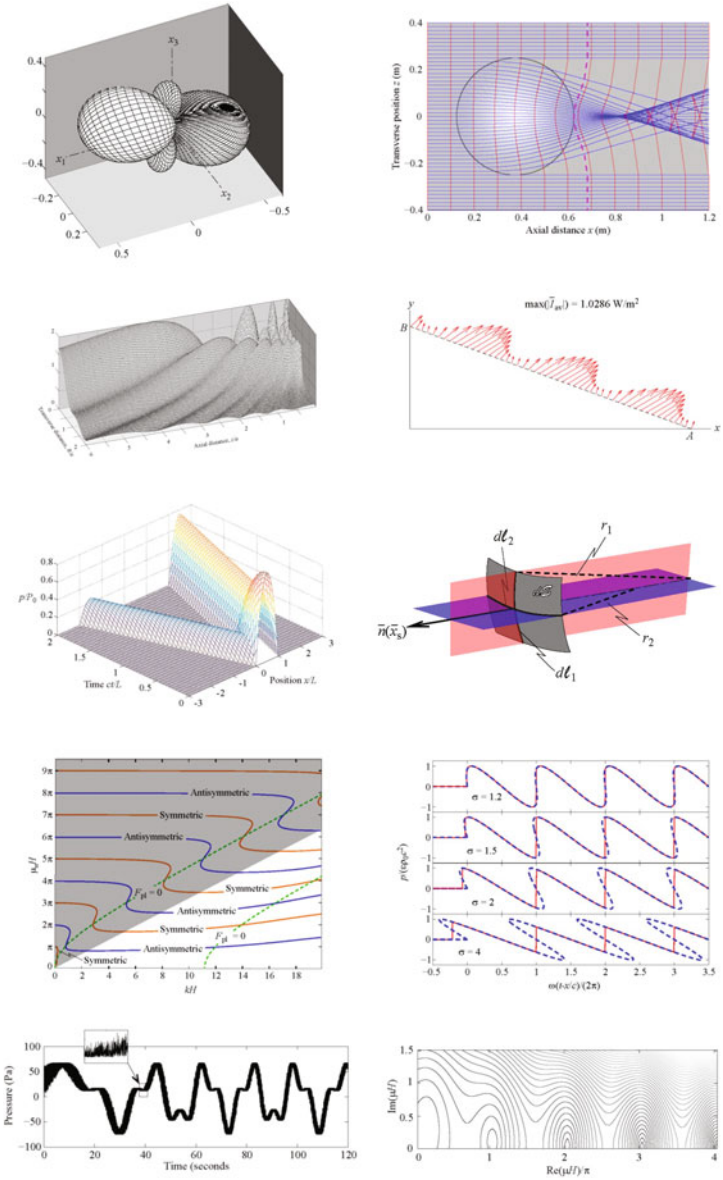
Acoustics—A Textbook for Engineers and Physicists



Transverse position z (m)
Axial distance x (m)
max(|$\bar{I}_{av}$|) = 1.0286 W/m^2
Time ct/L
Position x/L
p/P_0
$d\ell_2$
$d\ell_1$
r_1
r_2
$\bar{n}(\bar{x}_s)$
Antisymmetric
Symmetric
$F_{\mu l} = 0$
$\mu_a H$
kH
σ = 1.2
σ = 1.5
σ = 2
σ = 4
ω(t-x/c)/(2π)
Pressure (Pa)
Time (seconds)
Im(μl)
Re(μl)/π

Jerry H. Ginsberg

Acoustics—A Textbook for Engineers and Physicists

Volume I: Fundamentals

ASA Press

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The ASA Press

The ASA Press imprint represents a collaboration between the Acoustical Society of America and Springer dedicated to encouraging the publication of important new books in acoustics. Published titles are intended to reflect the full range of research in acoustics. ASA Press books can include all types of books published by Springer and may appear in any appropriate Springer book series.

ASA Press

The Acoustical Society of America

On December 27, 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 May 10–11, 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.

To Leah Morgan, Elizabeth Rachel,
and Abigail Rose, my grandchildren.
Each is talented, each is beautiful,
each is unique, each is amazing.
I love them.

