the last 15 years on noise control, much of which is listed in Appendix III of this reprint, is not too formidable to peruse. Finally, I have made corrections to all the known errata in the book.

I wish to thank the Acoustical Society of America for their interest in reprinting *Acoustics*. I hope their faith in this portion of the acoustical literature is substantiated by the assistance it may give students and engineers in learning and practicing in the field of electroacoustics.

Leo L. Beranek
June 1986

CHAPTER 1

INTRODUCTION AND TERMINOLOGY

PART I *Introduction*

1.1. A Little History. Acoustics is entering a new era—the precision-engineering era. One hundred years ago acoustics was an art. For measuring instruments, engineers in the field used their ears primarily. The only controlled noise sources available were whistles, gongs, and sirens. Microphones consisted of either a diaphragm connected to a mechanical scratcher that recorded the shape of the wave on the smoked surface of a rotating drum or a flame whose height varied with the sound pressure. About that time the great names of Rayleigh, Stokes, Thomson, Lamb, Helmholtz, König, Tyndall, Kundt, and others appeared on important published papers. Their contributions to the physics of sound were followed by the publication of Lord Rayleigh's two-volume treatise, "Theory of Sound" (1877 and 1878). Acoustics rested there until W. C. Sabine, in a series of papers (1900–1915), advanced architectural acoustics to the status of a science.

Even though the contributions of these earlier workers were great, the greatest acceleration of interest in the field of acoustics followed the invention of triode-vacuum-tube circuits (1907) and the advent of radio-broadcasting (1920). With vacuum-tube amplifiers available, loud sounds of any desired frequency could be produced, and the intensity of very faint sounds could be measured. Above all it became feasible to build measuring instruments that were compact, rugged, and insensitive to air drafts.

The progress of communication acoustics was hastened, through the efforts of the Bell Telephone Laboratories (1920*ff*), by the development of the modern telephone system in the United States.

Architectural acoustics received a boost principally from the theory and experiments coming out of Harvard, the Massachusetts Institute of Technology, and the University of California at Los Angeles (1930–1940), and several research centers in England and Europe, especially Germany.

In this period, sound decay in rectangular rooms was explained in detail, the impedance method of specifying acoustical materials was shown to be useful, and the computation of sound attenuation in ducts was put on a precise basis. The advantages of skewed walls and of using acoustical materials in patches rather than on entire walls were demonstrated. Functional absorbers were introduced to the field, and a wider variety of acoustical materials came on the market.

The science of psychoacoustics was also developing. At the Bell Telephone Laboratories, under the splendid leadership of Harvey Fletcher, the concepts of loudness and masking were quantified, and many of the factors governing successful speech communication were determined (1920–1940). Acoustics, through the medium of ultrasonics, entered the fields of medicine and chemistry. Ultrasonic diathermy was being tried, and acoustically accelerated chemical reactions were reported.

Finally, World War II came, with its demand for the successful detection of submerged submarines and for highly reliable speech communication in noisy environments such as aircraft and armored vehicles. Great laboratories were formed in England, Germany, France, and in the United States at Columbia University, Harvard, and the University of California to deal with these problems. Research in acoustics reached proportions undreamed of a few years before and has continued unabated.

Today, acoustics is passing from being a tool of the telephone industry, a few enlightened architects, and the military into being a concern in the daily life of nearly every person. International movements are afoot to legislate and to provide quiet housing. Labor and office workers are demanding safe and comfortable acoustic environments in which to work. Architects in rapidly increasing numbers are hiring the services of acoustical engineers as a routine part of the design of buildings. In addition there is the more general need to abate the great noise threat from aviation—particularly that from the jet engine, which promises to ruin the comfort of our homes. Manufacturers are using acoustic instrumentation on their production lines. Acoustics is coming into its own in the living room, where high-fidelity reproduction of music has found a wide audience.

This book covers first the basic aspects of acoustics: wave propagation in the air, the theory of mechanical and acoustical circuits, the radiation of sound into free space, and the properties of acoustic components. Then follow chapters dealing with microphones, loudspeakers, enclosures for loudspeakers, and horns. The basic concepts of sound in enclosures are treated next, and practical information on noise control is given. The text deals finally with measurements and psychoacoustics. Throughout the text we shall speak to *you*—the student of this modern and interesting field.

