8.5 Properties of Sound Waves

Sound waves form one of our major sensory links to the world, so it is important to understand their properties. Without sound, we would be unable to communicate by speech, hear music, or know when someone has approached us from behind.

Categories of Sound Waves

audible sound wave sound wave in the range of human hearing, 20 Hz to 20 kHz

infrasonic wave sound wave with a frequency below 20 Hz

ultrasonic wave sound wave with a frequency above 20 kHz

Sound waves fall into three categories covering different ranges of frequencies. **Audible sound waves** lie within the range of sensitivity of the human ear, approximately 20 Hz to 20 kHz for healthy young adults. The human ear is most effective at detecting sound in the range of 1 kHz to 5.5 kHz. **Infrasonic waves** have frequencies below the audible range. Earthquake waves are an example of infrasonic waves (Chapter 10). **Ultrasonic waves** have frequencies above the audible range for humans.

Applications of Ultrasonic Waves

Ultrasonic waves (ultrasound) are widely used in medical applications, both as a diagnostic tool and in certain treatments. Internal organs can be examined using the images produced by the reflection and absorption of ultrasonic waves. Although ultrasonic waves are far safer than X-rays, their images may not have as much detail.

Figure 1 This ultrasound image shows a healthy fetus, about 6 months old.

Physicians commonly use ultrasound to observe fetuses (**Figure 1**). This technique presents far less risk than using X-rays, which deposit more energy in cells and can produce birth defects. An image of the fetus is obtained by using a transducer placed on the mother's abdomen, which emits the ultrasonic waves. The waves reflect off the fetus and other tissue, and the reflected sound waves are picked up by the transducer. They are then converted to an electric signal, which is used to form an image on a fluorescent screen. Difficulties such as the likelihood of spontaneous abortion are easily detected with this technique. Fetal abnormalities such as water on the brain are also readily observed.

Ultrasound is also used to break up kidney stones that are otherwise too large to pass. Previously, invasive surgery was more often required.

CAREER LINK

Radiologists and ultrasound technicians use ultrasound waves and computer imaging to scan patients' bodies, to gauge the progress of pregnancies, to detect tumours, and more. To learn more about these careers,

GO TO NELSON SCIENCE

Another application of ultrasound is the ultrasonic ranging unit used in some cameras. This unit provides an almost instantaneous measurement of the distance between the camera and the object to be photographed. The principal component of this technology is a crystal that acts as both a loudspeaker and a microphone. An ultrasound pulse is transmitted from the transducer to the object, which then reflects part of the signal, producing an echo that is detected by the device. An **echo** is the sound that reflects off a surface back to the device (or person) that produced the sound. The time interval between the outgoing pulse and the echo is electronically converted to a distance, using the known quantity of the speed of sound.

echo the sound energy reflected off a surface back to the producer of the sound

Research This

Using Ultrasound Technology in Medicine

Skills: Researching, Analyzing, Communicating — SKILLS HANDBOOK A5.1

A relatively new medical application using ultrasound technology is the cavitron ultrasonic surgical aspirator (CUSA).

1. Research this technology using the Internet and/or print resources.

A. What does this technology do? K/U

B. Explain how this technology works. K/U C

C. Why is this technology preferred over traditional surgery? T/I C

GO TO NELSON SCIENCE

The Speed of Sound

It has been determined experimentally that the speed of sound through air depends on the density of the air and its temperature. This value increases by 0.606 m/s for every increase of 1 °C. Using the equation below, you can calculate the speed of sound in air at different temperatures:

$$v = 331.4 \text{ m/s} + (0.606 \text{ m/s/°C})T$$

where T is the temperature in degrees Celsius. Tutorial 1 shows how to calculate the speed of sound in air using this equation.

Tutorial 1 Calculating the Speed of Sound

Sample Problem 1: Determining the Speed of Sound at a Certain Temperature

The temperature outside is 23 °C. What is the speed of sound in air at this temperature?

Given: $T = 23$ °C

Required: v

Analysis: The information given can be directly substituted into the equation for the speed of sound in air: $v = 331.4 \text{ m/s} + (0.606 \text{ m/s/°C})T$

Solution:

$$\begin{aligned} v &= 331.4 \text{ m/s} + (0.606 \text{ m/s/°C})T \\ &= 331.4 \text{ m/s} + (0.606 \text{ m/s/°C})(23 \text{ °C}) \\ v &= 345 \text{ m/s} \end{aligned}$$

Statement: The speed of sound in air at 23 °C is 345 m/s.

Sample Problem 2: Determining Air Temperature

If the speed of sound is measured to be 318 m/s, what is the current air temperature?