Preface

The Basic Concept

As is stated by its title, this is a textbook. It is not a treatise that will make the reader an expert in any topic. However, it also is not merely an introduction to acoustics. The intent is to provide students with a foundation of core concepts and tools that will permit in-depth study of any of the physics and engineering acoustics specialties. This book, like my others in engineering dynamics and vibrations, is based on some basic precepts. A textbook must prepare a student to work in an area where phenomena are complicated. These complications must be addressed in a manner that is accessible to students. Rather than merely deriving and applying basic formulas, a textbook should assist the reader to recognize the connection between formulas and physical phenomena and correspondingly to use understanding of each of these aspects to anticipate and explain results from the other. Equally importantly, a well-done text should motivate students for further study by exposing them to the many remarkable phenomena that make the subject of acoustics so interesting. In view of these objectives, the coverage is quite comprehensive. I have not found some of the topics fully addressed in other textbooks. Indeed, some I developed especially for this book. Furthermore, almost every chapter has features that are not commonly encountered in other texts. In my estimation, complete coverage of all topics would require more than a two-semester course sequence. In recognition of the conflict between depth and breadth, each chapter is organized such that instruction of the early sections, which address fundamental concepts, should be adequate to proceed to the next chapter.

I have taken great care to explain analytical steps, the physical interpretation of key results, and especially how the student should proceed to solve problems in each topic. Some of the derivations and explanations I believe are unique to this book. Examples are numerous, and most are more than simple applications of derived formulas. Rather, they are intended as case studies that explain why the example is important, why the solution proceeds as it does, how to perform unfamiliar operations, what can be learned from the results about fundamental behaviors, and why the qualitative aspects of the results are consistent with the underlying fundamental principles. Some examples analyze systems by more than one method. This serves to enhance the student's fundamental understanding of the underlying physical processes, as well as enhancing the ability to make the appropriate line of attack when confronted with a new situation. All of the 122 examples are my own creation. With the exception of established standards, all data and graphs are newly generated. The advent and wide availability of computational software is exploited to lend greater realism to some examples. When the usage of software entails any potentially problematic aspects, especially concerning algorithms and their implementation, those issues are addressed explicitly, sometimes with program fragments. An examination of the List of Examples will help one see the diversity of the examples that receive this type of treatment. In recognition of the importance of computations, and as an aid to students to succeed in their efforts to solve homework exercises, the MATLAB code used to solve the examples is available for download from the Springer server.

A broad range of physical principles and mathematical concepts arise in the various topics of acoustics, but students enter the study of acoustics from a variety of paths. Consequently, it is likely that a student cohort will not have equal preparation to handle the task at hand. The presentation assumes that the reader is familiar with the basic concepts of algebra, vector analysis, calculus, and ordinary differential equations with constant coefficients, but little else. Any aspect of a derivation or problem solution that has a degree of subtlety is fully explained. Mathematics is essential, but this book is not a treatise in applied mathematics. Nevertheless, some topics do require sophisticated operations. If that is the case, the steps are carefully explained.

One of the features that will not be found herein is extensive use of analogies. This decision stems in part from the diverse background of students. An analogy that is meaningful to an electrical engineering student might be merely something else to learn for a physics student. Furthermore, I believe that one should learn a subject at its core. Analogies to me are equivalent to listening or reading a foreign language by translating it mentally. The best way to learn a foreign language is to become immersed in it, and a thorough immersion is the best way to learn acoustics. Recognition of connections between subjects is best attained by understanding each profoundly.

Technical Content

The organization of the topics is my vision of how the realm of acoustics fits together. My education was in civil engineering as an undergraduate and then in engineering mechanics as a graduate student. I had a rather extensive background in applied mathematics, dynamics, vibrations, and solid and fluid mechanics, but no formal education in acoustics. (I did become involved for a short time with a project involving sonic booms prior to embarking on my doctoral work analyzing nonlinear vibrations of shells.) My acoustics efforts began six years after I became an assistant professor. That work was in nonlinear waves, and it caused me to begin to interact with acousticians. Several years later, I had the good fortune to meet Allan Pierce when I moved to Georgia Tech. It was he and his wonderful book, *Acoustics*, that were responsible for most of my early education in the subject. I continued to work in nonlinear acoustics and also pursued research in structural acoustics and vibration. My interests were broadened by teaching a two-semester acoustics sequence several times. With each meeting of the Acoustical Society of America, I came to realize how much was left to learn. Writing this book has served to fill that gap because it has caused me to delve into topics with which I had little prior experience. This is especially so because I wished that each topic be given an extensive treatment, and I could not write without thoroughly understanding what I was writing about.