1.2. What Is Sound? In reading the material that follows, your goal should be to form and to keep in mind a picture of what transpires when the diaphragm on a loudspeaker, or any surface for that matter, is vibrating in contact with the air.

A sound is said to exist if a disturbance propagated through an elastic material causes an alteration in pressure or a displacement of the particles of the material which can be detected by a person or by an instrument. Because this text deals primarily with devices for handling speech and music, gases (more particularly, air) are the only types of elastic material with which we shall concern ourselves. Fortunately, the physical properties of gases are relatively easy to express, and we can describe readily the nature of sound propagation in such media.

Imagine that we could cut a tiny cubic "box" out of air and hold it in our hands as we would a block of wood. What physical properties would it exhibit? First, it would have weight and, hence, mass. In fact, a cubic meter of air has a mass of a little over one kilogram. If a force is applied to it, the box will then accelerate according to Newton's second law, which says that force equals mass times acceleration.

If we exert forces compressing two opposing sides of the little cube, the four other sides will bulge outward. The incremental pressure produced in the gas by this force will be the same throughout this small volume. This obtains because pressure in a gas is a scalar, *i.e.*, a nondirectional quantity.

Imagine the little box of air to be held tightly between your hands. Still holding the box, move one hand forward so as to distort the cube into a parallelepiped. You find that no opposition to the distortion of the box is made by the air outside the two distorted sides. This indicates that air does not support a shearing force.†

Further, if we constrain five sides of the cube and attempt to displace the sixth one, we find that the gas is elastic; *i.e.*, a force is required to compress the gas. The magnitude of the force is in direct proportion to the displacement of the unconstrained side of the container. A simple experiment will convince you of this. Close off the hose of an automobile tire pump so that the air is confined in the cylinder. Push down on the plunger. You will find that the confined air behaves as a simple spring.

The spring constant of the gas varies, however, with the method of compression. A force acting to compress a gas necessarily causes a displacement of the gas particles. The incremental pressure produced in the gas will be directly proportional to the incremental change in volume. If the displacement takes place slowly one can write

$$\Delta P = -K\,\Delta V \qquad \text{slow process}$$

where K is a constant. If, on the other hand, the displacement, and

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† This is only approximately true, as the air does have viscosity, but the shearing forces are very small compared with those in solids.

hence the change in volume, takes place rapidly, and further if the gas is air, oxygen, hydrogen, or nitrogen, the incremental pressure produced is equal to $1.4K$ times the incremental change in volume.

$$\Delta P = -1.4K\,\Delta V \qquad \text{fast process, diatomic gas}$$

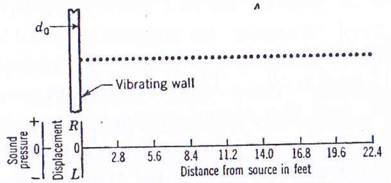
Note that a positive increment (increase) in pressure produces a negative increment (decrease) in volume. Processes which take place at intermediate rates are more difficult to describe, even approximately, and fortunately need not be considered here.

What is the reason for the difference between the pressure arising from changes in volume that occur rapidly and the pressure arising from changes in volume that occur slowly? For slow variations in volume the compressions are *isothermal*. By an isothermal variation we mean one that takes place at constant temperature. There is time for the heat generated in the gas during the compression to flow to other parts of the gas or, if the gas is confined, to flow to the walls of the container. Hence, the temperature of the gas remains constant. For rapid variations in volume, however, the temperature rises when the gas is compressed and falls when the gas is expanded. There is not enough time during a cycle of compression and expansion for the heat to flow away. Such rapid alternations are said to be *adiabatic*.

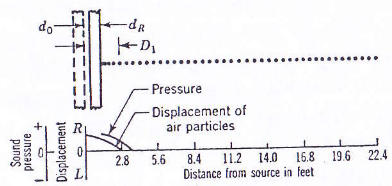
In either isothermal or adiabatic processes, the pressure in a gas is due to collisions of the gas molecules with container walls. You will recall that pressure is force per unit area, or, from Newton, time rate of change of momentum per unit area. Let us investigate the mechanism of this momentum change in a confined gas. The container wall changes the direction of motion of the molecules which strike it and so changes their momentum; this change appears as a pressure on the gas. The *rate* at which the change of momentum occurs, and so the magnitude of the pressure, depends on two quantities. It increases obviously if the number of collisions per second between the gas particles and the walls increases, or if the amount of momentum transferred per collision becomes greater, or both. We now see that the isothermal compression of a gas results in an increase of pressure because a given number of molecules are forced into a smaller volume and will necessarily collide with the container more frequently.

