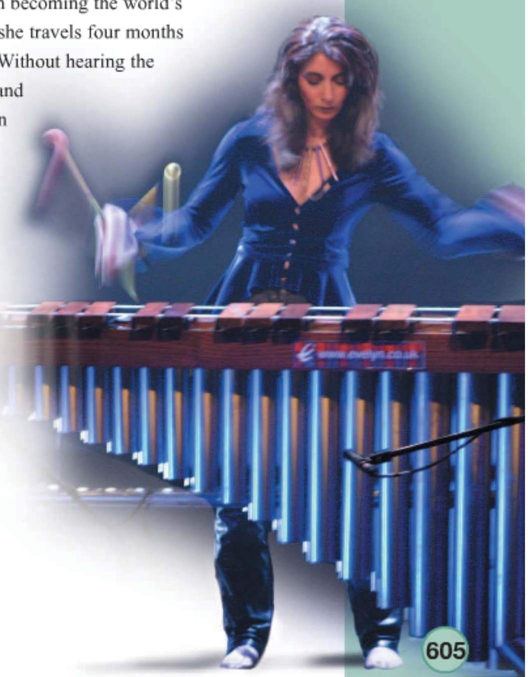
Chapter 24
Waves and Sound

What is sound? Is it something you hear? For many people, the answer is yes. However, for professional percussionist Evelyn Glennie, sound is something she feels. Glennie lost most of her hearing at age 12, but that didn't stop her from becoming the world's only full-time classical percussion soloist. As a professional musician, she travels four months of every year to give about 100 performances to awestruck audiences. Without hearing the music, how is she able to play so well? First of all, she plays barefoot and feels the vibrations through her feet! She can distinguish notes based on where on her body she feels the sound. In other words, sound is more than something to be heard. As you have learned, it's a type of wave. The next time you rap your pencil on your desk or play an instrument, pay attention to the sound waves you are making. Can you feel them? In this chapter, you will learn about waves, including the special kinds of waves we call sound.

Source: Evelyn Glennie, http://www.evelyn.co.uk used with permission.

Key Questions

- ✔ How can you describe the speed of a wave?
- ✔ How are water waves and sound waves similar and different?
- ✔ What makes each human voice unique?



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24.1 Harmonic Motion

We all use linear motion to travel from one place to another, either on foot or by bicycle or car. **Linear motion** goes from one place to another without repeating (Figure 24.1A). This chapter is about another type of motion. **Harmonic motion** is motion that repeats in cycles (Figure 24.1B). For example, water waves are a form of harmonic motion. The four seasons are caused by Earth's harmonic motion. Other types of harmonic motion cause your heartbeat and create sounds.

VOCABULARY

linear motion - motion that goes from one place to another without repeating.

harmonic motion - motion that repeats in cycles.

cycle - a unit of motion that repeats.

pendulum - a device that swings back and forth due to the force of gravity.

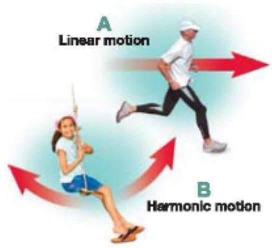


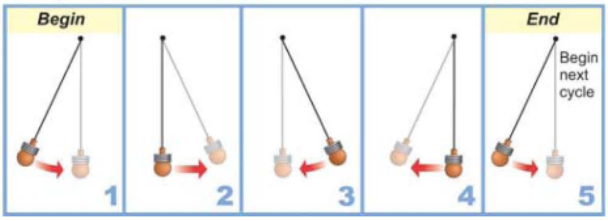
Figure 24.1: *(A) A sprinter is a good example of linear motion. (B) A person on a swing is a good example of harmonic motion.*

Motion in cycles

What is a cycle? To describe harmonic motion, we need to learn how to describe a repeating action or motion. A **cycle** is one unit of harmonic motion. This motion can be back and forth or a full revolution, or rotation. One full swing of a child on a swing is one cycle. As the child continues to swing, the back-and-forth motion, or cycle, repeats over and over again.

Looking at one cycle A **pendulum** is a device that swings back and forth. We can use a pendulum to better understand a cycle. Each box in the diagram below is a snapshot of the motion at a different time in one cycle.

The Cycle of a Pendulum



The cycle of a pendulum The cycle starts with (1) the swing from left to center. Next, the cycle continues from (2) center to right, and (3) back from right to center. The cycle ends when the pendulum moves (4) from center to left because this brings the pendulum back to the beginning of the next cycle. Once a cycle is completed, the next cycle(s) begins without any interruption in the motion.

Frequency and period

Oscillators An **oscillator** is a physical system that has repeating cycles (harmonic motion). A child on a swing is an oscillator, as is a vibrating guitar string. A wagon rolling down a hill is not an oscillator.

A period is the time to complete one cycle Because the speed of an oscillator constantly changes during its cycle, we don't use the term *speed* to describe how quickly a cycle repeats itself. Instead, we use the terms *period* and *frequency*. The time it takes for one complete cycle to happen is called a **period**. A clock pendulum with a period of one second will complete one full back-and-forth swing each second.

Frequency is the number of cycles per second The **frequency** is the number of complete cycles per second. The unit of one cycle per second is called a **hertz** (Hz). Something that completes 10 cycles each second has a frequency of 10 Hz. A guitar string playing the note A vibrates back and forth at a frequency of 220 Hz (Figure 24.2). Your heartbeat has a frequency from one-half to two cycles per second (0.5 Hz–2 Hz).

Frequency is the inverse of period Frequency and period are inversely related. The period is the number of seconds per cycle. The frequency is the number of cycles per second. For example, if the period of a pendulum is 2 seconds, its frequency is 0.5 cycles per second (0.5 Hz).