Given: $v = 318$ m/s

Required: T

Analysis: To solve for the temperature of the air, rearrange the original equation. Then substitute the given variable and calculate the answer: $v = 331.4 \text{ m/s} + (0.606 \text{ m/s/°C})T$

Solution:

$$\begin{aligned} v &= 331.4 \text{ m/s} + (0.606 \text{ m/s/°C})T \\ T &= \frac{v - 331.4 \text{ m/s}}{0.606 \text{ m/s/°C}} \\ &= \frac{318 \text{ m/s} - 331.4 \text{ m/s}}{0.606 \text{ m/s/°C}} \\ T &= -22.1 \text{ °C} \end{aligned}$$

Statement: The temperature of the air is −22.1 °C.

Practice

1. If the temperature of the air in your region is 32 °C, what is the speed of sound in air at that temperature? T/I [ans: 351 m/s]
2. If the speed of sound near you is 333 m/s, what is the ambient temperature? T/I [ans: 2.64 °C]
3. If the speed of sound near you is 350 m/s, what is the ambient temperature? T/I [ans: 31 °C]

Investigation 8.5.1

Measuring the Speed of Sound **(p. 404)**

In this investigation, you will predict the speed of sound on a certain day and then measure it. Make sure you understand how the equation for calculating the speed of sound works.

Mach Number

Mach number (M) the ratio of the airspeed of an object to the local speed of sound

Ernst Mach (1838–1916), an Austrian physicist, researched sound waves and devised a way to describe air speeds of objects in terms of the speed of sound. Mach's approach relates the local speed of sound and the airspeed (speed relative to the surrounding air) of an object, such as an aircraft. (Section 8.6 describes what happens when aircraft travel at the speed of sound, as well as the history of aircraft attempting to reach that speed.) The ratio of the airspeed to the local speed of sound is called the **Mach number**:

$$M = \frac{\text{airspeed of object}}{\text{local speed of sound}}$$

Note that the ratio has no units. For this reason, when describing the speed of an object using the Mach number, we say Mach 1, Mach 2, and so on. Mach 1, for instance, means that the object is travelling at the speed of sound. An aircraft's Mach number is not fixed—it changes depending on the speed of sound in its vicinity. For example, an aircraft travelling at fixed speed from Helsinki, Finland, to Havana, Cuba, would have different Mach numbers at the two places because of different air temperatures and pressures. Tutorial 2 shows how to calculate Mach numbers.

Tutorial 2 Calculating the Mach Number

Sample Problem 1

An aircraft is flying at 905 km/h in air at the temperature −50.0 °C. Calculate the Mach number associated with this speed.

Given: $T = -50.0\ °\text{C}$; $v = 905\ \text{km/h}$

Required: M

Analysis: Calculate the speed of sound in air at a temperature of −50.0 °C. The speed of the airplane must be converted into metres per second and the calculation made using the Mach number equation.

Solution:

$$v = 331.4\ \text{m/s} + (0.606\ \text{m/s/°C})T$$
$$= 331.4\ \text{m/s} + (0.606\ \text{m/s/°C})(-50.0\ °\text{C})$$
$$v = 301.1\ \text{m/s (one extra digit carried)}$$

$$905\ \frac{\cancel{\text{km}}}{\cancel{\text{h}}} \times \frac{1000\ \text{m}}{1\ \cancel{\text{km}}} \times \frac{1\ \cancel{\text{h}}}{3600\ \text{s}} = 251.4\ \text{m/s}$$

$$M = \frac{\text{airspeed of object}}{\text{local speed of sound}}$$
$$= \frac{251.4\ \text{m/s}}{301.1\ \text{m/s}}$$
$$M = 0.835$$

Statement: The Mach number is 0.835.

Practice

1. If the local speed of sound is 344 m/s and an aircraft is flying at 910 km/h, what is the Mach number? T/I [ans: 0.73]
2. If the Mach number is 0.93 and the local speed of sound is 320 m/s, what is the speed of an airplane in these conditions? T/I [ans: 3.0×10^2 m/s = 1100 km/h]
3. If the Mach number is 0.81 and the speed of an airplane measured by radar is 850 km/h, what is the local speed of sound in kilometres per hour? T/I [ans: 290 m/s = 1.0×10^3 km/h]

The Speed of Sound in Various Media

As you learned in Section 8.4, waves travel more rapidly in certain solids (rigid intermolecular forces) and in hotter gases than in cooler gases. Thus, the speed of sound depends not only on the temperature of the medium but also on the medium's properties. **Table 1** lists the speed of sound in different media.

