Introduction to Sound

Acoustics for the Hearing and Speech Sciences

Fifth Edition

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With Contributions From

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Preface

The mission for this fifth edition remains unchanged. The aim is to *teach* the fundamental concepts of acoustics, particularly for students in the speech-language-hearing sciences. There have been a few modest changes in the ten chapters from the fourth edition. Each change was motivated by the desire to improve clarity in writing.

However, there is one spectacular change for this edition. Dr. Raymond Kent has consented to contribute a new chapter on **speech acoustics**. **Chapter 10** focuses on the acoustic theory of speech production, with a strong influence from the works of Gunnar Fant and Kenneth Stevens. **Chapter 10** is a survey of the acoustic properties of speech sound classes and some aspects of prosody. Professor Kent is a Fellow of the Acoustical Society of America, the International Society of Phonetic Sciences, and the American Speech-Language-Hearing Association. He is greatly respected for his expertise in acoustics of speech production and acoustic analysis of speech. He has been an outstanding teacher for many years at the University of Wisconsin-Madison. Ray also is highly regarded for his clarity of writing and for a passion that he shares with me—to teach fundamental concepts in a way that is easily understood. Ray's chapter will make this fifth edition a more comprehensive resource for students in the speech-language-hearing sciences.

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Chapter 10

CHAPTER 1

The Nature of Sound Waves

"If a tree falls in a forest and no one is around to hear it, is there sound?" The answer depends on the distinction between two different perspectives for defining sound: *physical* and *psychological*.

Albers (1970) wrote that sound "in the strict sense, is a compressional wave that produces a sensation in the human ear" (p. 36). When "sensation of hearing" is included in the definition of sound, the *psychological* attributes of sound are invoked: pitch, loudness, and timbre. In other words, from a psychological point of view, "sound is what we hear."

We certainly are aware of the many "sounds" around us—sounds such as human speech, the barking of a dog, the crying of an infant, the cooing of a dove or of a "significant other," music of all forms, thunder, traffic noises, and the exhilarating roar of water cascading down the side of a mountain. A psychological approach to defining sound is tempting. It might seem that it would be easier to understand the *physical events* that characterize sound by reference to the psychological sensations or feelings that are associated with the many sounds that we experience daily. But the reverse is more correct; it is easier to explore the nature of the psychological sensations to sound if we thoroughly understand the physical characteristics.

An alternative is to define sound from a *physical* perspective. Sound is defined by reference to properties of the *source* of the event called "sound" and to properties of a *medium* in which, or along which, sound is transmitted. When *physical* properties of sound are emphasized, sound does exist *even if the receiver is absent or is not functional.* In other words, sound exists even if no one is in the forest.

Many objects can serve as a source of sound: vocal folds; the strings of a piano, guitar, or violin; the membrane of a drum; the bars of a xylophone; the metal plates of cymbals; and so on. In each case there is one essential prerequisite for a body to be a source of sound—*it must be able to vibrate*. That requires two physical properties: **mass** and **elasticity.** All bodies in nature possess both of those two properties to some degree.

When a potential source of sound is set into *vibratory motion, or oscillation,* sound occurs, and the sound that is created can then be transmitted from the source through, or along, some medium. Air is probably the most familiar medium that we encounter. But, as we shall see, other molecular structures, such as, for example, water, wires, strings, glass, wood panels, steel rails, and so forth can also transmit sound. Because all molecular structures have some finite **mass** and **elasticity**, each is capable of being both a source of sound and a medium for its transmission. Of course, some structures will be more effective sources or more effective transmitters than others.

Although the properties that permit a structure to be a source of sound are essentially the same as the properties that permit a medium to transmit sound, it is convenient to describe the properties of the transmitting medium and the properties of the source separately.

PROPERTIES OF THE TRANSMITTING MEDIUM

Consider air as a medium for transmitting sound. Air consists of approximately 400 billion billion (4×10^{20}) molecules per cubic inch (**in.**). In the quiescent state (before a source of sound begins to vibrate), the air molecules move randomly at speeds that average nearly 940 miles per hour (**mph**), or 1,500 kilometers per hour (**kph**). Although molecular motion is random, the molecules maintain some *average distance* from one another. Thus, we can envision the molecules as being distributed evenly throughout the air space.

