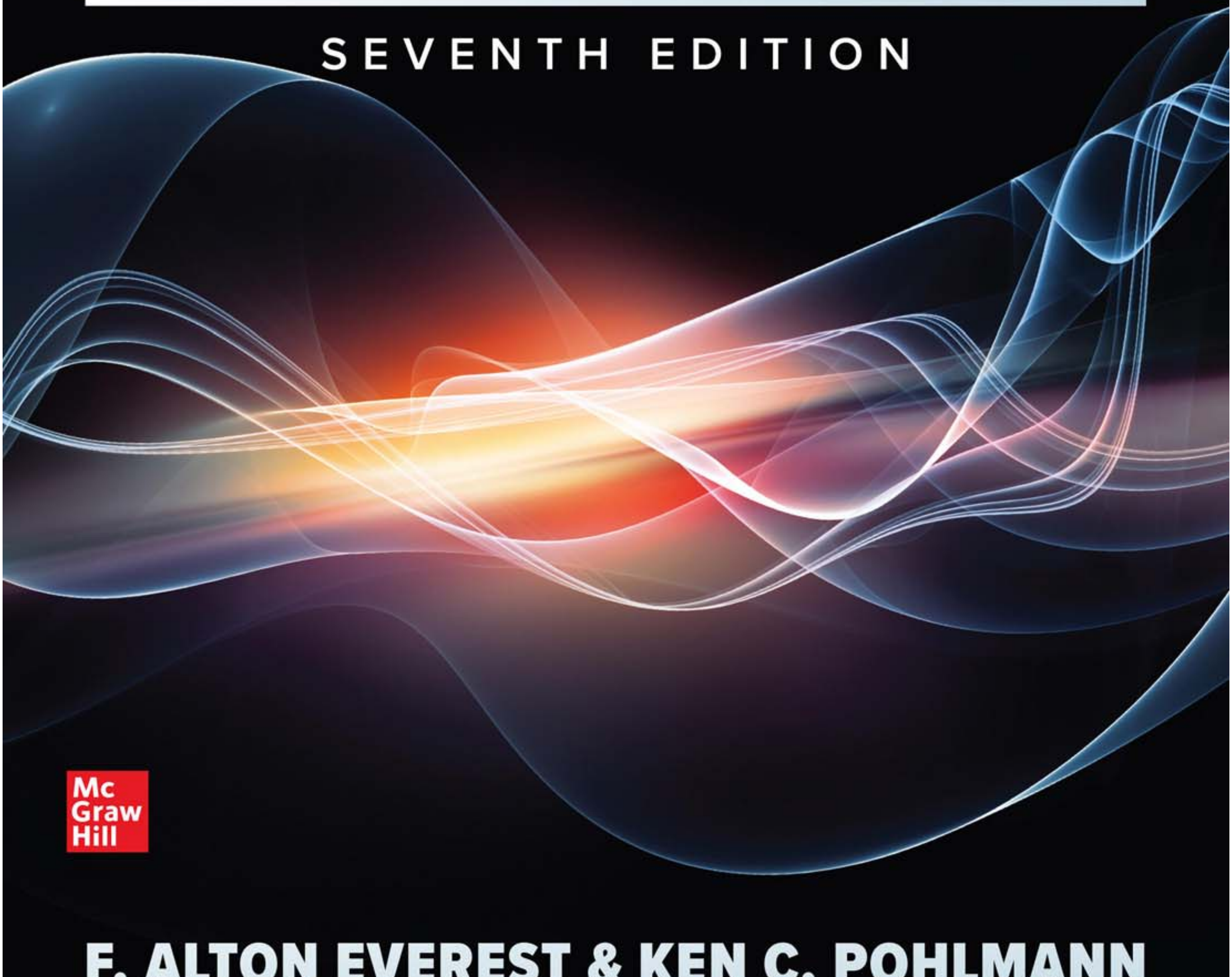
MASTER HANDBOOK OF ACOUSTICS

SEVENTH EDITION



McGraw Hill

F. ALTON EVEREST & KEN C. POHLMANN

Master Handbook of Acoustics

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F. Alton Everest was a leading expert and authority in the field of acoustics. He was an emeritus member of the Acoustical Society of America, a life member of the Institute of Electrical and Electronics Engineers, and a life fellow of the Society of Motion Picture and Television Engineers. He was cofounder and director of the Science Film Production division of the Moody Institute of Science, and was also section chief of the Subsea Sound Research section of the University of California.

