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CHAPTER 1 Musical Physics

Anyone reading this book is probably involved with sound in one way or another. After all, sound is the most fundamental building block of music. Most people can subjectively describe a sound as loud or soft and specify a pitch as high or low, and it's relatively easy to distinguish between a violin and a trombone. But what are the physical characteristics of sound that cause these perceptions?

If you've never been exposed to the fundamental principles of sound, take heart: they're easy to understand. In this chapter, you'll learn about the physical phenomena associated with sound as well as some basic terms used to describe its properties.

Acoustics

Sound begins when something vibrates. For example, this something can be a woodwind reed, brass player's lips, guitar string, or speaker cone. For now, I'll use the example of a drum, but the principles are the same for all sound sources.

When you hit a drum, the drum head vibrates. This motion imparts a certain amount of energy to the air molecules immediately adjacent to the drum head, momentarily creating a region of higher than normal air pressure as the head moves outward. However, air is elastic, which means it tends to return to its normal pressure if it's not constrained. The energy imparted by the vibrating head must go somewhere, so it moves on to the neighboring air molecules a bit farther from the head. These molecules then become momentarily compressed with higher-than-normal pressure.

This starts a chain reaction in which a region of air is compressed and then returns to its normal pressure, passing the energy of the compression to the adjoining region. It is important to understand that the air molecules themselves do not travel along with the region of high pressure; they vibrate in their own vicinity, somewhat like walking in place. It is the energy that travels outward from the source. Meanwhile, the drum head moves inward, creating a momentary region of lower-than-normal pressure adjacent to its surface. This region also moves away as the drum head pushes outward again and creates another temporary region of high pressure. This process repeats itself as long as the drum head continues to vibrate, causing alternating regions of high and low air pressure to expand and move away from the drum.

All sound sources vibrate in some manner, causing a similar pattern of expanding high- and low-pressure regions. This pattern is called a sound wave. Again, it's important to remember that the air molecules themselves do not travel along with the sound wave, as many people mistakenly believe. Individual air molecules vibrate in their own vicinity as the air pressure around them changes. It is the pattern of high and low pressure that travels, or propagates, outward from the source (see Fig. 1-1).

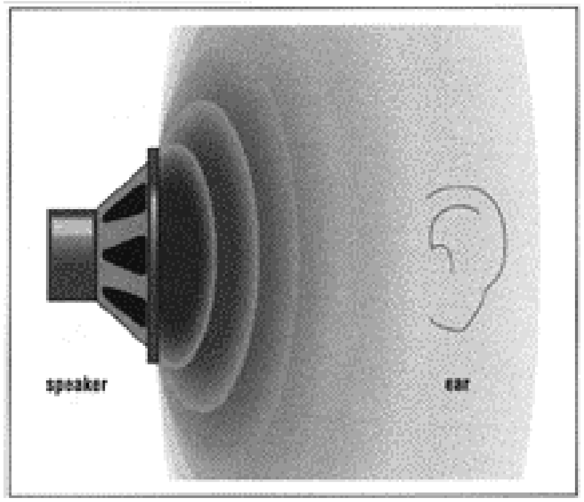

Figure 1-1. Sound waves consist of alternating areas of high and low air pressure that propagate from a vibrating speaker cone or other acoustic source through the air to our ears.

Wave Terms

If you measure the air pressure at a particular point in space, you will find that it alternates between slightly higher than normal and slightly lower than normal as a sound wave passes by. This is often depicted in a graph of the pressure as it changes over time (see Fig. 1-2a).

