intellectual generosity of Isadore Rudnick (1917–1996), Martin (Moe) Greenspan (1912–1987), Seth Putterman, and Greg Swift. Oddly, all four started their careers as theorists and ended up becoming extraordinarily competent experimentalists.

I am also indebted to the Acoustical Society of America (ASA). It has been my professional home since 1972. In all of my experience with professional scientific societies, I have never found any similar organization that was more welcoming to students or more focused on meeting the needs of their members. I would not have begun this effort had I not been contacted by Allan Pierce, then the Society's Editor-in-Chief, who sent an e-mail message to several members saying that the ASA's Books+ Committee was going to expand from selling affordable reprints of classic acoustics textbooks into production and distribution of first editions that would be useful to ASA members.

I am glad to thank the Paul S. Veneklasen Foundation, and particularly Foundation board members, David Lubman and John LoVerde. When they heard that I was writing an acoustics textbook with a distinctively west coast perspective, they offered the Foundation's support to cover my editorial and graphic expenses.

Once I had completed my manuscript, the ASA assigned two technical content editors. I am very grateful to Prof. Peter Rogers, now retired from Georgia Tech, and Asst. Prof. Brian Anderson for accepting that assignment. Pete is one of the most accomplished acousticians of my generation and Brian is a recent addition to the Physics Department of Brigham Young University. I am indebted to both of them for their careful consideration of my manuscript and for their insightful comments and corrections. I am also grateful to my Penn State colleagues, Anthony Atchley, Tom Gabrielson, Jay Maynard, and Dan Russell, who have allowed me use some figures from their class notes in this textbook.

After enjoying a 40-year career as an academic acoustician, there are many others who have helped me refine and expand my understanding of sound and vibration. I have supervised more than 70 master's and Ph.D. thesis students, and each has challenged me in different ways that ultimately led to deeper understanding. That said, I must explicitly acknowledge David A. Brown and David L. Gardner who were my Ph.D. students in the Physics Department at the Naval Postgraduate School and Matthew E. Poese and Robert W. M. Smith who received their Ph.D. degrees from the Graduate Program in Acoustics at Penn State under my supervision. All four were gifted scientists and engineers before they joined my research group and all have continued to collaborate with me for decades. Besides benefiting from their ingenuity, perseverance, and wise counsel, I also have been continually amused and bolstered by their amazing sense of humor.

In addition to students, the perspectives reflected in this textbook benefit from long-time collaborations with some outstandingly knowledgeable and creative colleagues. I enjoyed working with Richard Packard both as the F. V. Hunt Fellow of the Acoustical Society of America while at the University of Sussex and following that year as a Miller Institute Postdoctoral Fellow at UC-Berkeley for 2 more years, where Prof. Packard was a member of the Physics Department and where I first met Greg Swift, who was one of Packard's many distinguished Ph.D. students. (Packard is shown on his fishing boat, *The Puffin*, in Alaska, in Fig. 4.13.) Oscar B. Wilson took me under his wing, both figuratively and literally (at one time he owned at least four aircraft and encouraged me to get my pilot's license), when I started my academic career at the Naval Postgraduate School. At the Naval Postgraduate School and later at Penn State, I benefited from collaborations with Thomas B. Gabrielson and Robert M. Keolian. In addition to their extraordinary competence as experimentalists, both are very gifted teachers, as are Matt Poese, Bob Smith, and David Brown.

The effort required to produce a textbook is significant and I required hundreds of day-long sessions that demanded uninterrupted concentration. Thanks to the Penn State library's online journal access and a year of sabbatical leave, I was able to write anywhere in the world that provided decent Internet access. I thank my son, Adam, who let me write in his Brooklyn apartment, my dear cousin, Karen Rothberg, who let me write from her beautiful home in Santa Barbara, California, my friends Susan Levenstein and Alvin Curran who let me write in their wonderful apartment in the heart of ancient Rome, and Anne-Sophie and Bernard Thuard who rented me an apartment above their bookstore in the center of Le Mans, France, where the largest portion of this book was written. I must also thank Guillaume Penelet, Pierrick Lotton, and Gaëlle Poignand, all associated with the Laboratoire d'Acoustique de l'Université du Maine. They made me feel at home in Le Mans, where I was also a member of their "Acoustics HUB" program that provided both a laboratory and office space in their acoustics program.

The Internet also made it possible to write from Los Angeles and Venice, California, Puerto Escondido, Mexico, and Haifa, Israel, where I was able to rent apartments and enjoy great weather and indigenous cuisines that were perfect for textbook writing. If you are considering writing a book, I will certify that there is nothing wrong with any of the venues I've mentioned that can also provide excellent weather.

The ASA made a very wise choice by teaming with Springer to publish their first editions. Springer's representative to the ASA during this entire process has been Sara Kate Heukerott. She has always responded to my multiple queries about mechanics and style quickly, completely, and with good humor. As of this date, the ASA has received over 30 book proposals from members interested in producing first editions. I look forward to reading many of them.

I close by thanking my daughter and son, Wendy and Adam, for their support during this process and for making sure that their father was amused and well fed. Thanks (in advance) to the students, teachers, and researchers who will contact me to let me know how this textbook might have better served their needs.

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About the Author

Steven L. Garrett received his Ph.D. in Physics from UCLA in 1977. He continued research in quantum fluids at the University of Sussex in England, followed by 2 years in the Physics Department at the University of California at Berkeley as a Fellow of the Miller Institute for Basic Research in Science. Prof. Garrett joined the faculty of the Naval Postgraduate School in 1982 where his research efforts were concentrated on the development of fiber-optic sensors and thermoacoustic refrigerators. Prof. Garrett left NPS in 1995 to assume a position as Professor of Acoustics in the Graduate Program in Acoustics at Penn State from which he retired in 2016. In 2001, he was a Fulbright Fellow at the Danish Technical University and in 2008 a Jefferson Fellow in the US State Department. Prof. Garrett is a Fellow of the Acoustical Society of America and recipient of their Interdisciplinary Medal in Physical and Engineering Acoustics as well as the Popular Science Magazine Award for Environmental Technology, the Helen Caldecott Award for Environmental Technology, and the Rolex Award for Enterprise (environment category). He has been issued over two dozen patents.