PRINCIPLES OF ACOUSTICS

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Contents

Summary

The chapter begins with a brief history of acoustics from Pythagoras to the present times. Then the main physical and mathematical principles on acoustics are reviewed. A general description of waves is given first, then the characteristics of sound and some of the most common phenomena related to acoustics like echo, diffraction and the Doppler effect are discussed. Next, the human ear is described in detail. Finally some applications are explained.

1. Introduction

Acoustics is the science of sound: its production, transmission, detection and all of its effects. The scope of acoustics is not limited to those phenomena that can be heard by humans and animals, but includes all phenomena that are governed by the same physical principles. For example, disturbances with frequencies so low (infrasound) or so high (ultrasound) that cannot be heard by a normal person are also considered sound. Sound is a vibration that travels through a substance; it is a wave that propagates in a material medium. Electromagnetic waves do not need a material medium to propagate, and do not behave like sound.

Most of our daily experience with acoustics is involuntary. Disturbances produced by nature and by human activity travel continuously around us: in the air, in the water and in solids. Some of these perturbations are heard as noise, others are agreeable to our ear, and others are not heard but felt as vibrations. There are sounds produced voluntarily for communication or for pleasure. 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.

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. The physical effects of sound on substances and bodies with which it interacts present other areas of concern and of technical application.

2. History

Humankind has been concerned about sound for as long as it asked itself questions about the world that surrounds it. However the science of acoustics that we know, started with Pythagoras during the sixth century B. C. As opposed to light, sound has always been considered a wave. The Pythagoreans believed that all phenomena were manifestations of Mathematics. Their contributions to acoustics were basically related to the musical intervals called harmonics. The octave, the fifth and the fourth were identified with ratios of simple numbers supporting their mathematical doctrine. They also suggested musical harmony in the organization of celestial bodies. It is believed that Pythagoras (550 B. C.) invented the monochord, and was the first to establish an inverse proportionality between the length of a vibrating string and the pitch of the sound produced. He claimed that a vibrating body would produce a vibration of the same frequency in the surrounding air. The first musical scale of the western world comes also from the Pythagorean School.

The speculation, that sound is a wave phenomenon grew out of observations of water waves. 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.

A major role in the development of laws for the natural frequencies of the vibrating strings was played by Marin Mersenne (1588-1648), a French natural philosopher often referred to as the "father of acoustics". In his *Harmonie Universelle* (1636) Mersenne describes the first absolute determination of the frequency of an audible tone (at 84 Hz). This 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.

In 1638, Galileo Galilei (1564-1642) published the *Mathematical Discourses Concerning Two New Sciences* that contained the most lucid statement and discussion given up until then of the frequency equivalence.

The analogy with water waves was strengthened by the belief that the 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. 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.

However, 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 the number of atoms emitted per unit time.

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. The mathematical analysis was limited to waves of constant frequency and was universally difficult to decipher. However, once deciphered, it is consistent with more modern treatments.

Newton determined theoretically the speed of sound. His proposition that sound speed could be not only measured but also calculated was a major contribution. However his result was about 16% less because he assumed an isothermal (constant temperature) instead of an adiabatic (no heat exchange) process.

During the eighteenth century, substantial progress was made by Euler (1707-1783) and

Lagrange (1736-1813) toward the development of a theory of sound propagation based on firmer mathematical and physical concepts. The wave equation emerged in a number of contexts, including the propagation of sound in air. Modern theories can be regarded as refinements of those developed by Euler and his contemporaries.

In 1826, J.D. Colladon and J.K.F. Sturm measured the velocity of sound in Lake Geneva. In 1880-1881 J. P. Curie discovered the connections between pressures applied to certain crystals and their resulting electric fields (piezoelectricity).

Reynolds and Rayleigh used Ray concepts to explain acoustic phenomena, in the nineteenth century. Rays were regarded as mathematical approximations to a then well-developed wave theory. The successful incorporation of geometrical optics into wave theory had demonstrated that 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 use of magnetostrictive and piezoelectric devices to produce ultrasound at controllable frequencies started in the 1900. In. 1915 P. Langevin used a magnetostrictive device and later a quartz piezoelectric device to radiate sound into water. Submarine detection became thus possible.

Sabine (1895), considered the father of modern acoustical architecture, studied the reverberation processes in closed amphitheaters, and determined the variables that influence the intelligibility of words. He determined the effect of absorption coefficients in the sonority of theaters.
At about the same period, Helmholtz studied the process of resonance in tubes and the physiological and psychological effects of the tone on humans.

Between 1925 and 1950 G. von Bekesy applied for the first time the principles of physics in a prolonged experimental study of the operations of the ear (Nobel Prize in Physiology, 1961).

The discovery in the early forties of the "SOFAR channel" that confines sounds to a thin layer within the ocean, made possible very long-range sound communication in the ocean. In 1958, J. MacVickar, I. Donald, and T.G. Brown used ultrasound to examine a fetus. The first cochlear implants started in the 60’s (A.S. House and F.B. Simmons). Ray tracing and other sophisticated signal processing techniques were put into wide use at the same time. By 1975 the use of ultrasound to image fetus, kidneys, brain and other internal organs was widespread.

Since 1985 focused shock waves are used to break up kidney stones and gallstones.

3. Basic Concepts

3.1. What is Sound?

Sound is the periodic variation of pressure produced by the vibration of any material medium: gas, liquid or solid. Sound cannot travel in a vacuum. The vibration of the medium can be the result of a vibrating solid like in a drum or a bell, or can be produced by motions in the medium like noise generated by a very fast flow. There is a coordinated motion, and the individual molecules of the substance vibrate. Each molecule hits another, transmits energy and returns to its original position. The result is that regions of the medium become alternately more dense (condensations), and less dense (rarefactions) as energy is propagated. This wave is called longitudinal because the direction of vibration of the molecules is the same as the direction of propagation of the wave.

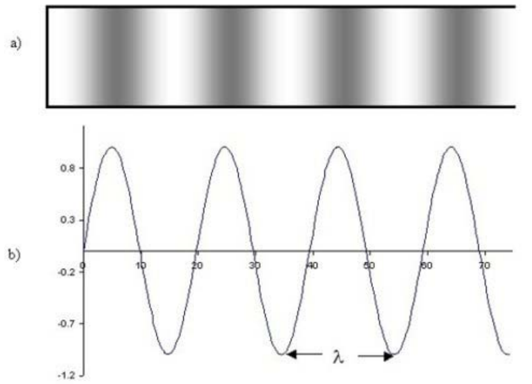

Figure 1. a). A sound wave is composed of alternating zones where the material medium becomes more dense (condensations) and less dense (rarefactions). The individual molecule oscillates in the direction of propagation of the wave. b) A graph of pressure as a function of position gives a sine wave

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Biographical Sketches

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