As I said, the content is organized in a manner that seems to me to be most logical. Much of Chap. 1 is not specific to acoustics. It introduces the basic tools of complex representation of harmonic functions, Fourier series, complex frequency response functions, and fast Fourier transforms, all of which are core concepts for any discipline that is concerned with oscillations. However, the discussion of frequency bands, musical scales, and noise models distinguishes this treatment from those for other applications. All readers should find the last example, which analyzes the spectral properties of noise data measured in the open fuselage of NASA's SOFIA aircraft, to be quite interesting.

Chapter 2 is devoted to time-domain analysis of plane waves. One-dimensional conservation laws are derived as the foundation of the derivation of the wave equation. The derivation of the d'Alembert solution follows a heuristic, but rigorous, approach. This solution, which describes waves in an unbounded medium, is used as the building block for construction of solutions for initial conditions and for boundary excitation of semi-infinite and closed waveguides. This is done by the development of the method of wave images, which converts multiple reflections to an equivalent problem in an unbounded medium. This content is somewhat lengthy to develop, but it offers numerous rewards. Most importantly, it greatly enhances a student's ability to switch between spatial and temporal views of waves. The development introduces some basic phenomena, such as multiple reflections, standing waves, natural frequencies, modal patterns, and resonance, through a set of simple operations. Doing so should enhance a student's desire for further study. The results of Example 2.7, which concerns the transient response of a closed waveguide that is resonantly excited, are likely to surprise many readers.

Chapter 3 examines from a frequency-domain perspective many of the topics in Chap. 2. This arrangement is chosen in order to avoid the tendency of students to forget that acoustics signals evolve in time, as well as propagating spatially. The frequency-domain formulation is essential because it allows for the development of techniques that are required for more general systems, and it allows for introduction of the local impedance model for boundaries. One of the highlights of this chapter is the analysis of synthetic data for an impedance tube, which amply demonstrates how small measurement errors can seriously lessen the quality of experimental results. The treatment of various dissipation mechanisms and their influence on the propagation properties is comprehensive, yet it should be accessible to students who do not have an extensive background in fluid mechanics and thermodynamics. The treatment of waveguide networks using transfer functions is a concept I refined for this book. The topic is not essential for later study, but the variety of systems it can analyze serves to motivate students by allowing them to exercise their creativity, simultaneously with introducing them to real-world issues.

Chapter 4 focuses on the core principles governing multidimensional waves. The derivations of the continuity equation and of the momentum-impulse equation differ from those in Chap. 2 by using the tools of vector calculus, which also are needed for many later topics. The analysis of plane waves propagating in an arbitrary sense in a three-dimensional sense introduces the fundamental concept of a wavenumber vector without simultaneously dealing with the task of solving the wave equation in several spatial coordinates. The concluding example in Chap. 4 uses a crude model of the field radiated by a piston to demonstrate the utility of the power balance principle. Seeing how the combination of a basic principle and some fundamental reasoning can provide a "back of the envelope" prediction reinforces a student's confidence that acoustics is an accessible subject.

Various phenomena that arise when a plane wave is obliquely incident at a planar interface are the subject of Chap. 5. This chapter establishes the concepts of subsonic and supersonic trace velocities, which are core factors for a wide range of later topics. Diagrams illustrating the difference between the propagating and evanescent transmitted fields enhance the mathematical descriptions. To my knowledge, the algorithm for propagation through multiple layers has not appeared in prior publications.

The time-domain analysis of radially symmetric spherical waves opens Chap. 6. The study of transient radiation from a vibrating sphere is followed by a thorough exploration of the transient waves in a spherical cavity. The example that illustrates the analysis of the singularity at the center tends to be especially interesting to students because it leads to the concept underlying a lithotripter. The sequence of topics for the frequency-domain analysis of spherical waves follows the time-domain treatment. Intensity and power flow for combinations of sources receive special attention. A thorough exposition on the meaning of a Green's function leads to the concept of a point source. Combinations of point sources to create dipole and quadrupole fields are analyzed by Taylor series expansions. The reader will find the diagrams illustrating various combinations of lateral and longitudinal quadrupoles to be quite informative. Chapter 6 closes with an examination of the Doppler effect for various moving sources. The analysis and results for a supersonically moving, harmonically varying, point source were developed for this book. Many individuals might be unaware of the effects that are identified.

