Chapter 1
Sound, Music, and Science

Sound is all around us. It warns us of danger, enables us to communicate with others, annoys us with its noise, entertains us by radio and iPods, and captivates us in music. It is an important part of the daily lives of hearing people.

We are concerned here with a *science* of sound, especially musical sound. There is something of a paradox in this concept. Sound itself tends to be personal and it often brings up an emotional response. On the other hand there is science, supposedly rational and objective. Merging these two aspects of human experience is the science and art of acoustics.

Acoustics is foremost a science. As such it is quantitative, attempting to account for the physical world and our perception of it in ways that can be measured with experiments and described with mathematical models. A quantitative science like acoustics operates with a number of ground rules:

- *Definitions*: We need precise definitions for ideas and for quantities. We often take common words and give them meanings that are more tightly constrained than in everyday speech. For instance, in the next chapter the word "period" will be given a precise mathematical meaning.
- *Simplification*: The real world is complicated. Science gains its power by simplification. For instance, everyday materials are complex compounds and mixtures of dozens of chemical elements, but the chemist uses pure chemicals to gain control of his experiment. In the same way, speech and music are complicated signals, but the acoustician uses signals that are no more complicated than necessary for the intended purpose.
- *Idealization*: The technique of idealization is like simplification in that it is a scientific response to a messy world. Idealization applies to the conceptual models that we use to explain some aspect of the world. An idealized model attempts to capture the essence of something, even though the model may not explain every detail. For instance, there is the concept that planets, like the Earth and Mars, orbit the Sun because of the Sun's strong gravitational attraction. That is a powerful model of our solar system. But, it is not a perfect model because the

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planets attract one another too, and this is not included in the basic heliocentric model of orbital motion. Nevertheless, the model successfully abstracts the most important character of planetary motion from a complicated real-world situation. This model is a useful idealization.

And so we begin with the science of acoustics ...

An acoustical event consists of three stages as shown in Fig. 1.1: First, the sound is generated by a *source*. Second, the sound is *transmitted* through a medium. Third, the sound is intercepted and processed by a *receiver*. These three stages form the basis of acoustical science. We consider them in turn and **highlight** items that we expect to study in detail.

1.1 The Source

The source of a sound is always a vibration of some kind. For example, it might be the vibration of a drumhead. A drum is a **traditional musical instrument**, and our approach makes a study of traditional musical instruments by their families: brass instruments, woodwind instruments, string instruments, and percussion instruments.

The **human voice** is another source of sound, arguably the most important of all. The basic science of the human voice is enormous fun because a few simple principles serve to take us a long way toward understanding what is going on acoustically.

A more modern source of sound is the **loudspeaker**. It too is a vibrating system, but unlike the other vibrating systems, it is not caused to vibrate directly by human action. The loudspeaker is a **transducer** that converts electronic signals into acoustical signals. This marriage of electronics and acoustics is called **audio**; its technological and cultural significance is so important that it is impossible to imagine modern life without it. It is closely allied with **broadcasting** by radio and TV. Audio technology has made possible two other kinds of musical instrument. One is the electrified instrument, where the vibrations of a physical object are converted into electronic form. For instance, the vibrations of a guitar string can be converted by a pickup into an electrical signal. The other is an **electronic instrument**, analog or digital, where the original vibrations are generated electronically.

Vibrations are so basic in the study of acoustics that the first chapters are dedicated to developing the terminology and basic mathematical relations for the study of vibration. These chapters also introduce electronic **instrumentation** used to study vibrations.

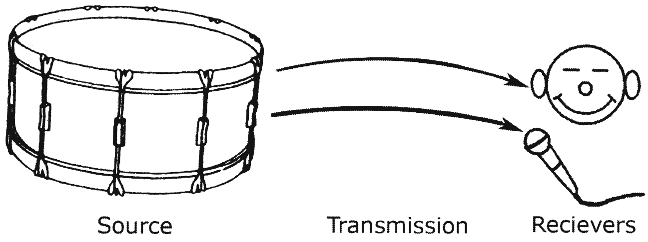

Fig. 1.1 A sound from a source is transmitted to two receivers, a human listener and a microphone

1.2 Transmission

The vibration of the drumhead causes the air around it to vibrate. This vibration propagates as a wave through the air. Accordingly, the study of waves occupies an important place in musical acoustics. The physics of waves is actually a long and deep subject because there is a rich variety of **wave phenomena**. We shall deal with some of the most fundamental properties. Wave motion is not only a characteristic of sound waves (acoustics), but also characterizes the transmission of light and radio waves. The wave principles that one learns in studying acoustics apply directly to optics (light) and electromagnetic radiation in the form of radio waves. Therefore, by learning about the weird things that can happen to an acoustical wave you immediately understand something about optical mirages and problems with your cell phone.