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F. Alton Everest

Ken C. Pohlmann

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Dedicated to the memory of F. Alton Everest

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Introduction

You hold in your hands, either physically or electronically, the seventh edition of the *Master Handbook of Acoustics*. Mr. F. Alton Everest was the original author of this book. In 1981 he devised the formula for an acoustics book that balanced theory and practice. Many engineering books sprinkle examples and problems throughout the text, to inform the reader of practical applications. He improved on that model by presenting basic theory combined with a significant quantity of pragmatic information, then attaching entire chapters, comprising a substantial portion of the book, that are purely devoted to practical examples. These chapters are particularly essential for anyone building a room with similar characteristics.

Mr. Everest understood that this was the perfect way to teach introductory acoustics while simultaneously providing practical guidance to anyone undertaking a construction project. He thus created a valuable tool that we know and trust, a book that has become a classic. The acoustical engineering community grieved when Mr. Everest passed away in 2005 at the age of 95.

I was honored when McGraw-Hill asked me to prepare a fifth, a sixth, and now this seventh edition of the *Master Handbook of Acoustics*. I had used the handbook since it was first published, and was well familiar with its value as a teaching text and reference handbook. Readers who are familiar with another of my books, *Principles of Digital Audio*, may be surprised to learn that my passion for digital technology is equaled by my enthusiasm for acoustics. I taught courses in architectural acoustics (in addition to classes in digital audio) for 30 years at the University of Miami, where I directed the Music Engineering Technology program. Throughout that time, I also consulted on many acoustics projects, ranging from recording studio to listening room design, from church acoustics to community noise intrusion. As with many practitioners in the field, it was important for me to understand the fundamentals of acoustical properties, to be able to articulate those principles to clients, and also to stay current with the practical applications and solutions to today's acoustical problems. This essential equilibrium was the guiding principle of Mr. Everest's original vision for this book, and I have continued to seek that same balance. Further, through Mr. Everest's four editions, and my three editions, this book has improved steadily to reach a high level of refinement.

Occasionally, and particularly among newbies to the field of acoustics, the question arises, "Why is it important to study acoustics?" One reason, among many, is that you will be joining in, and hopefully contributing to, a noble scientific undertaking. Since antiquity, some of the world's greatest scientists and engineers have studied acoustics and its elegant complexities. Greek philosophers including Pythagoras, Aristotle, and

Euclid began the exploration of the nature of musical harmonics and how we hear sound. The great Roman engineer and architect Vitruvius carefully analyzed echo and reverberation in his building projects. Over the years, heavyweights such as Ptolemy, Galileo, Mersenne, Kircher, Hooke, Newton, Laplace, Euler, D'Alembert, Bernoulli, Lagrange, Poisson, Faraday, Helmholtz, Ohm, Doppler, and Sabine all made contributions. In all, countless men and women have worked to evolve the science of acoustics to a high degree of sophistication.

But, pressing the question, in today's binary world, is acoustics still important? Consider this: We rely on our eyes and ears. Our eyes close when we sleep; we cannot see in the dark; someone can sneak up on us unseen from behind. But from birth to death, awake or asleep, in light and in dark, our ears are always sensitive to our world around us. Whether we are hearing sounds that give us pleasure, or sounds that alert us to danger, whether they are sounds of nature, or sounds of technology, the properties of acoustics and the way that architectural spaces affect those sounds are woven into every moment of our lives. Is acoustics important? I think it is. And I'm pretty sure Mr. Everest would agree.

Ken C. Pohlmann

CHAPTER 1

Fundamentals of Sound

Sound can be considered as wave motion in air or other elastic media. In this case, sound acts as a stimulus. Sound can also be considered as an excitation of the hearing mechanism that results in its perception. In this case, sound is a sensation. This duality of sound is familiar to those interested in audio and music. The type of problem at hand dictates our approach. If we are interested in the physical disturbance of the air in a room, it is a problem of physics. If we are interested in how that disturbance is perceived by a person listening in the room, psychoacoustical methods must be used. Because this book addresses acoustics in relation to people, both aspects of sound will be considered. That being said, because we are primarily interested in how room materials and geometry affect the disturbance, our investigations will mainly deal with physics.

