The Wave Theory of Sound

Excerpts from Chapter 1 of

Acoustics: An Introduction to Its Physical Principles and Applications

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Acoustics is the science of sound, including its production, transmission, and effects. In present usage, the term *sound* implies not only phenomena in air responsible for the sensation of hearing but also whatever else is governed by analogous physical principles. Thus, disturbances with frequencies too low (*infrasound*) or too high (*ultrasound*) to be heard by a normal person are also regarded as sound. One may speak of underwater sound, sound in solids, or structure-borne sound. Acoustics is distinguished from optics in that sound is a mechanical, rather than an electromagnetic, wave motion.

The broad scope of acoustics as a area of interest and endeavor can be ascribed to a variety of reasons. First, there is the ubiquitous nature of mechanical radiation, generated by natural causes and by human activity. Then, there is the existence of the sensation of hearing, of the human vocal ability, of communication via sound, along with the variety of psychological influences sound has on those who hear it. Such areas as speech, music, sound recording and reproduction, telephony, sound reinforcement, audiology, architectural acoustics, and noise control have strong association with the sensation of hearing. That sound is a means of transmitting information, irrespective of our natural ability to hear, is also a significant factor, especially in underwater acoustics. A variety of applications, in basic research and in technology, exploit the fact that the transmission of sound is affected by, and consequently gives information concerning, the medium through which it passes and intervening bodies and inhomogeneities. The physical effects of sound on substances and bodies with which it interacts present other areas of concern and of technical application.

Some indication of the scope of acoustics and of the disciplines with which it is associated can be found in Fig. 1-1 . The first annular ring depicts the traditional subdivisions of acoustics, and the outer ring names technical and artistic fields to which acoustics may be applied. (The chart is not intended to be complete, nor should any rigid interpretation be placed on the depicted proximity of any subdivision to a technical field. A detailed listing of acoustical topics can be found in the index classification scheme reprinted with the index of each volume of the *Journal of the Acoustical Society of America*.)

A LITTLE HISTORY

The speculation that sound is a wave phenomenon grew out of observations of water waves. The rudimentary notion of a *wave* is an oscillatory *disturbance* that moves away from some source and transports no discernible amount of matter over large distances of *propagation*. The possibility that sound exhibits analogous behavior was emphasized, for example, by the Greek philosopher Chrysippus (c. 240 B.C.), by the Roman architect and engineer Vetruvius (c. 25 B.C.), and by the Roman philosopher Boethius (A.D. 480-524). The wave interpretation was also consistent with Aristotle's

(384-322 B.C.) statement to the effect that air motion is generated by a source, "thrusting forward in like manner the adjoining air, to that the sound travels unaltered in quality as far as the disturbance of the air manages to reach."

A pertinent experimental result, inferred with reasonable conclusiveness by the early seventeenth century, with antecedents dating back to Pythagoras (c. 550 B.C.) and perhaps further, is that the air motion generated by a vibrating body sounding a single musical note is also vibratory and of the same frequency as the body. The history of this is intertwined with the development of the laws for the natural frequencies of vibrating strings and of the physical interpretation of musical consonances. Principal roles were played by Marin Mersenne (1588-1648), a French natural philosopher often referred to as the "father of acoustics," and by Galileo Galilei (1564-1642), whose *Mathematical Discourses Concerning Two New Sciences* (1638) contained the most lucid statement and discussion given up until then of the frequency equivalence.

Mersenne's description in his *Harmonic universelle* (1636) of the first absolute determination of the frequency of an audible tone (at 84 Hz) implies that he already demonstrated that the absolute-frequency ratio of two vibrating strings, radiating a musical tone and its octave, is as 1 : 2. The perceived harmony (consonance) of two such notes would be explained if the ratio of the air oscillation frequencies is also 1 : 2, which in turn is consistent with the source-air-motion-frequency-equivalence hypothesis.

The analogy with water waves was strengthened by the belief that air motion associated with musical sounds is oscillatory and by the observation that sound travels with a finite speed. Another matter of common knowledge was that sound bends around corners, which suggested diffraction, a phenomenon often observed in water waves. Also, Robert Boyle's (1640) classic experiment on the sound radiation by a ticking watch in a partially evacuated glass vessel provided evidence that air is necessary, either for the production or transmission of sound.

The wave viewpoint was not unanimous, however. Gassendi (a contemporary of Mersenne and Galileo), for example, argued that sound is due to a stream of "atoms" emitted by the sounding body; velocity of sound is the speed of atoms; frequency is number emitted per unit time.

The apparent conflict between ray and wave theories played a major role in the history of the sister science optics, but the theory of sound developed almost from its beginning as a wave theory. When ray concepts were used to explain acoustic phenomena, as was done, for example, by Reynolds and Rayleigh, in the nineteenth century, they were regarded, either implicitly or explicitly, as mathematical approximations to a then well-developed wave theory; the successful incorporation of geometrical optics into a more comprehensive wave theory had demonstrated that viable approximate models of complicated wave phenomena could be expressed in terms of ray concepts. (This recognition has strongly influenced twentieth-century developments in architectural acoustics, underwater acoustics, and noise control.)

