PRINCIPLES OF PHYSICS SERIES

AN INTRODUCTION TO ACOUSTICS

by

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PREFACE

Anyone who has thoughtfully taught the subject of acoustics for any length of time must surely be struck by the basic nature of the material, both in the fields of pure and of applied physics. For the student who has completed a general college course in physics there is hardly a better starting point for more advanced study. A course in acoustics very naturally begins with a study of vibrations, as preliminary to the introduction of the wave equations. It is impossible to overemphasize the importance of the two subjects — vibrations and waves — to all branches of physics and engineering. In addition, there are distinct advantages in first discussing waves of the mechanical type, rather than electromagnetic waves, with their more abstract nature and added subtleties.

Of growing importance during the last ten or twenty years is the very fruitful use of electrical analogs in acoustics. Electrical engineers are most aware of the extreme usefulness of the analog method, particularly in problems originating during World War II. In a book of this type no attempt can be made to give a complete treatment, even in the field of acoustics alone, of the use of analogs taken from electrical circuits. However, the author believes that so useful a tool in this and other branches of physics and engineering should be given more attention than is ordinarily afforded in an intermediate text.

In connection with these more quantitative aspects of the subject, it might be said that the great difficulty of setting down the features of most actual acoustical problems in precise mathematical form is of great instructive value to the physics student. Coming fresh from more elementary courses, where the problems supply just the necessary data to achieve the exact answer, he may be appalled at the extent to which approximations *must* be made to get any kind of an answer at all in acoustical problems. Experience of this kind is good preparation for the later practical use of, say, electromagnetic field equations which involve complicated boundary conditions, where the mathematical problems are very similar. A course in acoustics may incidentally serve to discourage a pure mathematician, to whom some of the approximations of physics are anathema, from entering upon a career unsuited to his temperament and point of view.

The average undergraduate is greatly interested in many of the more popular and applied features of the subject. Among these are the physics of musical instruments, peculiarities of hearing, the design of radio loudspeakers, some consideration of electronic devices as used in electroacoustical equipment, the acoustics of auditoriums, etc. As one whose interest in acoustics was originally aroused, in part, by a love of music, the author believes no text in acoustics should omit some reference to these subjects, which are as essential in their way as a consideration of the wave equations.

There are a number of elementary books on acoustics published in this country, of which Colby and Watson are good examples. Above this level there is quite a choice of specialized books on the engineering or graduate level. By far the most original and thoughtful general book on acoustics is Morse's *Vibration and Sound*. While of considerable use as a reference, this book is too difficult as a whole for undergraduate use. Chapter 5 has drawn generously upon certain parts of Morse. Mention should also be made of *Acoustic Measurements* by L. L. Beranek, an excellent survey of modern experimental techniques in acoustics. In Chapter 10 frequent reference is made to Beranek's work. There is practically no book available at the intermediate level except for the British imports, and it is hoped that the present book will help to fill the gap.

A year of college physics and a year of calculus constitute a minimum preparation for the subject as presented here. A previous knowledge of the complex notation, as used in a.c. circuit analysis, would be helpful, but Chapter 5 contains a summary of the essential material sufficient to the understanding of the text. While the book has been written mainly for undergraduates in physics, it is believed that engineering students who may later wish to specialize in communications and electroacoustics would greatly profit from a basic course using this kind of book.

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INTRODUCTION

There is no branch of classical physics that is older in its origins and yet more modern in its applications than that of acoustics. As long ago as the time of Galileo, quantitative experiments were performed on the vibrations of strings and the sound that is so produced. Boyle, Hooke, and Newton were interested in sound, and Newton undertook to compute, theoretically, its speed. Later on, the great mathematicians Laplace, Euler, d'Alembert, Bernoulli, Lagrange, and Poisson laid the bases for what was to become the general subject of hydrodynamics, although there was a great scarcity of experimental data with which to test their conclusions. In the nineteenth century, the results of the experiments of Doppler, Kundt, Kelvin, and others added to the growing body of the subject. Helmholtz, that Leonardo da Vinci of modern times, wrote his monumental work, the *Sensations of Tone*, largely from the physiological approach. Late in the nineteenth and during the early twentieth century, finishing touches to the already elegant formulation of the mechanics of sound propagation were added by Rayleigh and Lamb, whose writings on the subject have become "standard" treatises.