The billions upon billions of molecules exert a pressure on whatever they encounter. For example, when the randomly moving air molecules impinge on the human eardrum (or any other structure), pressure is exerted on the drum. Interestingly, as we shall see later, *that does not yet produce a sensation of "hearing" sound*. At sea level that pressure, which is called "atmospheric pressure," amounts to about 14.7 pounds (**lb.**) per square in. (**lb./in.^{2}**), and 14.7 lb./in.^{2} in the English measurement system is equivalent to approximately 100,000 newtons (**N**) per square meter (**N/m^2**) or 1,000,000 dynes per square centimeter (**dynes/cm^2**) in the metric systems. The **N/m^2** and **dyne/cm^2** will be defined later when the concepts of both force and pressure are developed more fully.

To conceptualize the pressure in air, consider the cylindrical tube shown in Figure 1–1, which has a cross-sectional area of 1 in.^{2} and extends from sea level to a height of more than 25 miles. At sea level, in the quiescent state, there is a pressure of approximately 14.7 lb./in.^{2} acting downward. At 10 miles above sea level, the pressure is reduced to about 1.57 lb./in.^{2}, and at a height of 25 miles, it is only a negligible 0.039 lb./in.^{2}

Air, and all other bodies that can serve to transmit sound, is characterized by two essential physical properties: **mass** and **elasticity**.

Mass

Mass is *the amount of matter present.* Air is a gaseous matter, but the definition of mass also holds for liquids and solids.

Mass Contrasted With Weight

Mass sometimes is confused with **weight**. **Mass** refers to the quantity of matter present, whereas **weight** refers to *the attractive gravitational force exerted on a mass by the earth.* For example, a person is said to weigh 160 lb. because the earth attracts the person with a force of 160 lb. If that person is flown to the moon, the same amount of matter is present, but because of the lessened gravitational pull, the weight amounts to about 27 lb. because the force of gravity is only about one-sixth as great on the moon as it is on earth. The

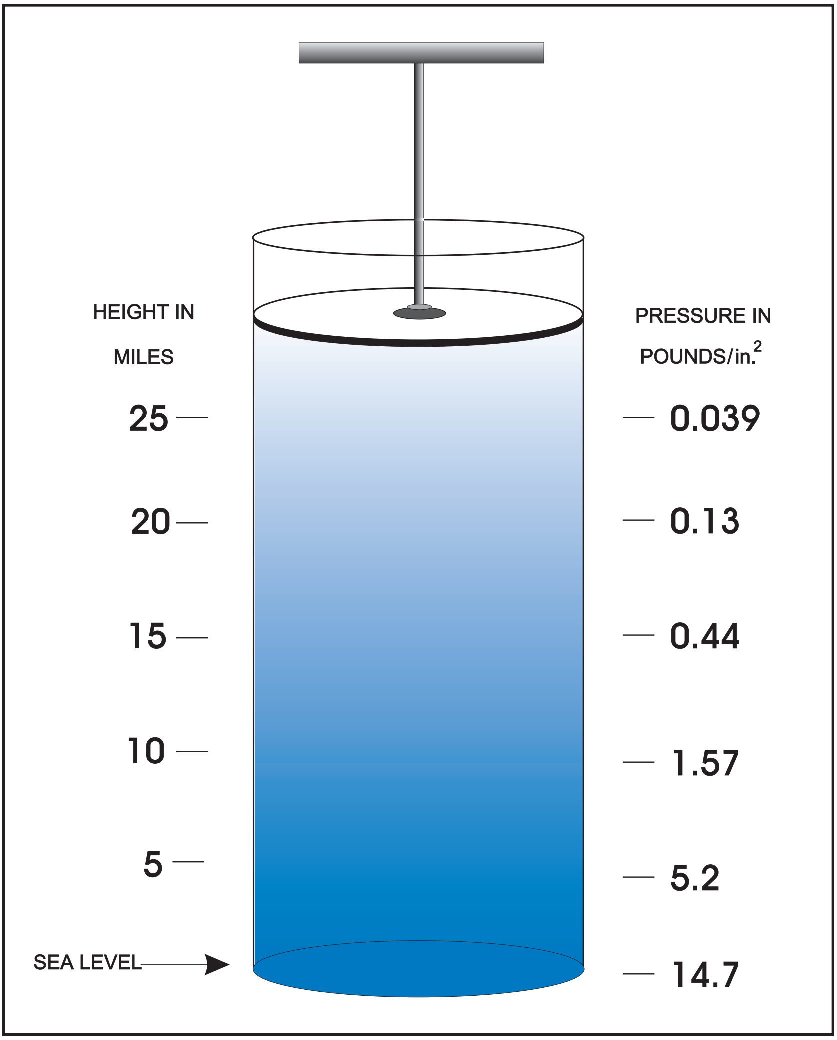

Figure 1–1. A cylindrical tube with a cross-sectional area of 1 in.^{2} that reflects how **pressure** and **density** in an air medium vary with height above sea level.