The mathematical theory of sound propagation began with Isaac Newton (1642-1727), whose *Principia* (1686) included a mechanical interpretation of sound as being "pressure" pulses transmitted through neighboring fluid particles. Accompanying diagrams (see Fig. 1-2) illustrated the diverging of wave fronts after passage through a slit. The mathematical analysis was limited to waves of constant frequency, employed a number of circuitous devices and approximations, and suffered from an incomplete definition of terminology and concepts. It was universally acknowledged by his successors as difficult to decipher, but, once deciphered, it is recognizable as a development consistent with more modern treatments. Some textbook writers, perhaps for pedagogical reasons, stress that Newton's one quantitative result that could then be compared with experiment, i.e., the speed of sound, was too low by about 16 percent. The reason for the discrepancy and how it was resolved is discussed below (Sec. 1-4 of Pierce's book), but it is a relatively minor aspect of the overall theory, whose resolution required concepts and experimental results that came much later.

Substantial progress toward the development of a viable theory of sound propagation resting on firmer

mathematical and physical concepts was made during the eighteenth century by Euler (1707-1783), Lagrange (1736-1813), and d'Alembert (1717-1783). During this era, continuum physics, or field theory, began to receive a definite mathematical structure. The wave equation emerged in a number of contexts, including the propagation of sound in air. The theory ultimately proposed for sound in the eighteenth century was incomplete from many standpoints, but modern theories of today can be regarded for the most part as refinements of that developed by Euler and his contemporaries.

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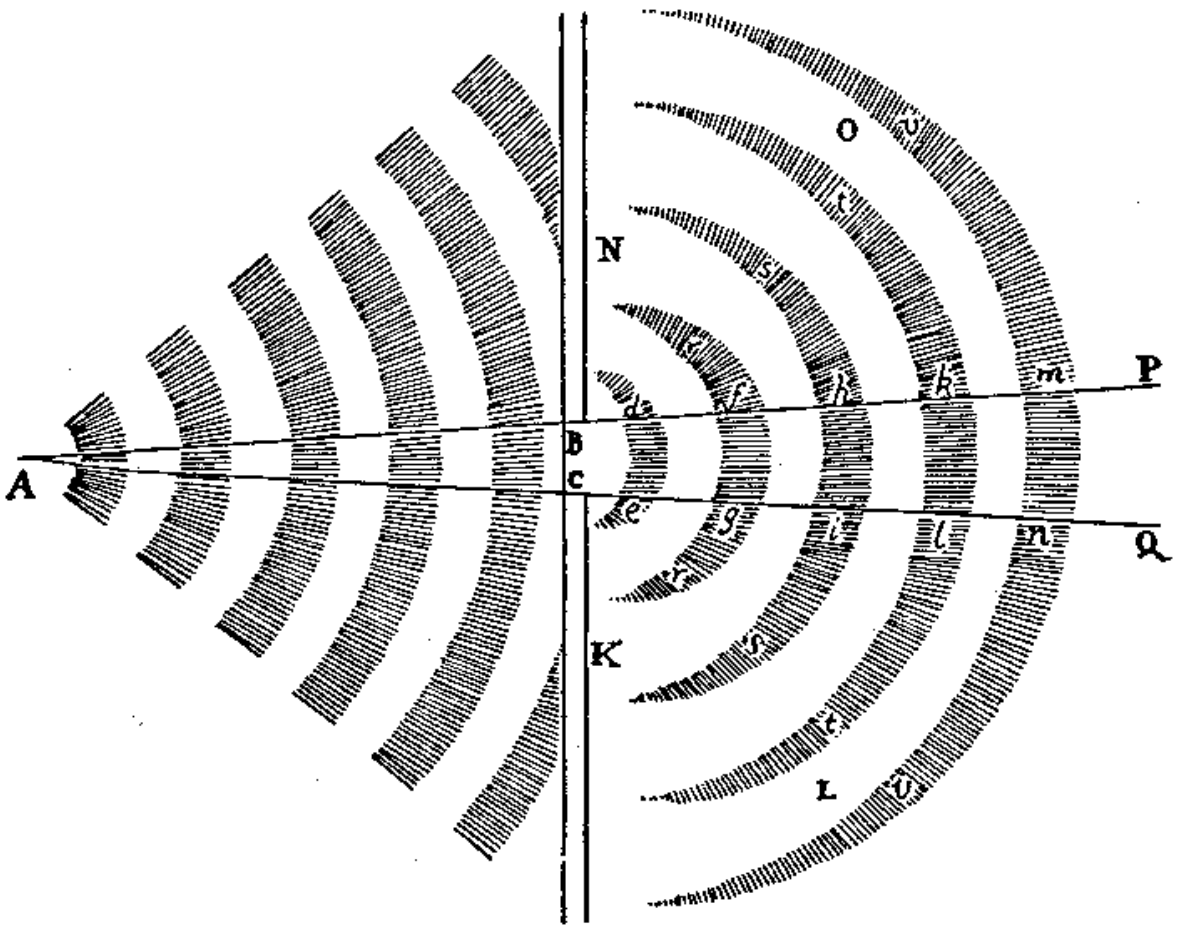

Figure 1-2 Sketch in Newton's *Principia* (1686) of the passage of waves through a hole. The source is at point *A*; the hole is described by points *B* and *C*; *de, fg, hi,* etc., describe the "tops of several waves, divided from each other by as many intermediate valleys or hollows." *(Adapted from Sir Isaac Newton's Principia, 4th ed., 1726, reprinted 1871, by MacLehose, Glasgow, p. 359.)*