On the other hand, although the adiabatic compression of a gas results in an increase in the number of collisions as described above, it causes also a further increase in the number of collisions and a greater momentum transfer per collision. Both these additional increases are due to the temperature change which accompanies the adiabatic compression. Kinetic theory tells us that the velocity of gas molecules varies as the square root of the absolute temperature of the gas. In the adiabatic process then, as contrasted with the isothermal, the molecules get hotter; they move faster, collide with the container walls more frequently, and, having greater momentum themselves, transfer more momentum to the walls during each individual collision.

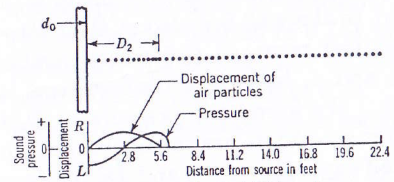
For a given volume change ΔV, the rate of momentum change, and therefore the pressure increase, is seen to be greater in the adiabatic process. It follows that a gas is stiffer—it takes more force to expand or compress it—if the alternation is adiabatic. We shall see later in the text that sound waves are essentially adiabatic alternations.



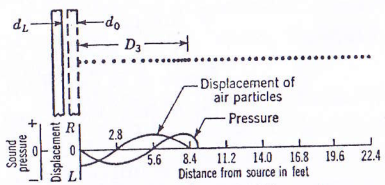
(a) Start of cycle, 0 seconds



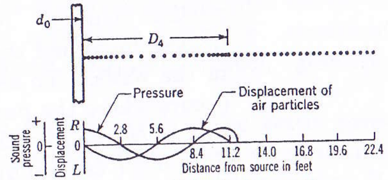
(b) $\frac{1}{4}$ cycle, 0.0025 seconds



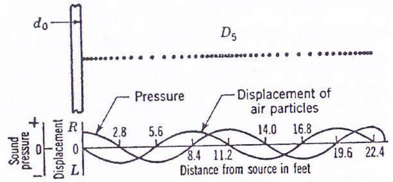
(c) $\frac{1}{2}$ cycle, 0.005 seconds



(d) $\frac{3}{4}$ cycle, 0.0075 seconds



(e) 1 cycle, 0.01 seconds



(f) 2 cycles, 0.02 seconds

FIG. 1.1 Pressure and displacement in a plane sound wave produced by a sinusoidally vibrating wall. D_1 = one-fourth wavelength; D_2 = one-half wavelength; D_3 = three-fourths wavelength; D_4 = one wavelength; D_5 = two wavelengths. R means displacement of the air particles to the right, L means displacement to the left, and O means no displacement. Crowded dots mean positive excess pressure and spread dots mean negative excess pressure. The frequency of vibration of the piston is 100 cycles per second.

1.3. Propagation of Sound through Gas. The propagation of sound through a gas can be fully predicted and described if we take into account the factors just discussed, *viz.*, the mass and stiffness of the gas, and its conformance with basic physical laws. Such a mathematical description will be given in detail in later chapters. We are now concerned with a qualitative picture of sound propagation.

If we put a sinusoidally vibrating wall in a gas (see Fig. 1.1*a*), it will accelerate adjacent air particles and compress that part of the gas nearest to it as it moves forward from rest. This initial compression is shown in Fig. 1.1*b* as a crowding of dots in front of the wall. The dots represent air particles. These closely crowded air particles have, in addition to their random velocities, a forward momentum gained from the wall. They collide with their neighbors to the right and during the collision transfer forward momentum to these particles, which were at rest. These particles in turn move closer to their neighbors, with which they collide, and so on. Progressively more and more remote parts of the medium will be set into motion. In this way, through successive collisions, the force built up by the original compression may be transferred to distant parts of the gas.