Sound can be characterized by objective phenomena. For example, frequency is an objective property of sound; it specifies the number of waveform repetitions per unit of time (usually 1 second). Frequency can be readily measured on an oscilloscope or a frequency counter. From a physics standpoint, the concept of frequency is straightforward. We will have much more to say about the objective qualities of sound, particularly in the way that the properties of sound are dictated by the rooms we inhabit.

On the other hand, that rate of repetition can be characterized subjectively. Frequency is then considered in terms of pitch, which is a subjective property of sound. Perceptually, we hear different pitches for soft and loud 100-Hz tones. As intensity increases, the pitch of a low-frequency tone goes down, while the pitch of a high-frequency tone goes up. Harvey Fletcher found that playing pure tones of 168 and 318 Hz at a modest level produces a very discordant sound. At a high intensity, however, the ear hears pure tones in the 150- to 300-Hz octave relationship as a pleasant sound. We cannot equate frequency and pitch, but they are analogous. Another objective/subjective duality exists between intensity and loudness. Similarly, the relationship between waveform (or spectrum) and perceived quality (or timbre) is not linear. A complex waveform can be described in terms of a fundamental and a series of harmonics of various amplitudes and phases. But perception of timbre is complicated by the frequency-pitch interactions in the human hearing mechanism as well as other factors.

The interaction between the physical properties of sound, and our perception of them, poses delicate and complex issues. It is this complexity in audio and acoustics that creates such interesting problems. On one hand, the design of a loudspeaker or a concert hall should be a straightforward and objective engineering process. But in practice, that objective expertise must be carefully tempered with purely subjective wisdom. As has often been pointed out, loudspeakers are not designed to play sine waves into calibrated microphones placed in anechoic chambers. Instead, they are designed to play music in our listening rooms. In other words, the study of audio and acoustics involves both art and science. To learn the complexities of audio and acoustics, we begin with the science, keeping in mind that our ears will ultimately determine the success or failure of our projects.

Simple Harmonic Motion and the Sine Wave

The weight (mass) and the spring shown in Fig. 1-1 comprise a vibrating system. Moreover, the weight moves in what is called simple harmonic motion. When the weight is at rest, the system is said to be in equilibrium. If the weight is pulled down to the –5 mark and released, the spring pulls the weight back toward 0. However, the weight will not stop at 0; its inertia will carry it beyond 0 almost to +5. The displacement of the weight defines the amplitude of the motion.

The weight will continue to vibrate, or oscillate. Each up/down repetition is called a cycle, and the motion is said to be periodic. In the arrangement of a mass and a spring, vibration or oscillation is possible because of the elasticity of the spring and the inertia of the weight. Elasticity and inertia are two things all media must possess to be capable of conveying sound. In this practical example, the amplitude of motion will slowly decrease due to frictional losses in the spring and the air around it.

Harmonic motion is a basic type of oscillatory motion, and it yields an equally basic wave shape in sound and electronics. To illustrate this, if a pen is fastened to the weight's pointer, as shown in Fig. 1-2, and a strip of paper is moved past it at a uniform speed, the resulting trace is a sine wave. The sine wave is a pure waveform closely related to simple harmonic motion. In this figure, the sine wave traced by the pen has completed one full period and is more than halfway through a second period. The periodic motion of the weight will continue to trace the sine wave indefinitely. (For a moment, we are ignoring the frictional losses that would decrease amplitude.) This simple oscillatory system will always create sinusoidal motion; without outside forces, no other motion is

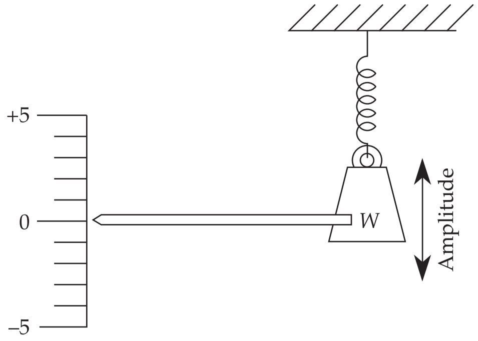

Figure 1-1 A weight on a spring vibrates at its natural frequency because of the elasticity of the spring and the inertia of the weight.