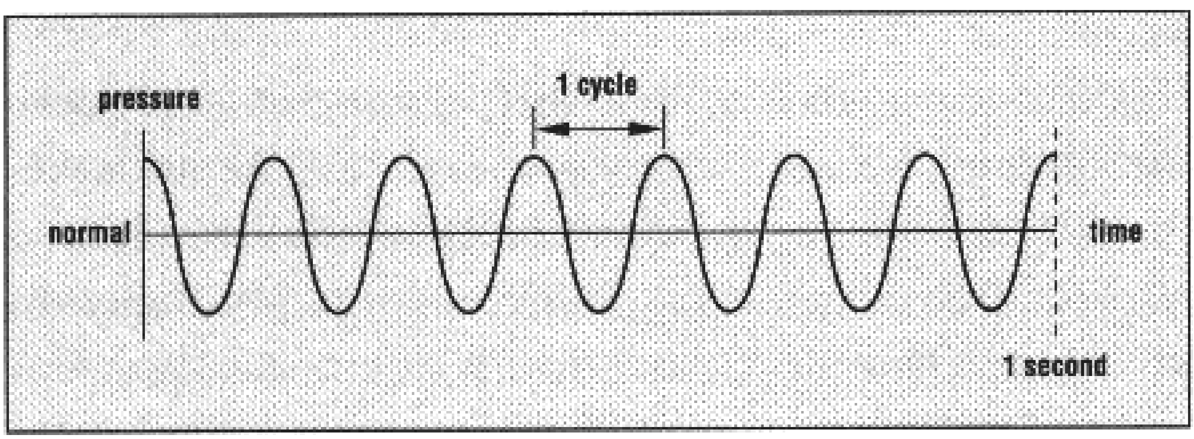

Figure 1-2a. Frequency of a sound wave. In this example, the frequency is 7 cycles/second, or 7 Hz, which means that each cycle takes 1/7 second to complete.

The variation of pressure from its maximum value to its minimum value and back to its maximum value is called one cycle of the sound wave. The number of cycles through which the pressure fluctuates in one second is called the frequency. As you might guess from this definition, frequency is measured in cycles per second. In honor of the contributions to the study of sound by the German physicist Heinrich Hertz, cycles per second are also called hertz (abbreviated Hz). As human beings, we are unable to perceive a sound wave with a frequency of 7 Hz, as shown in Fig. 1-2a. Theoretically, the lowest frequency that we can detect is 20 Hz; the highest is 20,000 Hz, or 20 kilohertz (abbreviated kHz). In musical terms, this is a range of about ten octaves. As we grow older, the upper end of this range drops; most adults have an upper limit of about 14 to 15 kHz or so. What we perceive as musical pitch is determined primarily by frequency. For example, the note A above middle C that is normally used to tune an orchestra is at a frequency of 440 Hz. As the frequency increases, we describe the note as being higher in pitch. The lower the frequency, the lower the pitch.

The speed at which a sound wave travels through a particular medium depends on the elastic properties and density of the medium; as the density decreases, the speed of sound increases. Typically, we are most interested in the speed of sound in the air under what are called the standard conditions (i.e, sea-level air pressure and a temperature of about 70 degrees Fahrenheit or 21 degrees Celsius). Under these conditions, the speed of sound is approximately 1,130 feet/second. However, as the temperature increases, the density decreases because the pressure remains constant if it is not completely confined. As a result, the speed of sound increases with temperature.

The speed of sound is very different in other media. For example, the speed of sound in fresh water at the standard temperature is 4,856 feet/second. This might seem odd considering that the density of water is much higher than air, but water is incompressible, whereas air is highly compressible. This property is related to the elasticity of the medium, which also affects the speed of sound. The elasticity of water causes the speed of sound to be much greater than it is in air, even though the density of water is greater than air. Interestingly, the speed of a sound wave does not depend on its frequency; all frequencies travel at the same speed through a given medium.

The physical distance between one area of maximum pressure and the next (or between one area of minimum pressure and the next) is called the wavelength. This can be depicted in a graph of the air pressure as it changes over distance (see Fig. 1-2b).