The transmission of sound from a source to a receiver does not take place entirely by a straight line path. The sound waves are reflected from the walls of a room and by other surfaces in the room. The character of the room puts its indelible stamp on the sound wave as it is finally received. This is the subject of **room acoustics**. It covers a lot of ground, from the problem of noise in your residence to the design of multi-million-dollar concert halls.

1.3 Receiver

The most important receiver of sound is the human ear and brain—the human auditory system. Sound waves, of the kind that we study in the musical acoustics, are meant to be heard, understood, and appreciated. In the final analysis, the strengths and limitations of the human auditory system determine everything else we do in acoustics. There are two basic divisions of subject matter in the study of human hearing; the first is the **anatomy** and **physiology** of the auditory system, the second is the **psychoacoustics**. The anatomy and physiology describe the tools we have to work with as listeners; the psychoacoustics describes the function of these tools, converting sound waves into perceptions. Important perceptual properties of sound include the **loudness** of tones, **pitch**, **tone color**, and **location**.

These three stages: source, transmission, and reception, appear in any acoustical experiment or experience, and they can be separately identified. The chapters that follow try to deal with the details of each stage in turn. It all starts with a source, specifically with vibration, which we begin in earnest in Chap. 2.

Comparisons

We make comparisons everyday. It is part of living. Some things are better—other things are worse. In a science like acoustics comparisons are usually quantitative. This section describes the most important quantitative comparisons.

Differences:

Quantitatively, difference means subtraction. We obtain a difference by subtracting two values. Thus if A has a length of 2 m and B has a length of 2.1 m, then the difference between B and A is a length of $2.1 - 2 = 0.1$ m.

You will notice that a difference has units—such as meters. It has the units of the quantities that are subtracted. It follows that we can only take differences between quantities that have the same kind of units. For instance, it is not possible to find the difference between 2 m and 3 kg.

It is possible, however, to find the difference between 2 m and 210 cm. Although meters and centimeters are different units, they are the same *kind* of units. They are both lengths. Still, one cannot take the difference directly. The difference calculation $210-2$ would give a nonsensical answer. To take differences of quantities expressed in different units of the same kind requires a conversion of units so that the quantities being subtracted have identical units. In this instance we might chose to convert 210 cm to 2.1 m and take the difference $2.1-2.0-0.1$ m, as before. Alternatively, we might choose to convert 2 m to 200 cm and take the difference $210 - 200 = 10$ cm. Either way is correct.

Ratios

Quantitatively, ratio means division. Two quantities are compared by dividing one by the other. Thus if A has a length of 2 m and B has a length of 2.1 m, then the ratio of B to A is $2.1/2.0 = 1.05$. Another word that is often used in connection with the ratio concept is the word "factor." We say that B is greater than A by a factor of 1.05. The implication of this statement is that we can find out how big B is by starting with A and multiplying by a factor of 1.05. If "ratio" means divide, then "factor" means multiply.

You will notice that a ratio does not have any units. That makes it very different from a difference. So whereas $2.1-2.0 = 0.1$ and $210-200 = 10$, the ratio 2.1/2.0 equals 1.05 and the ratio 210/200 also equals 1.05. We can go further: A length of 2.1 m is 82.677 in. and a length of 2.0 m is 78.74 in. The ratio 82.677/78.74 is also equal to 1.05. Coming out in a unitless way like this gives the ratio comparison a certain conceptual advantage over the difference comparison. But in order for the ratio comparison truly to have no units, the quantity in the numerator and the quantity in the denominator must have the *same* units. Thus it would be wrong to find the ratio of (210 cm)/(2 m) = 105. The number 105 is not a correct ratio.

Of course, there are division operations that are not ratio comparisons. For example 100 km driven in 2 h corresponds to an average speed of 50 km/h. Dividing 100 km by 2 h leads to a speed which has physical units and therefore is not a ratio comparison.

Percentages

Percentages are just like ratios. If A is 2.0 and B is 2.1, then the ratio of A to B is 2.0/2.1, which is about 0.952. We say that A is 95.2 % of B. Alternatively we could calculate the ratio $2.1/2.0 = 1.05$ and say that B is 105 % of A. Either way, we get a percentage comparison by multiplying a ratio by 100.