When the wall reverses its motion, a rarefaction occurs immediately in front of it (see Figs. 1.1*c* and 1.1*d*). This rarefaction causes particles to be accelerated backward. and the above process is now repeated in the reverse direction, and so on, through successive cycles of the source.

It is important to an understanding of sound propagation that you keep in mind the relative variations in pressure, particle displacement, and particle velocity. Note that, at any one instant, the maximum particle displacement and the maximum pressure do not occur at the same point in the wave. To see this, consider Fig. 1.1*c*. The maximum pressure occurs where the particles are most tightly packed, *i.e.*, at $D_2 = 5.6$ ft. But at D_2 the particles have not yet moved from their original rest position, as we can see by comparison with Fig. 1.1*a*. At D_2, then, the pressure is a maximum, and the particle displacement is zero. At this instant, the particles next to the wall are also at their zero-displacement position, for the wall has just returned to its zero position. Although the particles at both D_2 and d_0 have zero displacement, their environments are quite different. We found the pressure at D_2 to be a maximum, but the air particles around d_0 are far apart, and so the pressure there is a minimum. Halfway between d_0 and D_2 the pressure is found to be at the ambient value (zero incremental pressure), and the displacement of the particles at a maximum. At a point in the wave where pressure is a maximum, the particle displacement is zero. Where particle displacement is a maximum, the incremental pressure is zero. Pressure and particle displacement are then 90° out of phase with each other.

At any given point on the wave the pressure and particle displacement are varying sinusoidally in time with the same frequency as the source. If the pressure is varying as $\cos 2\pi ft$, the particle displacement, 90° out of phase, must be varying as $\sin 2\pi ft$. Particle velocity, however, is the time derivative of displacement and must be varying as $\cos 2\pi ft$. At any one point on the wave, then, pressure and particle velocity are in phase.

We have determined the relative phases of the particle displacement, velocity, and pressure at a point in the wave. Now we ask, What phase

relationship exists between values of, say, particle displacement measu
at two different points on the wave? If the action originating from
wall were transmitted instantaneously throughout the medium, all p
ticles would be moving in phase with the source and with each oth
This is not the case, for the speed of propagation of sound is finite, and
points increasingly distant from the source there is an increasing delay
the arrival of the signal. Each particle in the medium is moved ba
ward and forward with the same frequency as the wall, but not at
same time. This means that two points separated a finite distance fr
each other along the wave in general will not be moving in phase wi
each other. Any two points that are vibrating in exact phase will, in th
example of a plane wave, be separated by an integral number of wav
lengths. For example, in Fig. 1.1*f* the 11.2- and 22.4-ft points
separated by exactly one wavelength. A disturbance at the 22.4-ft poi
occurs at about 0.01 sec after it occurs at the 11.2-ft point. This co
responds to a speed of propagation of about 1120 ft/sec. Mathema
ically stated, a *wavelength* is equal to the speed of propagation divided
the frequency of vibration.

$$\lambda = \frac{c}{f} \qquad (1.$$

where λ is the wavelength in meters (or feet), c is the speed of propagatio
of the sound wave in meters (or feet) per second, and f is the frequency
cycles per second.

It is an interesting fact that sound waves in air are longitudinal; *i.e.*, th
direction of the vibratory motion of air particles is the same as the dire
tion in which the wave is traveling. This can be seen from Fig. 1.
Light, heat, or radio waves in free space are transverse; *i.e.*, the vibration
of the electric and magnetic fields are perpendicular to the direction
which the wave advances. By contrast, waves on the surface of wate
are circular. The vibratory motion of the water molecules is in a smal
circle or ellipse, but the wave travels horizontally.

1.4. Measurable Aspects of Sound. Consider first what measure
ments might be made on the medium before a sound wave or a disturban
is initiated in it. The gas particles (molecules) are, on the average,
rest. They do have random motion, but there is no net movement of th
gas in any direction. Hence, we say that the *particle displacement* is zer
It follows that the *particle velocity* is zero. Also, when there is no dis
turbance in the medium, the *pressure* throughout is constant and is equa
to the *ambient pressure*, so that the *incremental pressure* is zero. A valu
for the ambient pressure may be determined from the readings of
barometer. The *density*, another measurable quantity in the medium,
defined as usual as the mass per unit volume. It equals the *ambien*
density when there is no disturbance in the medium.