Radiation from vibrating objects is the subject of Chap. 7. The development begins with derivation of the general spherical harmonic solution for axisymmetric signals. The first applications are to vibrating spheres for cases of an imposed vibration pattern, followed by forced response of an elastic spherical shell. An important aspect is a detailed examination of the influence of the acoustic surface impedance on the occurrence of fluid-loaded resonances. Radiation from infinitely long cylinders leads to a representation of the field as a result of helical surface waves. The Kirchhoff-Helmholtz integral theorem for enclosed and open domains is derived. An example uses the analytical solution for the radially symmetric field interior to a vibrating sphere to generate the surface pressure required to formulate KHIT. The pressure along a line running from the center of the sphere out to a distant location is found by evaluating the integral. Examination of the result very close to the surface illustrates the analytical prediction that the pressure computed from the theorem at a field point interior to a radiating body will be the actual pressure, whereas the computed pressure at any interior point will be zero. Moreover, it goes on to presage the limiting form known as the Surface Helmholtz Integral Equation, which is the basis for several boundary element formulations. Finite length effects for radiation from a cylinder are assessed with a pair of examples, one for a line source and the other using the Helmholtz integral theorem. Once again, the objective of these examples is to demonstrate that one can employ their knowledge of fundamental concepts and the behavior of related systems to address issues that would not be accessible otherwise. This chapter closes with treatments of numerical techniques that are frequently used to evaluate radiation from nonstandard bodies, specifically source superposition, boundary elements, and finite elements.

Although the field generated by a piston embedded in a baffle is a type of acoustic radiation, it is treated separately in Chap. 8. This arrangement was chosen because analytical results are available for a wide range of parameters and locations, and also because the phenomena have much importance. Students tend to be motivated by the relevance of the results to their experiences. The standard topics are addressed, but extensive mappings of the entire field, which recall a classical computation, are seldom found in other texts. Seeing these properties helps students understand the rational for a simplified standard model and also serves to place the various specialized analyses on a common foundation. An example applies the radiation impedance formulas in combination with Fourier series analysis to evaluate the instantaneous power required to make a piston execute a square wave oscillation. Students interested in transducers find this example to be quite interesting.

The field within a waveguide is the subject of Chap. 9. First to be studied is the Webster horn equation for one-dimensional waveguides. The closure of this topic is an example that compares the analysis according to the WKB solution to a numerical analysis for the case of an extreme narrowing of the cross section. The discussion of these analyses, which shows that both have faults, is intended to encourage students to be critical of any results with which they are presented. The remainder of Chap. 9 is devoted to two-dimensional and three-dimensional rectangular and cylindrical waveguides. Modal decomposition of the pressure dependence transverse to the direction of propagation is a common thread. Special consideration is devoted to the analysis of waveguides whose walls are locally reactive. An example of the analysis of a two-dimensional waveguide whose walls are elastic plates has numerous interesting features, including a novel technique for identifying dispersion curves.

Chapter 10 is devoted to the sound field within an enclosed region. It begins by using the waveguide representation to explain the alternative descriptions of the field as a set of waves that propagate in multiple directions, or as a set of cavity modes that are standing waves. Both analytical descriptions are developed, with emphasis on the situations where each is best employed. An example uses an infinite series of cavity modes to describe the field within a two-dimensional rectangular enclosure due to a point source. Using the viewpoint of the method of images to assess the modal solution serves multiple purposes, including refreshing students' capabilities with earlier topics, recognizing that the selection of an analytical approach sometimes requires consideration of what one wishes to learn, and understanding of the computational issues that might arise when a modal description is used for highly localized excitations. The closure of this chapter describes two widely employed approximate treatments: the Rayleigh-Ritz method and an analysis based on Dowell's approximation. The former is often included in standard texts, but the latter is relatively recent.

Chapter 11 is devoted to geometrical acoustics. This is a rather thorough development of the subject, except for the exclusion of mean flow effects. The development begins with a discussion of the basic concepts associated with the description of rays and wavefronts. An example of reflection from a spherical mirror introduces the concept of a caustic. The initial development is limited to vertically stratified media, which is typified by a large body of water heated from above. Descriptions of the ray path and time of travel are derived as integrals. Examples consider a channel whose vertical sound speed varies quadratically with depth, and a channel whose sound speed profile was suggested as a prototype for studies of propagation in the ocean. The former leads to a sequence of foci with increasing range, whereas shadow zones and caustics are displayed for the latter sound speed profile. Surface reflections are shown to have a major effect. The treatment of vertically stratified fluids closes with discussions of how an eigenray may be determined and how energy conservation may be employed to analyze the amplitude dependence along a ray. The next part of Chap. 11 is devoted to ray tracing equations, which describe propagation through an arbitrary heterogeneity. The application of numerical methods to the solution of these equations, as well as the transport equation, is given a detailed development. The primary example for these topics analyzes refraction of a plane wave as it passes transversely through a cylindrical region in which the sound speed is a function of radial distance from the axis. The field is shown to contain a single caustic. A fine-scale scan shows that the wavefront is folded after it passes through the caustic, and the numerical evaluation of the transport equation shows the amplitude enhancement in the vicinity of the caustic. This chapter closes with the presentation of Fermat's principle. The calculus of variations is developed here in the context of a proof that the Euler-Lagrange equation derived from Fermat's principle is the same as the general ray tracing equations.