Percentage Change

The percentage *change* is a more common comparison than the percentage comparison. The percentage change combines the concepts of difference and ratio. It is the difference between two quantities divided by one of those two original quantities. In terms of a fraction, the difference is in the numerator and one of the two quantities is in the denominator. The quantity in the denominator is the reference quantity. The concept of change is that we start with something and end up with something else. The reference quantity is what we start with.

In terms of quantities A and B, the percentage change from A to B has A in the denominator.

$$\text{Percent change} = (B - A)/A \tag{1.1}$$

We can apply this equation to a change in height.

Example 1: At age 16 Shaquille O'Neal was A = 201 cm tall. By age 21 he had grown to be B = 216 cm tall. The percentage change is a growth of $(216 - 201)/201 = 0.075$ or 7.5 %. The reference quantity is the height in the starting year, namely 201 cm.

Example 2: Alternatively we might start with a sandwich that is A = 2.1 m long and nibble on it until it is B = 2.0 m long. The percentage is a decrease, namely a negative change, $(2.0 - 2.1)/2.1 = -0.0476$, a decrease of 4.76 %. The reference quantity is the starting sandwich length of 2.1 m.

There is a simple relationship between the ratio and the percentage change indicated by the end of Eq. (1.2)

$$\text{Percent change} = (B - A)/A = B/A - 1. \tag{1.2}$$

Equation (1.2) shows that the percentage change is always the difference between a ratio (like B/A) and the number 1. That little bit of algebra will prove helpful in some of the exercises later in this book. Like a ratio, the percentage change has no units.

Example 3: At the start of the year 2009, the Dow Jones Industrial Average of stock prices was 8776. At the end of the year, it was 10428. The change for 2009 was

$$10428./8776. - 1. = 0.188 \tag{1.3}$$

or 18.8 %.

Powers of ten

Powers of ten are illustrated with their prefixes by introducing the fictitious unit of the Snurk.

One gigaSnurk = 10^9 Snurks = 1,000,000,000 Snurks (one billion)*
One megaSnurk = 10^6 Snurks = 1,000,000 Snurks (one million)
One kiloSnurk = 10^3 Snurks = 1,000 Snurks (one thousand)
One milliSnurk = 10^{-3} Snurks = 1/1000 Snurks (one thousandth)
One microSnurk = 10^{-6} Snurks = 1/1,000,000 Snurks (one millionth)
One nanoSnurk = 10^{-9} Snurks = 1/1,000,000,000 Snurks (one billionth)

Scientific notation

21,000 Snurks = 2.1×10^4 Snurks
0.00345 Snurks = 3.45×10^{-3} Snurks

*As of 1975, 1,000,000,000 is both the American and the British billion.

Exercises

Exercise 1, Classification
In the categories of Source, Transmission, and Receiver, how would you classify a reflecting wall? A musical instrument? A microphone?

Exercise 2, Sound goes everywhere
Sound not only propagates in air, but also propagates in water and even in solids. What good is that?

Exercise 3, Bad conditions
Under what conditions have you had difficulty hearing something that you wanted to hear?

Exercise 4, Idealized models

Sam says, “Models of the world are essential for human thought. Without models every experience would be a brand new event. Models provide a context in which experiences fit, or don’t fit.”

Pam says, “Models of the world can be dangerous. They lead to assumptions about events and people that may not be true. Models can prevent you from seeing things as they truly are.”

Defend Sam or Pam, or both.

Exercise 5, More waves

The text mentions sound waves, light waves, and radio waves. What other kinds of waves do you know?

Exercise 6, More Shaq

At age 16 Shaquille O’Neal weighed 120 kg. At age 21 his weight was 137 kg. Calculate the difference, the ratio, and the percentage of change over those 5 years.

Exercise 7, Investment experience

On Monday your investment loses 10 % of its value. However, on Tuesday your investment gains 10 %. Do those two changes perfectly cancel each other? (a) Show that these two changes actually cause you to lose 1 %. (b) Would the net result be different if you gained 10 % on Monday and lost 10 % on Tuesday?

Exercise 8, Powers of ten

Recall that $10^3 \times 10^5 = 10^8$. Now evaluate the following:

(a) $10^3 \times 10^2 \;=?$ (b) $10^3/10^2 \;=?$ (c) $10^3 \times 10^{-2} \;=?$ (d) $10^3/10^{-2} \;=?$ (e) $10^3 + 10^2 =?$

Exercise 9, Scientific notation

Express the following in scientific notation: (a) $20 billion. (b) Ten cents. (c) 231,000. (d) 0.00034.

Exercise 10, micro, milli, kilo, mega

(a) How many seconds in a megasecond? (b) How many microseconds in a second? (c) How many milliseconds in a kilosecond?

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