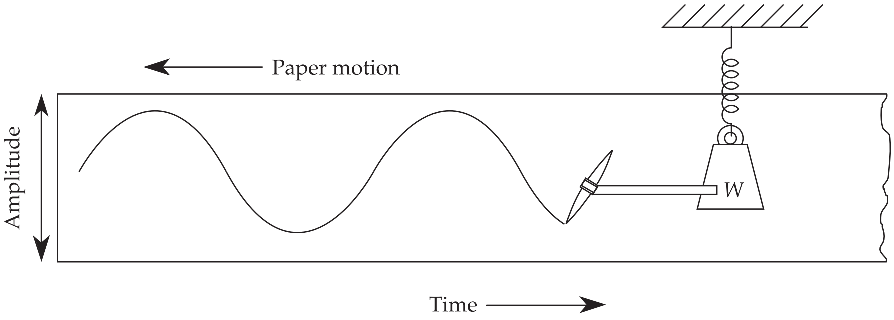

Figure 1-2 A pen fastened to the vibrating weight traces a sine wave on a paper strip moving at a uniform speed. This shows the basic relationship between simple harmonic motion and the sine wave.

possible with this system. However, this graph of a sine wave, showing amplitude versus time, sets precedence for plotting many different wave shapes.

As another example of oscillatory motion, consider a piston in an internal-combustion automobile engine that is connected to the crankshaft by a connecting rod. The rotation of the crankshaft and the up-and-down motion of the pistons illustrate the relationship between rotary motion and linear simple harmonic motion. As with the weight on a spring, the piston position plotted against time produces a sine wave.

Sound in Media

The weight and spring system in the previous example models the motion of air molecules. If an air particle is displaced from its original position, elastic forces of the air tend to restore it to its original position. Because of the inertia of the particle, it overshoots the resting position, bringing into play elastic forces in the opposite direction, and so on.

An elastic medium is essential to the existence of sound waves. Because air is such a common agent for the conduction of sound, it is easy to forget that other media are also conductors of sound. Thus, sound is readily conducted in gases, liquids, and solids such as air, water, steel, concrete, and so on, which are all elastic media. Imagine a railroad track; a friend stationed a distance away strikes a rail with a rock. You will hear two sounds, one sound coming through the rail and one through the air. The sound through the rail arrives first because the speed of sound in steel is faster than in air. Similarly, liquids can be very efficient conductors of sound; underwater sounds can be detected after traveling thousands of miles through the ocean.

Without a medium, sound cannot be propagated. In the laboratory, an electric buzzer is suspended in a heavy glass bell jar. As the button is pushed, the sound of the buzzer is readily heard through the glass. As the air is pumped out of the bell jar, the sound becomes fainter and fainter until it is no longer audible. The sound-conducting medium, the air inside the jar, has been removed between the source and the ear. Outer space is an almost perfect vacuum; no sound can be conducted except in the tiny island of atmosphere within a spaceship or a spacesuit.

Particle Motion

Waves created by the wind travel across a field of grain, yet the individual stalks remain firmly rooted as the wave travels on. In a similar manner, particles of air propagating a sound wave do not move far from their undisplaced positions, as shown in Fig. 1-3. The disturbance travels on, but the propagating particles move only in localized regions (with perhaps a maximum displacement of a few ten-thousandths of an inch). Note also that the velocity of a particle is maximum at its equilibrium position, and zero at the points of maximum displacement (a pendulum has the same property). The maximum velocity is called the velocity amplitude, and the maximum displacement is called the displacement amplitude. The maximum particle velocity is very small, less than 0.5 in/sec for even a loud sound. As we will see, to lower the level of a sound, we must reduce the particle velocity.

There are three distinct forms of particle motion. For sound traveling in a gaseous medium such as air, the particles move in the direction the sound is traveling. This motion is described as longitudinal waves, which expand and contract in the direction of propagation, as shown in Fig. 1-4A. As we will see, this oscillation causes high- and low-pressure regions. The instantaneous pressure on opposite sides of a pressure minimum has opposite polarity. The pressure on one side is increasing, whereas the pressure on the other side is decreasing. A second type of wave motion is illustrated by a violin string, as shown in Fig. 1-4B. The tiny elements of the string move transversely, or at right angles to the direction of travel of the waves along the string. Thirdly, if a stone is dropped on a calm water surface, concentric waves travel out from the point of impact, and the water particles trace circular orbits (for deep water, at least), as shown in Fig. 1-4C.