Table 1 Speed of Sound in Various Media

Medium	Speed of sound (m/s)
air (20 °C)	344
air (0 °C)	331
air (−20 °C)	319
glass (Pyrex)	5170
steel	5000
water	1496
wood (maple)	4110

Sound Intensity

Loudness describes how humans perceive sound energy. Loudness depends on a quantity called sound intensity.

It is important to think about how humans experience the transfer of energy in a wave. In Section 8.2, you learned that sound energy is a longitudinal wave and that the amplitude of a longitudinal wave is a difference in pressure. **Pressure** is defined as the force per unit area. Mathematically,

$$p = \frac{F}{A}$$

pressure (p) the force per unit area

You have also learned that waves transfer energy. The amplitude of a wave is an indirect measure of how much energy the wave is transferring. So, for a sound wave, the larger the amplitude, the louder the sound you perceive. This energy transfer is also related to area. Recall from Chapter 5 that the rate of energy transfer is called power and its unit is the watt (W). The amount of sound energy being transferred per unit area is called the **sound intensity**. The units of sound intensity are watts per square metre, or W/m^2.

sound intensity the amount of sound energy being transferred per unit area; unit W/m^2

Human Perceptions of Sound Intensity

In terms of sound intensity, the threshold of hearing ranges from about 1×10^{-12} W/m^2 to about 1 W/m^2—a range of approximately 12 magnitudes. A more convenient way to deal with this large range is to use a unit called the **decibel** (dB). The decibel is one-tenth of a bel, symbol B. This unit is named in honour of Alexander Graham Bell, the inventor of the telephone. When using decibels, we refer to sound level, instead of sound intensity. For example, the difference between sound intensities of 10^{-12} W/m^2 and 10^{-8} W/m^2 is 10 000 units. This is expressed as a difference of 40 dB (or 4 bels). An increase in 3 dB is actually a doubling of the sound energy. The decibel gives measurements on a scale of about 0 to 100, with exceptionally loud sound levels exceeding 100, but rarely exceeding 200. **Table 2** shows sound intensities along with their equivalents in decibels from the threshold of human hearing up to sound intensities that are very dangerous to humans.

decibel (dB) the unit of sound level used to describe sound intensity level

LEARNING TIP

Logarithms
The unit bel is logarithmic. A logarithm is the exponent of 10 that would produce a given number. For example, if $x = 10^y$, then y is the base 10 logarithm of x. As y increases by 1, x increases by a factor of 10.

Table 2 Typical Sound Levels

Type of sound	Typical sound intensity (W/m^2)	Sound level (dB)	Type of sound	Typical sound intensity (W/m^2)	Sound level (dB)
threshold of human hearing	1×10^{-12}	0	jet flyover (at 300 m)	1×10^{-2}	100
normal breathing (at 1 m)	1×10^{-11}	10	rock band	0.1	110
typical whisper (at 1 m)	1×10^{-10}	20	jet aircraft engine (at 80 m), power saw	1.0	120
empty classroom	1×10^{-9}	30	threshold of pain	10	130
computer (at 1 m)	1×10^{-8}	40	military jet taking off	100	140
library	1×10^{-7}	50	space shuttle (at 180 m)	316	145
alarm clock (at 1 m)	1×10^{-6}	60	sound cannon (at 1 m)	1 000	150
vacuum cleaner (at 2 m)	1×10^{-5}	70	1 tonne TNT (at 30 m) (buildings 50 % destroyed)	380 000	175.8
diesel locomotive (at 30 m)	1×10^{-4}	80	tornado	1×10^{12}	240
motorcycle (at 10 m)	1×10^{-3}	90	atomic bomb	1×10^{13}	250

Mini Investigation

Testing Loudness

Skills: Planning, Performing, Observing, Analyzing, Communicating

SKILLS HANDBOOK A1.2, A2.1

Equipment and Materials: sound level meter or decibel meter

1. Measure the sound levels of music from a car stereo system or radio using the sound meter. Start at low loudness levels, and then increase the level to the value you normally use.

Do not listen to sustained loud sounds; they may damage your hearing.