Along with this continuous scientific preoccupation with the problems of acoustics has gone a very lively interest, among laymen as well as among scientists, in the more qualitative aspects of the subject. Musicians are closer to science than they perhaps realize when they play musical instruments and wonder as to the quality of the sound flowing from them. Laymen of all kinds are interested in speech and song, music and noise. These are, it would appear, permanent interests which will probably persist, even with the competing glamour of the atom and its nucleus!

With the beginning of the twentieth century it would have been safe to say that the subject of acoustics was as nearly complete as it would ever be. Even were this so, a study of acoustics would still be a "must" for the proper understanding of the great body of related scientific literature. Vibrations, whether connected with strings and diaphragms or with subatomic oscillators radiating electromagnetic waves, are all of a kind, and to understand the one type is a great help towards understanding the other. In addition, the "fields" of sound and the "fields" of electromagnetic radiation are kindred in more ways than one, with the former a preferred starting point from the standpoint of concreteness and simplicity.

Two developments in the field of applied acoustics have given impetus, in recent years, to further study and growth of the subject. The first is the rise of a whole new industry, devoted to the realistic reproduction of speech and music through the mediums of the radio and the phonograph.

The second, less beneficent in nature, arose as the result of war needs, both in the field of undersea signaling and in connection with problems in aeronautics. As so often occurs when interest in a subject revives, other fields, like those of medicine and pure physics, have been stimulated to make use of new tools and new refinements of the older theoretical work. Thoughtful comparison between acoustics and other branches of physics and engineering has brought to light little realized interrelations, of great use to all fields concerned. The electrical circuit analogs discussed in Chapter 5 are a good example of this.

As an introduction to a logical presentation of the subject, a broad outline of the scope of acoustics, together with a certain definition of terms, will be helpful.

I–1 Sound vs acoustics. In the strict sense, the word *sound* should be used only in connection with effects directly perceivable by the human ear. These effects are ordinarily due to the wave motion set up in air by the vibration of material bodies, the frequencies which are audible to the ear being in the approximate range of 30 to 15,000 cycles/sec. In this book we shall consider the word *sound* to cover the entire wave phenomena in air of this frequency range and we shall use it as a qualifying adjective in connection with such wave properties as "particle displacement," "excess pressure," and the like. Whenever the frequencies are well outside the above range, we shall call the disturbance a longitudinal *wave*, rather than a sound. Waves set up in media other than air we shall also not call sound, since the ear is not ordinarily capable of responding to this type of energy directly. Waves set up within solid rods, crystals, etc., are of this type.

For no very good reason, the word *acoustics*, originally associated with the sound properties of rooms, auditoriums, etc., has been broadened to include almost the whole field of mechanical vibration and waves, whether of audible frequencies or not, and without regard to the medium. While the emphasis is still on what can be heard, many of the most interesting recent applications in acoustics are concerned with a range of frequencies well outside the audible range, particularly in the ultrasonic (high-frequency) region. Some of these applications will be discussed later in this book.

I–2 Vibrating bodies. Before there can be sound waves in air, there must be vibration of some material body. The character of the sound is so dependent upon the nature of this vibration that a careful study of the possible kinds of vibration is imperative. The simplest type of vibration to discuss is that of an idealized particle. Under certain special conditions, as will be seen, actual sound sources may be discussed as if they were particles. More often than not, due to the complexity of shape and motion of actual sound sources, such a simple picture is inadequate. Nevertheless, a consideration of particle vibration theory is basic to the understanding of the more complicated motions of extended bodies such as strings, bars, plates, etc., to be considered later.