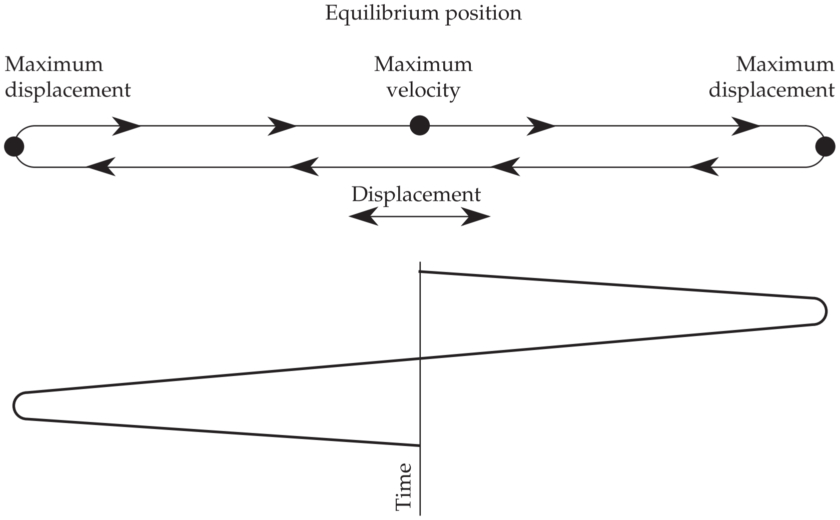

FIGURE 1-3 An air particle is made to vibrate about its equilibrium position by the energy of a passing sound wave because of the interaction of the elastic forces of the air and the inertia of the air particle.

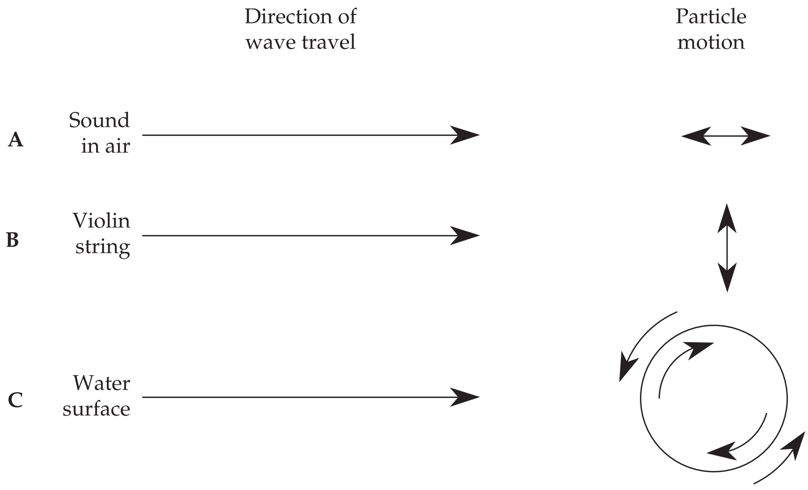

FIGURE 1-4 Particles involved in the propagation of sound waves can move with (A) longitudinal motion in air, (B) transverse motion on a string, or (C) circular motion on the water surface.

Propagation of Sound

How are air particles, moving slightly back and forth, able to carry music from a loudspeaker to our ears? The dots of Fig. 1-5 represent air molecules with different density variations. The molecules crowded together represent areas of compression (crests in the wave shape) in which the air pressure is slightly greater than the prevailing atmospheric pressure (typically about 14.7 lb/in^2 at sea level). The sparse areas represent rarefactions (troughs in the wave shape) in which the pressure is slightly less than atmospheric pressure. The arrows (see Fig. 1-5) indicate that, on average, the molecules are moving to the right of the compression crests and to the left in the rarefaction troughs between the crests. Any given molecule, because of elasticity, after an initial displacement, will return toward its original position. It will move a certain distance to the right and then approximately the same distance to the left of its undisplaced position as the sound wave progresses uniformly to the right. Sound propagates because of the transfer of momentum from one particle to another.

In this example, why does the sound wave move to the right? The answer is revealed by a closer look at the arrows (see Fig. 1-5). The molecules tend to bunch up where two arrows are pointing toward each other, and this occurs a bit to the right of each compression region. When the arrows point away from each other, the density of molecules decreases. Thus, the movement of the higher-pressure crest and the lower-pressure trough accounts for the progression of the sound wave to the right.

As mentioned previously, the pressure at the crests is higher than the prevailing atmospheric barometric pressure and lower than the atmospheric pressure at the troughs, as shown in the sine wave of Fig. 1-6. These fluctuations of pressure are very small indeed. The faintest sound the ear can hear (20 μPa) exists at a pressure some 5,000 million times smaller than atmospheric pressure. To summarize, typical sounds such as speech and music are represented by correspondingly small ripples in pressure superimposed on the atmospheric pressure.