2. Record the readings, and compare them to the values listed in Table 2.

A. Summarize your findings in a short report. Include a safety warning for this activity. T/I C

Table 3 Loudness as a Function of Distance

Distance (m)	Sound level (dB)
1	120
10	100
50	86
100	80
200	74
500	66
1 000	60
2 000	54
5 000	46
10 000	40

CAREER **LINK**

An audio technician operates and maintains audio equipment during such events as media broadcasts and theatrical performances. To learn more about becoming an audio technician,

GO TO NELSON SCIENCE

Loudness and Distance

You will have noticed that the farther you are from a sound, the quieter it becomes. As a sound wave expands from its source, the total energy it carries stays about the same, but the area of air that it acts upon increases greatly with distance. Therefore, the energy per unit area decreases, and your ear detects a quieter sound. **Table 3** shows examples of how distance affects the perceived loudness (sound level) we hear. Notice that the loudness drops off very quickly, but audible levels stay for quite a distance. However, as the distance increases, the sound level continues to decrease, but at a much-reduced rate. This is why you can hear aircraft that are 8 km in the air and fireworks in the distance.

Sound Safety

Any sound levels greater than 100 dB that persist for more than a few minutes will harm your hearing. If your job exposes you to such levels, you should wear hearing protection. Equipment for detecting loudness levels must be carefully calibrated. Such equipment is used to ensure safe working conditions as well as to monitor sound levels required for delicate equipment that can be damaged by high sound levels.

It is also important to realize that the louder a sound, the less time you can spend near it without damaging your hearing. **Table 4** shows some values of exposure time as a function of loudness. Notice that the times drop dramatically with louder sounds.

Table 4 Sound Exposure Times

Continuous dB	Permissible exposure time
85	8 h
88	4 h
91	2 h
94	1 h
97	30 min
100	15 min
103	7.5 min
106	3.75 min (<4 min)
109	1.88 min (<2 min)
112	0.94 min (~1 min)
115	0.47 min (~30 s)

8.5 Summary

- Audible sound waves range from 20 Hz to 20 kHz. Infrasonic waves have frequencies below 20 Hz. Ultrasonic waves have frequencies above 20 kHz.
- We can apply our understanding of the properties of sound to technologies that benefit society.
- The speed of sound through the atmosphere, in metres per second, is given by the relationship $v = 331.4\ \text{m/s} + (0.606\ \text{m/s/°C})T$, where T is the temperature in degrees Celsius.
- Sound intensity is a measure of the energy flowing through the unit area due to a sound wave.
- Human hearing can detect a range of sound intensities over many magnitudes in intensity.
- Loudness levels are usually described on the decibel scale, which is more convenient than the range of values for sound intensity. Loudness levels are dependent on the distance from the source of the sound.
- Sound levels in industry and recreation must be kept to a reasonable level to avoid hearing damage.

UNIT TASK **BOOKMARK**

You can apply what you learned about loudness to the Unit Task described on page 486.

8.5 Questions

1. Researchers at the University of Adelaide, Australia, are proposing to control cyanobacteria with ultrasound. Research this topic using Internet resources, and answer the following questions: A
   (a) What are cyanobacteria, and why are these bacteria important to control?
   (b) How are cyanobacteria traditionally controlled?
   (c) Why does the treatment propose using low-frequency ultrasound instead of high-frequency ultrasound?
2. An aircraft is flying at Mach 2. What does this mean? K/U
3. An aircraft is travelling at Mach 0.83 in air at 10 °C. What is its speed in kilometres per hour? T/I C
4. Explain why the speed of sound varies in the different materials in Table 1 on page 395. K/U C
5. In your own words, define (a) sound intensity, (b) loudness, and (c) decibel. K/U C
6. Why are different units required for sound intensity and loudness? K/U C
7. In your own words, describe the concept of sound intensity. K/U C
8. Research the loudness level that is safe for listening to music on, for example, a personal music player. T/I C
   (a) Is there a difference in the level depending on the length of exposure?
   (b) Suppose the volume scale of a personal music player ranges from 0 to 10. Suppose also that each level corresponds to an increase in volume of 10 dB. So volume 1 = 30 dB and volume 3 = 50 dB, and so on. What is the loudest level you should set your personal music player to if you listen to music for 2 h a day?
9. A busy city street can produce sound levels near 90 dB, depending on the number of large vehicles (**Figure 2**). Calculate the ratio of the sound intensity of a power saw to that of a city street. Refer to Table 2 on page 395. Express your answer in words. T/I C

Figure 2

10. A burglar coughs with an intensity of $2.35 \times 10^{-7}\ \text{W/m}^2$. The burglar alarm is sensitive to an intensity of $1.0 \times 10^{-10}\ \text{W/m}^2$ and will ring if the detected sound is 30 dB greater than its detection threshold. Will the burglar's cough be detected? T/I C
11. The federal government supports the construction of noise barriers (also called sound baffles) on the sides of highways that run through residential areas to reduce residential noise. Research highway traffic noise barriers. K/U A
    (a) What are the barriers made of?
    (b) How do they work?
    (c) How effective are the barriers in reducing residential noise?

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