I–3 Frequency. The *frequency* of a vibrating source of sound is the repetition rate of its periodic motion, assuming this to be simple harmonic. It is usually specified in cycles per unit time. In the wave phenomenon set up in the air, frequency refers to the vibration rate of layers of air, and is to be distinguished from *pitch*, a word used to describe the subjective sensation perceived by the listener. The sensation of pitch is a psychophysiological matter and is only imperfectly understood. As we shall see in Chapter 9, the relation between frequency and pitch is a complicated one. The range of frequencies to which a young, healthy ear will respond is enormous, from possibly as low as 15 cycles/sec. to as high as 20,000 cycles/sec. The ear is by no means of equal sensitivity over this frequency range, but in studying the complex thing called musical sound and in designing modern electrical and electromechanical apparatus to reproduce this sound, we must cover the extremes of the frequency range of the ear. The design of such equipment is difficult, as we shall see, and it is only recently that any considerable success has been achieved.

I–4 Amplitude. The *amplitude* of any vibratory motion has the usual meaning associated with simple harmonic motion, i.e., the maximum excursion from the mean central position. Such amplitudes may refer to the motion of the source, the motion of the receiver of the sound, or the motion of the layers of air where the wave exists. Everyone knows how a motion of small amplitude over a sufficiently large area may give rise to tremendous sound disturbances. At the receiving end, whether it be at the ear or at a microphone, amplitudes may be unbelievably small. An amplitude of motion of the air of 10^{-8} cm is by no means the least to which the ear will respond.

I–5 Waves. It is one peculiarity of a fluid like air, with little or no resistance to shear, that only longitudinal waves may be propagated. All disturbances of any other nature will tend to disappear at a small distance from the source. A consideration of the elastic and inertial properties of the medium leads to a beautiful and complete theory of longitudinal wave propagation which is useful as well as elegant. The great difficulty with the differential equations for sound waves is in obtaining all the details of particular solutions to practical problems. Sound sources are rarely simple or symmetrical in shape, and the irregularities in contour introduce serious trouble. Useful solutions *may* be obtained, if one is willing to accept certain approximations. As always, approximations are dangerous and must be made with the utmost care, keeping in mind the essential physics of the problem. The results of this process might appear to be crude in many cases, but the student should appreciate that the ear itself is, fortunately for the analyst, a rather crude device, incapable under ordinary conditions of detecting discrepancies of less than 10% to 20%.

I–6 Wavelength. Frequency in the wave. For disturbances of a simple harmonic nature, the *wavelength* is the distance, at any one instant, between adjacent wave crests. The frequency, within the body of the wave disturbance, may be defined as the number of crests passing any one point in space per unit time, and is ordinarily the same as the frequency of vibration of the source of the wave disturbance. If the source is not stationary with respect to the medium, the frequency in the wave is not the same as that of the source. This is a situation that is one cause of the well-known Doppler effect.

I–7 The principle of superposition. It is a general property of many mechanical systems that when two different types of motion are impressed simultaneously, the resultant total motion may be described as the sum effect of the two motions considered independently. This is one statement of the Superposition Theorem. It is a very broad principle in physics. The student of elementary physics has seen the general principle applied many times in connection with such subjects as the composition of force vectors, the summing up of assorted emf's in electrical circuits, the interference effects in light, etc. It will be a correct principle to use whenever the system is "linear," that is, whenever its behavior may be accurately described by a linear differential equation. The vibrations of material bodies and of the particles in a deformable medium like air obey such equations, provided the amplitudes of motion are small. Fortunately, this is usually so in acoustics. We shall make frequent use of the Superposition Theorem throughout this book.

I–8 Energy density. Intensity in the wave. The average energy per unit volume in the medium, due to the presence of a wave, is called the *energy density*. The *intensity* in the wave is defined as the energy flow, per unit time and per unit area, across an area taken normally with respect to the direction of wave propagation. Energy density and intensity are simply related through the velocity of wave propagation. Both these quantities may be computed from measurements made with suitable laboratory instruments, whose operation depends in no way upon the properties of the ear. The student is cautioned not to use the word "loudness" as synonymous with "intensity." The loudness of a sound, in the language of acoustics today, is a measure of the purely subjective sensation arising when a sound wave strikes the ear. The exact relationship between loudness and intensity is difficult to determine, as one would expect; the student is referred to Chapter 9 for a further discussion of this matter. (We are using "loudness" here in the purely qualitative sense. We shall later refer to the loudness *level*, a numerical measure of loudness which is defined directly in terms of the *pressure* in the wave disturbance, rather than the intensity.)