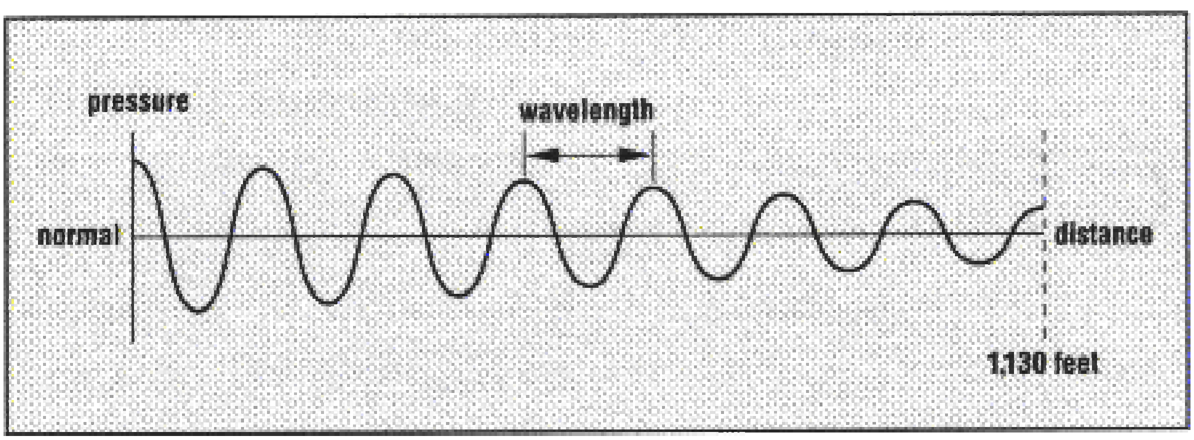

Figure 1-2b. Wavelength of a sound wave. As in Figure 1-2a, the frequency is 7 Hz, which means that the wavelength (in air) is 161.4 feet.

Wave Math

The frequency, wavelength, and speed of a sound wave are related. Using a simple formula, it's possible to calculate the wavelength of a sound wave if you know the frequency, and vice versa. The formula is:

wavelength = speed of sound / frequency

Let's try this formula on the lowest frequency that humans can perceive. At 20 Hz (assuming that the sound wave is traveling in air under standard conditions):

wavelength = 1,130 / 20 = 56.5 feet.

At the highest frequency detectable by humans:

wavelength = 1,130 / 20,000 = 0.0565 feet = 0.678 inches.

So the wavelengths of sounds we can hear range from over 56 feet to about two thirds of an inch.

This formula can also be expressed as follows:

frequency = speed of sound / wavelength

This explains why the pitch of wind and brass instruments is a bit flatter when they are first played than after they have warmed up. The temperature of the air in the instrument rises as it is played, so the speed of sound increases as the player's breath warms the air within. As the speed of sound increases, so does the frequency, which determines the pitch.

Another important characteristic of sound waves is the difference between the highest and lowest values of air pressure. This difference is called the amplitude, and it determines the volume or intensity of the sound. The greater the amplitude, or the greater the difference between the highest and lowest pressure in the wave, the louder the sound. In Fig. 1-2c, you'll notice that the amplitude decreases as you move away from the source. This is because there is a fixed amount of energy carried in a sound wave. As the wave travels away from the source, it expands in a more or less spherical pattern, similar to a balloon being blown up.

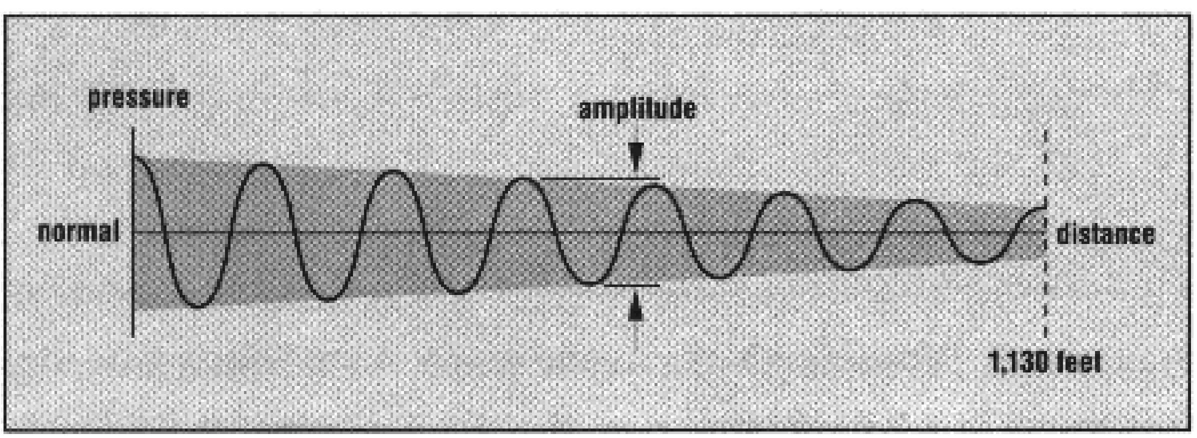

Figure 1-2c. Amplitude of a sound wave. As in Figures 1-2a and 1-2b, the frequency is 7 Hz. Notice that the amplitude decreases as you get farther away from the source. even though the wavelength and frequency remain unchanged.

A light bulb, which gives off a fixed amount of light, provides another analogy. The light from the bulb travels in all directions at once. As you move farther away from the bulb, the light appears to get dimmer. The bulb is producing a constant amount of light, but less of it is getting to your eye as you move farther away.