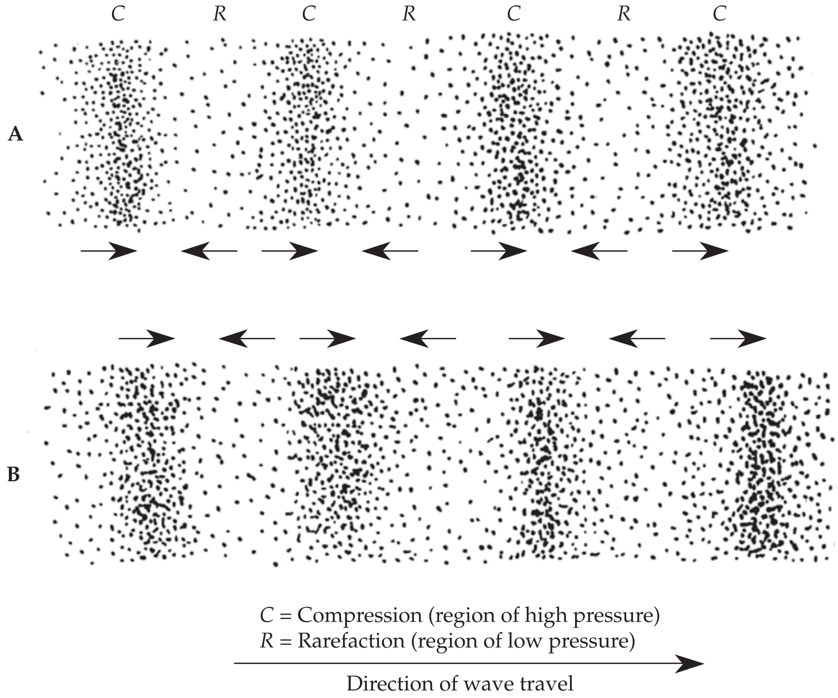

Figure 1-5 Sound waves traveling through a medium change the localized air particle density. (A) A sound wave causes the air particles to be pressed together (compression) in some regions and spread out (rarefaction) in others. (B) An instant later the sound wave has moved slightly to the right.

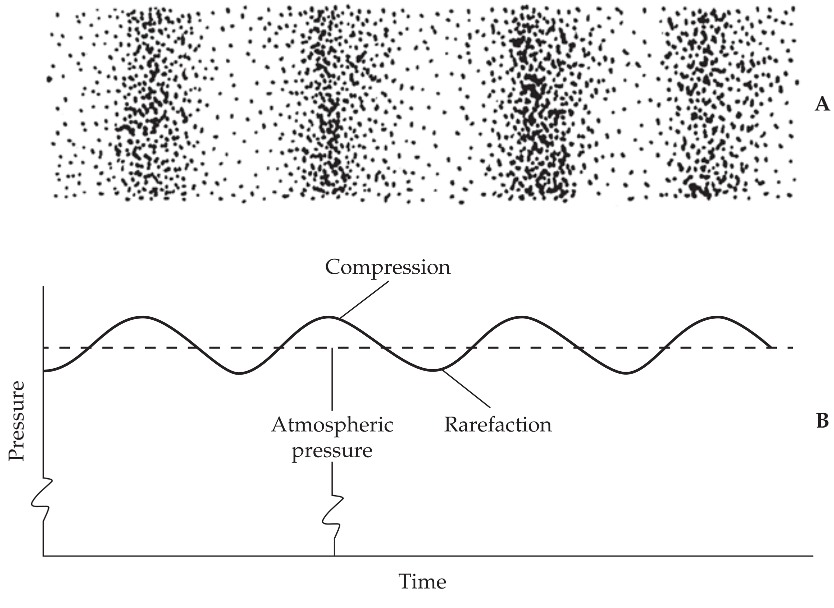

Figure 1-6 Pressure variations of sound waves are superimposed on prevailing barometric pressure. (A) An instantaneous view of the compressed and rarefied regions of a sound wave in air. (B) The compressed regions are very slightly above and the rarefied regions very slightly below atmospheric pressure.