Scattering from bodies surrounded by a fluid is the subject of Chap. 12. The Born approximation is derived and employed to evaluate monostatic scattering of a plane wave at arbitrary incidence to a cylindrical region containing a second fluid. Rayleigh scattering and its relation to the Born approximation are the next topic. The metrics commonly sought from a scattering study, such as target strength, are discussed. After that, Kirchhoff scattering theory and its relation to geometrical acoustics are explored. This chapter closes with the application of spherical harmonics to analyze scattering from a rigid sphere and a spherical shell. These studies shed light on the transition from Rayleigh to Kirchhoff scattering, as well as the fundamental importance of fluid loading relative to elasticity.

Chapter 13 closes the textbook with an exploration of nonlinear acoustic analyses and phenomena. The bulk of the chapter is devoted to simple plane waves. The Riemann solution, which is derived by the method of characteristics, is used as the foundation for qualitative and quantitative explorations of the distortion of waveforms and spatial profiles. Graphical interpretations are given much attention. FFT analysis of waveforms in an example of a multiharmonic excitation is used to anticipate the Fubini-Ghiron analysis of frequency content. Identification of criteria that mark the existence of shocks is followed by derivation of the Rankine-Hugoniot relations for weak shocks. These conditions lead to the equal-area rule for fitting shock discontinuities to a waveform. A numerical algorithm for implementing the equal-area rule is developed and applied to monitor an initially harmonic signal from its inception to the old-age stage. This development goes on to apply the equal-area rule to follow propagation of an initial square wave, which ultimately leads to explanation of the phenomenon of acoustic saturation. A nonlinear wave equation is derived as the basis for study of multidimensional nonlinear waves. Its first usage leads to differential equations governing the position dependence of Fourier series coefficients for a plane wave. The effects of dissipation are incorporated into these equations, which are solved numerically. The solution illustrates how dissipation effects tend to work counter to nonlinear distortion effects. Perturbation analysis techniques for the nonlinear wave equation are developed on the foundation of plane waves and then extended to radially symmetric spherical waves. This chapter closes with a study of the waves that radiate from a periodically supported vibrating plate. One of the interesting results of that analysis is interpretation that rays rotate periodically based on the tangential particle velocity. The result is the formation of caustics that periodically move closer and farther from the plate. These phenomena are not observed in nonlinear plane waves nor in any type of linear acoustic wave.

Although the overriding precept of the text is that all topics must be fully explained as they arise, two appendices are provided for further assistance. One is devoted to derivation of the coordinate transformations and vector differential operators in spherical and cylindrical coordinates. The second describes Fourier transforms and their application. Fourier transforms are invoked in the body of the text only for a few topics. One such situation is the analysis of radiation from a cylinder whose vibration pattern varies arbitrarily in the axial direction. The means for lessening the importance of this mathematical tool is the numerical implementation of FFT concepts. Nevertheless, familiarity with Fourier transforms is an essential skill for advanced studies, as well as for understanding much of the technical literature. This recognition was the primary reason that this mathematical tool was included.

Allan Pierce, in the Preface to *Acoustics*, wrote that "…a deep understanding of acoustical principles is not acquired by superficial efforts." I fully agree with this statement, yet somewhat paradoxically believe that such understanding is accessible to all students. The key is the support afforded to the student by the instructor, textbook, and supporting materials. I cannot do much about the discourse between student and instructor, but I have done my best to address the formal foundation for instruction. It is up to you, the reader, to decide whether I have met my objectives.