Sound works in a similar way. The sound source is producing a constant amount of sound, but less of it gets to your ear as you move farther away. Specifically, sound follows the inverse-square law, which states that the amplitude of a sound wave is inversely proportional to the distance from the source. For example, the amplitude of a sound wave at a distance of ten feet from the source is one quarter of the amplitude at a distance of five feet. This relationship often does not hold true in an enclosed space, where sound waves reflect from walls, ceilings, and floors.

Amplitude is specified in several ways; the most common is a unit of measurement called the sound-pressure level decibel (SPL). I'll go into more detail about decibels later in Chapter 4. For now, suffice it to say that humans can distinguish between about 250 different levels of amplitude, from the softest audible sound to a level that's painful to hear.

Waveforms

If you examine exactly how the pressure changes over the cycle of a sound wave, you can describe its wave form. Does the pressure suddenly switch from low to high and back again or does it change gradually up and down? Does it rise steadily from low to high, then suddenly drop to low before repeating the cycle? Does it change erratically with no apparent pattern? Fig. 1-3 illustrates some of the common wave forms that older analog synthesizers produce (which I'll explore in more detail in Chapter 2). As you can see, these waveforms are relatively simple. The wave forms produced by most acoustic musical instruments are far more complex. Even so, a waveform must be periodic (that is, it must repeat itself with a constant frequency) in order to exhibit a recognizable pitch.

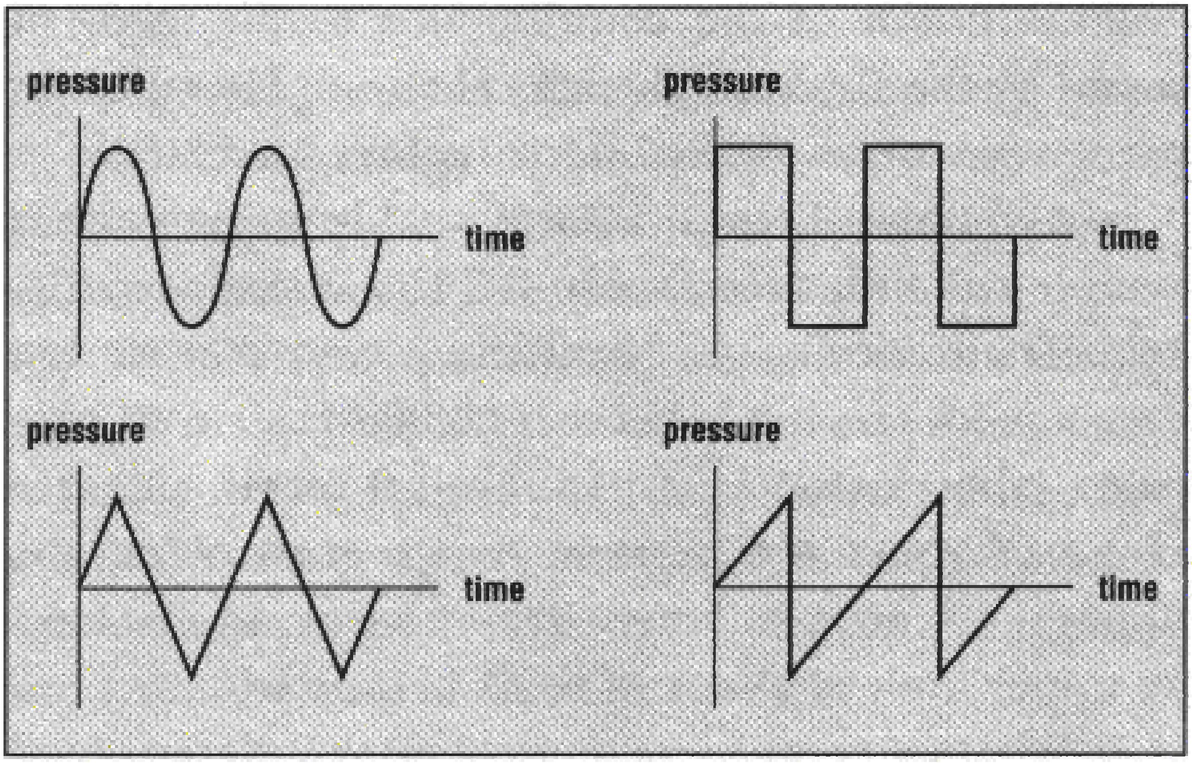

Figure 1-3. Four common synthesizer waveforms: sine. triangle, square, and sawtooth. These graphs represent the way in which the air pressure changes during several cycles.