Medium	Speed of Sound (ft/sec)	Speed of Sound (m/sec)
Air	1,130	344
Distilled water	4,915	1,498
Seawater	5,023	1,531
Wood, fir	12,470	3,800
Steel bar	16,570	5,050
Gypsum board	22,310	6,800

Table 1-1 Examples of Speed of Sound in Different Materials

Speed of Sound

The speed of sound in air is about 1,130 ft/sec (344 m/sec) at 70°F (21°C). This is about 770 mi/hr (1,239 km/hr). In the field of aerodynamics, this speed is known as Mach 1.0 (technically, it is air speed relative to the local speed of sound). This speed is not particularly fast in relation to familiar things. For example, commercial aircraft routinely travel at speeds that approach the speed of sound; for example, a Boeing 787 jetliner has a cruising speed of 561 mi/hr (Mach 0.85). The speed of sound is dramatically slower than the speed of light (670,616,629 mi/hr). It takes about 5 seconds for sound to travel 1 mile. You can gauge the distance of a thunderstorm by counting the time between the sight of the lightning flash and the sound of its thunder; if you count to 5 seconds, the storm is about a mile away. The speed of sound in the audible range is appreciably affected by temperature and slightly affected by humidity. It is not appreciably affected by the intensity of sound, its frequency, or by changes in atmospheric pressure. In some cases, some factors that would otherwise affect the speed of sound are offset by other factors, yielding insignificant changes.

Sound will propagate at a certain speed that depends on the medium and other factors. Other properties being equal, the stiffer or more rigid a medium, or the less compressible it is, the faster the speed of sound in it. Generally, sound travels faster in liquids than in air, and it travels faster in solids than in liquids. For example, sound travels at about 5,023 ft/sec in seawater and about 16,570 ft/sec in steel. Other examples are shown in Table 1-1. As noted, sound also travels faster in air as temperature increases (an increase of about 1.1 ft/sec for every degree Fahrenheit). Finally, humidity slightly affects the speed of sound in air; the more humid the air, the faster the speed. It should be noted that the speed (velocity) of sound is different from the particle velocity. The speed (velocity) of sound determines how fast sound energy moves through a medium. Particle velocity is determined by the loudness of the sound.

Wavelength and Frequency

A sine wave is illustrated in Fig. 1-7. The wavelength λ is the distance a wave travels in the time it takes to complete one cycle. A wavelength can be measured between successive peaks or between any two corresponding points on the cycle. This also holds for periodic waves other than the sine wave. The frequency f specifies the number of

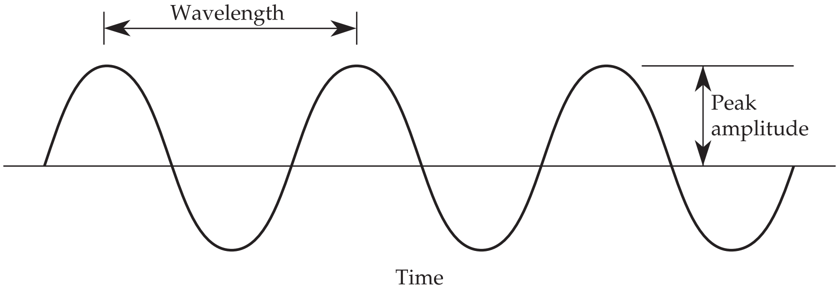

Figure 1-7 Wavelength is the distance a wave travels in the time it takes to complete one cycle. It can also be expressed as the distance from one point on a periodic wave to the corresponding point on the next cycle of the wave.

cycles per second, measured in hertz (Hz). Frequency and wavelength are related as follows:

$$\text{Wavelength (ft)} = \frac{\text{Speed of sound (ft/sec)}}{\text{Frequency (Hz)}} \tag{1-1}$$

which can also be written as

$$\text{Frequency (Hz)} = \frac{\text{Speed of sound (ft/sec)}}{\text{Wavelength (ft)}} \tag{1-2}$$

As noted, the speed of sound in air is about 1,130 ft/sec at normal conditions. For sound traveling in air, Eq. (1-2) becomes

$$\text{Wavelength (ft)} = \frac{1{,}130}{\text{Frequency (Hz)}} \tag{1-3}$$

This relationship is perhaps the most fundamentally important relationship in audio. Figure 1-8 gives two approaches for a graphical solution to Eq. (1-3).