weight of an object *is directly proportional to its mass,* but weight and mass are simply different concepts. ***Weight*** *is a force, whereas* ***mass*** *is the quantity of matter present.*

Air has weight as well as mass. A cubic meter of air weighs about 1.3 kilograms (**kg**), and the air in a classroom with the dimensions of 9×12×4 m weighs about 560 kg. For those who are not yet comfortable with meters and kilograms, a cubic yard (**yd**) of air weighs 35.1 ounces (**oz**), and the air in a classroom with the dimensions of 30×40×12 feet (**ft.**) weighs about 1,170 lb. From that we might conclude that professors who deliver long lectures in a classroom of that size are "throwing a lot of weight around."

Mass and Density

It also is important to distinguish between **mass** and **density**. Look again at the cylindrical tube filled with air in Figure 1–1. The air molecules are crowded closely together (darkened regions) near the bottom of the tube, whereas they are rather far apart (lighter regions) in the higher portions of the tube. This occurs because of the pull of gravity.

Because of gravity, the molecules of the atmosphere accumulate near the surface of the earth. A downward force causes the molecules to be compressed into a smaller volume. The volume near the bottom of the tube is more densely packed, and when a greater number of molecules is compressed into a volume of a certain size, the **density** is increased.

Density (ρ) is *the amount of mass per unit volume.* For example, if we exert a force that causes a volume of 1 cubic in. of air to contain 800 billion billion (8×10^{20}) molecules instead of 400 billion billion (4×10^{20}), the density—the mass per unit volume—is doubled. It is easy to see in Figure 1–1 that *the amount of mass per unit volume in the cylinder decreases with increasing height above sea level.*

It might be difficult to imagine the different densities associated with the invisible molecules in volumes of air, but there are more visible examples that might make the distinction between mass and density clear. Imagine a grocery bag with a volume of 0.06 cubic meters that is filled with 50 loosely crumpled sheets of newspaper. If you pack the paper more tightly until the same amount of paper (50 sheets) occupies only half of the bag's volume (0.03 cubic meters), the same amount of matter is present—the **mass**—but the matter is packed into a smaller volume. After compression, the amount of mass per cubic meter—the **density**—has doubled.

With respect to the first property of a transmitting medium, it is useful to refer to both the **mass** of a medium and to the **density** of a medium, a quantity derived from mass. We shall subsequently explain what is meant by "a quantity *derived* from another quantity."

Elasticity (E)

Elasticity is the second property of a transmitting medium. All matter, whether gaseous, liquid, or solid, undergoes distortion of either shape or volume or both when a force is applied to it. Moreover, all matter is characterized by the tendency to "recover" from that distortion. The property that enables recovery from distortion to either shape or volume is **elasticity.** We shall see subsequently that elasticity is more properly defined as *the ability to resist changes in shape, volume, or position* rather than the ability to recover from such changes.

Imagine a weight attached to a spring suspended from the ceiling. When the spring is stretched and then released, it returns to its original position (and beyond) unless it has been "overloaded." By "overloaded" we mean that the original stretching of the spring is sufficient to exceed its **elastic limit.** If the applied force exceeds the elastic limit, deformation is permanent. If the applied force exceeds the elastic limit by a sufficient amount, the object breaks.

A portable radio has a spring that holds the battery in place. If you remove the spring, you can verify that it is relatively easy to stretch it so far that it will not "spring back" when released. Its elastic limit was exceeded. In some forms of matter, the elastic limit is very small. In other forms, such as tempered steel, the elastic limit is very large. The elastic limit of air is so large that it need not concern us.

With air, the concept of elasticity means *the tendency of a volume of air to return to its former volume after compression.* Return to the air-filled cylinder in Figure 1–1. We know that air molecules are present, that they are in random motion, that—on average—they are equidistant from each other, and that the density of the air is greater near the bottom of the tube.

Suppose we now insert a plunger into the cylinder and push downward. All molecules that were present in the full length of the tube are crowded (compressed) into a smaller space; the **density** is increased. When the plunger is removed, the air molecules return to their former "position," or more appropriately, *the air volume resumes the density* that existed before compression. The density of the air is *restored,* and the restoring force is **elasticity**.