Almost 200 years ago, the French mathematician Jean Baptiste Joseph Fourier discovered that any waveform can be distilled into a series of sine waves, which are the simplest possible waveforms. These sine waves exhibit different frequencies and amplitudes, and they are collectively known as the harmonic spectrum of the waveform. Individually, they are called harmonic components. The harmonic spectrum is normally depicted in a bar graph that reveals the frequency and amplitude of each component (see Fig. 1-4). The component with the lowest frequency is called the fundamental.

The harmonic components of a complex waveform can be any frequency, but most waveforms with a recognizable pitch consist of components that are whole-number multiples of the fundamental frequency. For example, if the frequency of the fundamental is 100 Hz, the frequencies of the higher components would be 200 Hz, 300 Hz, 400 Hz, and so on. This special type of harmonic spectrum is known as the harmonic or overtone series.

Although many people use the terms "harmonic" and "overtone" interchangeably, they are not exactly synonymous. Harmonics include all harmonic components, even the fundamental, whereas overtones include only the components above the fundamental, not the fundamental itself. For example, the second harmonic is the same as the first overtone. Fig. 1-4 is an example of a harmonic series.

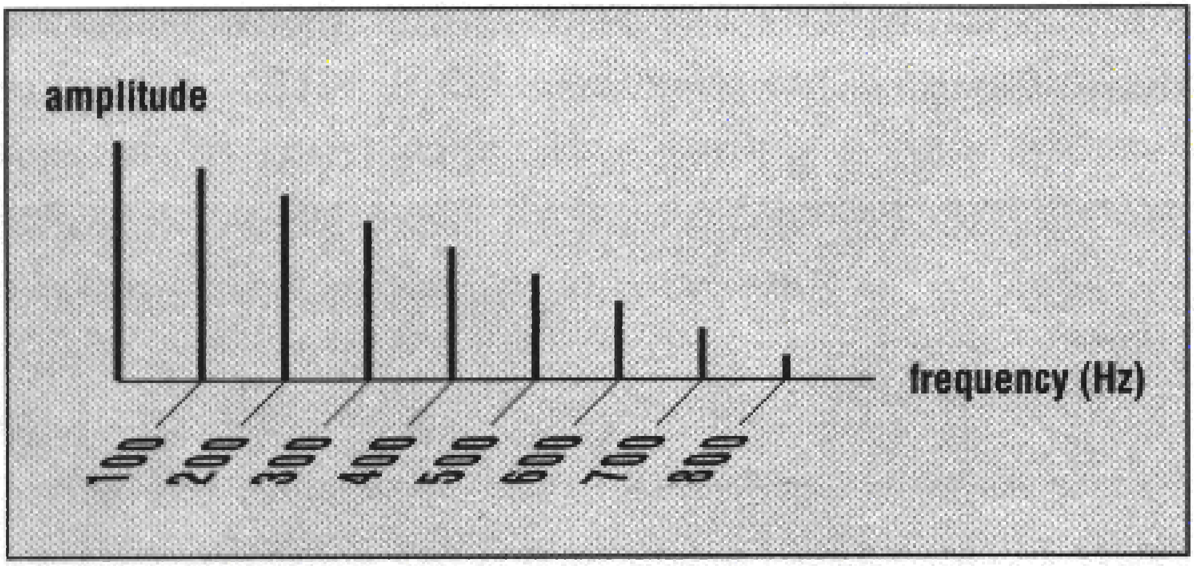

Figure 1-4. The harmonic spectrum of a sawtooth waveform. Each line represents one of the sine wave components. The horizontal position of each line indicates its frequency and the height indicates its amplitude relative to the other members of the spectrum.

Most musical instruments are especially resonant at certain frequencies, which are called formants. For example, the human vocal tract exhibits a formant at about 500 Hz, but trained singers can produce another formant at 2 to 3 kHz; this is known as the singer's formant. These frequencies are particularly pronounced in the spectrum of the instrument's sound regardless of the note being played. As a result, the shape of the harmonic spectrum changes as different notes are played.