Dunwoody, GA, USA Jerry H. Ginsberg

Acknowledgements

I am indebted to many individuals for providing motivation to write these books. Above all, neither would exist if I had not met my good friend, Allan Pierce, when I interviewed in 1980 for a professorship at the Georgia Institute of Technology. Working with him convinced me to extend my knowledge of acoustics beyond the specialized subject of nonlinear acoustics that was part of my early career. Over the years, our discussions were quite revelatory regarding where there were gaps in my knowledge of the subject. Furthermore, I hope he is not offended by this remark, but learning from, and then teaching from, his book convinced me of the necessity that I write *Acoustics—A Textbook for Engineers and Physicist.*

In the six-year interval during which I wrote these books what I needed most was assurance that the effort was worth pursuing. Some of my colleagues at Georgia Tech were quite supportive. Karim Sabra convinced me on several occasions that I would be filling an important need. Students solving the homework exercises should thank him because he suggested that the MATLAB code I used for the examples should be publically available. Pete Rogers provided extremely useful critical remarks for an early draft of my treatment of geometrical acoustics. My former Ph.D. students, especially J. Gregory McDaniel at Boston University and Kuangchung Wu at the NSWC Carderock Division of the Naval Sea Systems Command, were especially enthusiastic. I also am indebted to those attendees at many Acoustical Society of America meetings who I waylaid to discuss my writing efforts. They are too numerous to list, and I am sure that I have forgotten some names, but I greatly appreciate their attention. I owe Mark Hamilton of the University of Texas at Austin a special debt because he convinced me to participate in the ASA Book program under the aegis of Springer Publishing. Sara Kate Heukerott, my Editor at Springer, was quite understanding of my requests. Her expertise was a great aid as we assembled this project. Some might be surprised at the inclusion of my granddaughter, Leah Morgan Ginsberg, in the list of folks deserving recognition. Early in the writing stage, because she was a proficient clarinetist, I sought her assistance for the discussion of music in Chap. 1. Then at the conclusion, as she approached graduation from Georgia Tech in the

G. W. Woodruff School of Mechanical Engineering, from which I had retired, she served as my sounding board and spokeswoman for students when I deliberated how best to disseminate this work.

In addition to Leah's role, my family was essential to the effort. The forbearance of my wife, Rona, while I focused on writing, ignored other responsibilities, and forgot many things that I still cannot remember, astonishes me, even now that my efforts are over. She went through this experience before when I wrote my prior books on statics, dynamics, and vibrations. However, none of those experiences could have prepared her for the intensity and duration of the present effort. My sons, Mitchell and Daniel, had similar experiences when they lived at home. Although they and their wives, Tracie and Jessica, were not as strongly impacted now, I greatly appreciate their forbearance when I was not as communicative as I should have been. My granddaughters, Leah, Beth, and Abby, inspire me by their dedication to their own activities. I hope that recognition of the pleasure their Papa derived from creating these books will inspire them.

Dunwoody, GA, USA Jerry H. Ginsberg

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Volume I: Fundamentals

About the Author

Jerry H. Ginsberg began his technical education at the Bronx High School of Science, from which he graduated in 1961. This was followed by a B.S.C.E. degree in 1965 from the Cooper Union and an E.Sc.D. degree in engineering mechanics from Columbia University in 1970, where he held Guggenheim and NASA Fellowships. From 1969 to 1973, he was an Assistant Professor in the School of Aeronautics, Astronautics, and Engineering Science at Purdue University. He then transferred to Purdue's School of Mechanical Engineering, where he was promoted to Associate Professor in 1974. In the 1975–1976 academic year, he was a Fulbright-Hayes Advanced Research Fellow at the École Nationale Supérieure d'Électricité et de Mécanique in Nancy, France. He came to Georgia Tech in 1980 as a Professor in the School of Mechanical Engineering, which awarded him the George W. Woodruff Chair in 1989. He retired in June 2008. His prior publications include five textbooks in statics, dynamics, and vibrations, most in several editions, as well as more than one hundred and twenty refereed papers covering these subjects. Dr. Ginsberg became a Fellow of the Acoustical Society of America in 1987 and a Fellow of the American Society of Mechanical Engineers in 1989. The awards and recognitions he has received include Georgia Tech Professor of the Year (1994), ASEE Archie Higdon Distinguished Educator in Mechanics (1998), ASA Trent-Crede Medal (2005), ASME Per Bruel Gold Medal in Noise Control and Acoustics (2007), and the ASA Rossing Prize in Acoustics Education (2010). In addition to his technical activities, he is an exceptional photographer.

List of Examples