PROPERTIES OF THE SOUND SOURCE

Let us now consider bodies that can serve as a *source of sound*. We will consider the same two properties that characterized the transmitting medium: **mass** (or density) and **elasticity**.

Vibratory Motion of a Tuning Fork

A tuning fork, as shown in Figure 1–2, is one source of sound. The tuning fork is a U-shaped metal bar. The prongs, or tines, of the fork have **mass** (a quantity of matter is present) and they also possess the restoring force of **elasticity**. Because of their elasticity, the tines of the fork return to their former position after they have been displaced. This is illustrated by striking the fork gently with a soft hammer. The tines are set into vibration, which takes the form of each tine moving back and forth.[1]

View Animation 1_2.
The Vibrating Tuning Fork

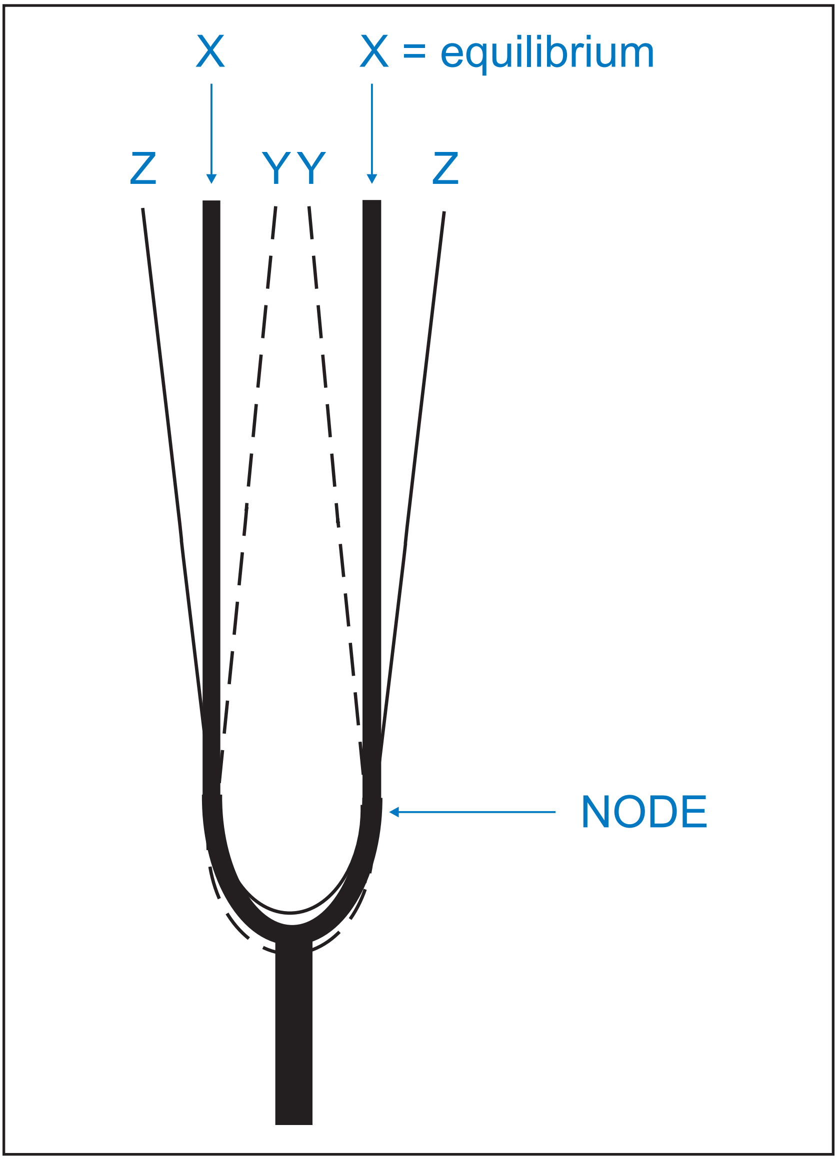

Figure 1–2. The vibratory pattern of a tuning fork, a U-shaped metal bar with the properties of **mass** and **elasticity**. Once struck, the tines move from **X** (equilibrium) to **Y** (maximum displacement in one direction), back to **X** to **Z** (maximum displacement in the other direction), and back to **X** to complete one **cycle** of vibration.

Displacement From Equilibrium

Imagine that we can "zoom in" and observe the pattern of vibration of the two tines. The position of the fork before a force is applied is its *equilibrium position*, and the heavy solid lines labeled **X** in