The familiar unit, the *decibel*, is fundamentally a quantitative measure of *relative* (not absolute) *intensity*, and is used to compare one sound intensity with another. The decibel scale is defined in a logarithmic manner, as will be seen in Chapter 2, to conform to the approximately logarithmic behavior of the ear. Its exact meaning and use will be made clear when it is needed.

I-9 Sound "quality." The *quality* of a musical note, as played on some instrument, or coming from a singer's throat, is a most important characteristic, connected, in part, with the physiological, the psychic, and the aesthetic in the listener. From a purely objective point of view, it has been common to explain quality as due solely to the number and prominence of the steady-state harmonic overtones. There are other factors to be considered, however. Recent studies by Fletcher have revealed the importance of the *transient* period of vibration, the time during which the instrument and sound vibrations are building up or dying down. There is even evidence that it is during the transient period of "attack," for instance, that a violin is recognized as such, rather than as, say, a cello. The ear will apparently tend to confuse the two instruments when a sustained note is being played.

I-10 The use of electrical analogs. While it is somewhat in the nature of a digression in the logical development of the subject, the discussion of sound waves along classical lines will be followed by a brief introduction to the electrical analog method as applied to acoustics, with chief emphasis upon the concept of "acoustic radiation impedance." Applied with equal success in the subject of electromagnetic radiation, this idea, borrowed from a.c. circuit theory, is of especial aid in predicting the total radiation of power from a given sound source. It is of considerable assistance in the design of aperiodic radiators, like radio loudspeakers, where the problem is too difficult for complete analysis by means of the classical wave equations.

I-11 Waves in solids. Plane longitudinal waves set up in solids are very similar to such waves in air, with, of course, different elastic and inertial factors. Unlike gases and liquids, solids, with their resistance to shear, can sustain transverse vibrations. The simplest of all transverse vibrations for an extended body are those of the ideal flexible string, whose standing wave characteristics are so important to all stringed instruments. In fact, a discussion of string vibrations leads quite naturally to a consideration of some design features of the violin, the piano, etc. In only a few cases, in particular for the piano, is the mathematics capable of predicting the intensity of some of the more important harmonics that are so essential to the quality of the emitted sound. The great difficulty in precisely describing the initial conditions, when the string is struck, plucked, or bowed, as the case may be, is the main stumbling block to exact analysis. When it is realized that not only the string properties but also the shape and complex characteristics of the body of the instrument greatly determine the nature of the radiated sound, one is ready to accept the fact that the design of a high quality musical instrument is as much a matter of art as of science.

The problems of the vibration of membranes, bars, and plates become progressively more complicated. The more important general features of such motions will be discussed in Chapter 7.

I–12 Experimental technique. Sound measurements are some of the more difficult in experimental physics. While sensitive linear microphones and associated electronic amplifiers are now available, there are always two major difficulties with their use in a "field" of sound. First, there is the precise, absolute calibration of the equipment over a wide range of sound frequencies and intensities. Second, there is the disturbing effect that any detection device whose dimensions are comparable to the wavelength of the sound introduces upon the field of sound itself. The errors involved are somewhat similar to the potential errors encountered in the use of a voltmeter; one would like to measure the potentials existing *before* connecting the meter! In addition, the standing wave patterns set up in any ordinary room make impossible any accurate measurement of the true radiation properties of the source itself. One is then driven either to outdoor experiments or to building very elaborate and expensive sound rooms with especially treated wall surfaces and complicated structural supports. These and other difficulties will be discussed in the chapter on experimental methods.

I–13 Applied acoustics. Much of the renewed interest in acoustics has come from the applied field. Music has long felt itself an art to be insulated as far as possible from the mechanics of science. Yet the advent of "canned" music, deplored by so many musicians, has stimulated the scientific study of the quality of sound to the point where it is deemed possible to create new instruments having tonal qualities undreamed of by the old masters. It is true that thus far the instruments born of modern