Complex Waveforms

Speech and music wave shapes depart radically from the simple sine wave and are considered as complex waveforms. However, no matter how complex the waveform is, as long as it is periodic, it can be reduced to sine components. The obverse of this states that any complex periodic waveform can be synthesized from sine waves of different frequencies, different amplitudes, and different time relationships (phase). Joseph Fourier was the first to prove these relationships. The idea is simple in concept but often complicated in its application to specific speech or musical sounds. Let us see how a complex periodic waveform can be reduced to simple sinusoidal components.

Harmonics

A simple sine wave of a given amplitude and frequency, f_1, is shown in Fig. 1-9A. Figure 1-9B shows the second harmonic sine wave f_2 that is twice the frequency and half the amplitude of f_1. Combining f_1 and f_2 at each point in time, the wave shape of

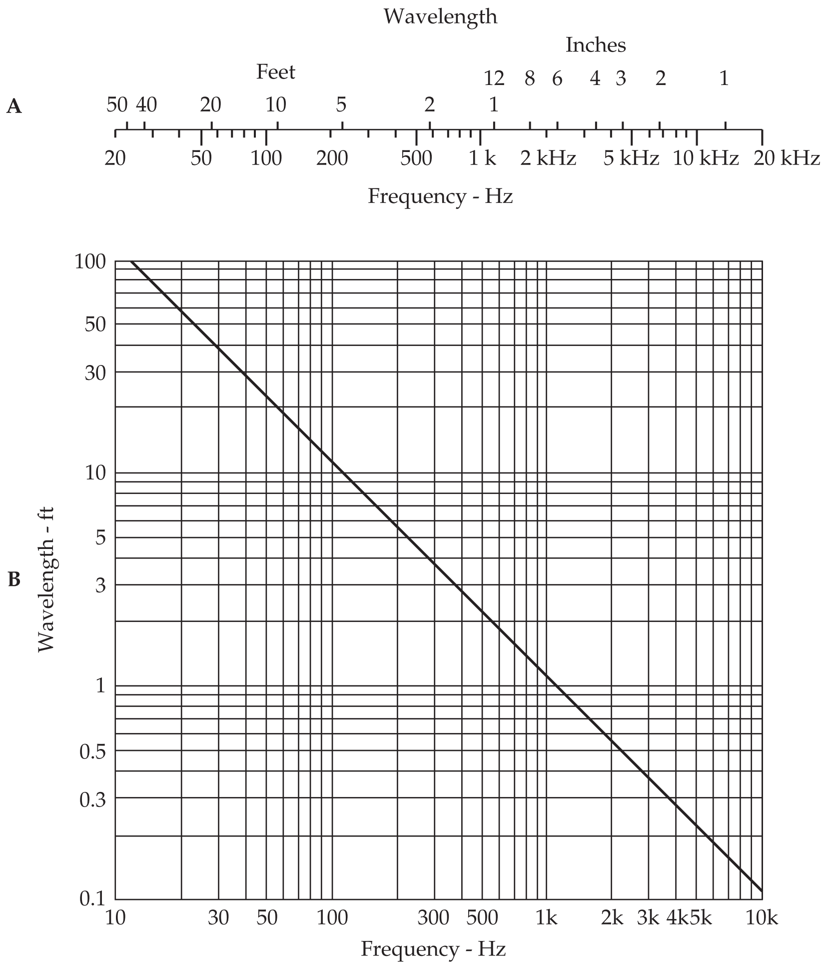

FIGURE 1-8 Wavelength and frequency are inversely related. (A) Scales for approximately determining wavelength of sound in air from a known frequency or vice versa. (B) A chart for determining the wavelength in air of sound waves of different frequencies. (Both are based on the speed of sound of 1,130 ft/sec.)

Fig. 1-9C is obtained. Figure 1-9D shows the third harmonic sine wave f_3 that is three times the frequency and half the amplitude of f_1. Adding this to the $f_1 + f_2$ wave shape of C, Fig. 1-9E is obtained. The simple sine wave of Fig. 1-9A has been progressively changed as other sine waves have been added to it; this is valid for both acoustic waves and electronic signals. The process can be reversed. The complex waveform of Fig. 1-9E can be disassembled, as it were, to the simple f_1, f_2, and f_3 sine components by either acoustic or electronic filters. For example, passing the waveform of Fig. 1-9E through a filter permitting only f_1 and rejecting f_2 and f_3, the original f_1 sine wave of Fig. 1-9A emerges in pristine condition.