PERIOD AND FREQUENCY

$$T = \frac{1}{f}$$

Period (s), Frequency (Hz)

$$f = \frac{1}{T}$$

Frequency (Hz), Period (s)

When to use period or frequency While both period and frequency tell us the same information, we usually use period when cycles are slower than a few per second. A simple pendulum has a period from 0.9 to 2 seconds. We use frequency when cycles repeat faster. For example, the vibrations that make sound in musical instruments have frequencies from 20 to 20,000 Hz.

VOCABULARY

oscillator - a physical system that has repeating cycles.

period - the time it takes for one complete cycle to happen.

frequency - how often something repeats, expressed in hertz.

hertz - the unit of frequency. One hertz is one cycle per second.

Figure 24.2: *All musical instruments use harmonic motion to create sound.*

Solving Problems: Frequency and Period

The period of an oscillator is 2 minutes. What is the frequency of this oscillator in hertz?

1. Looking for: You are asked for the frequency in hertz.

2. Given: You are given the period in minutes.

3. Relationships: Convert minutes to seconds using the conversion factor 60 s/1 min. Use the formula $f = {}^{1}/_{T}$.

4. Solution: 2 minutes × 60 seconds/1 minute = 120 seconds

The period (T) is 120 seconds.

f = 1/120 s = 0.008 Hz

Your turn...

a. A pendulum completes one cycle every 5 seconds. What are the period and frequency of this pendulum?

b. The period of an oscillator is 1 minute. What is the frequency of this oscillator in hertz?

c. How often would you push someone on a swing to create a frequency of 0.4 hertz?

d. Figure 24.3 shows the parts of a pendulum clock. The minute hand moves 1/60 of a turn after 30 cycles. What is the period and frequency of this pendulum?

e. A ferris wheel spins 5 times in 10 minutes. Calculate the period and frequency of the ferris wheel.

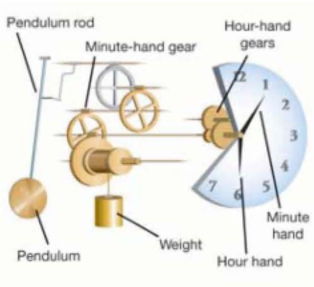


Figure 24.3: *The parts of a pendulum clock.*

SOLVE FIRST LOOK LATER

a. The period is 5 seconds and the frequency is 0.2 Hz.

b. The frequency is 0.02 Hz.

c. You would need to push once every 2.5 seconds.

d. There are 30 cycles/second, so the frequency is 30 Hz. The period is 0.03 second.

e. The frequency is 0.008 Hz. The period is 120 seconds, or 2 minutes.

Amplitude

Amplitude describes the "size" of a cycle

The "size" of a cycle is called **amplitude**. Figure 24.4 shows a pendulum with a small amplitude and one with a large amplitude. With a moving object like a pendulum, the amplitude is often a distance or angle. With other types of oscillators, the amplitude might be voltage or pressure. The amplitude of an oscillator is measured in units appropriate to the type of harmonic motion being described.

VOCABULARY

amplitude - the amount that a cycle moves away from equilibrium.

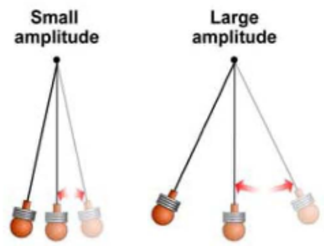
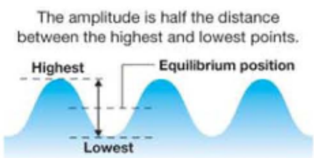


Figure 24.4: *Small amplitude versus large amplitude.*

How do you measure amplitude?

The amplitude is measured as the maximum distance the oscillator moves away from its equilibrium position. For the pendulum in Figure 24.5, the amplitude is 20 degrees because the pendulum moves 20 degrees away from the equilibrium position in either direction. The amplitude can also be found by measuring the distance between the farthest points the motion reaches. The amplitude is half this distance. The amplitude of a water wave is often found this way.



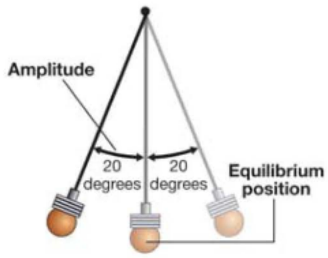
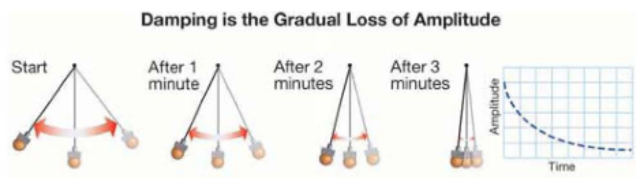


Figure 24.5: *A pendulum with an amplitude of 20 degrees swings 20 degrees away from the center in both directions.*

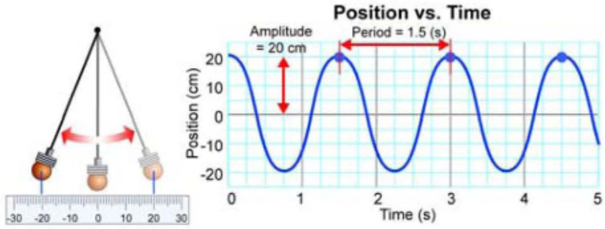
Damping and friction

Look at the illustration below. Friction slows a pendulum down, just as it slows all motion. That means the amplitude gets reduced until the pendulum is hanging straight down, motionless. We use the word *damping* to describe the gradual loss of amplitude. If you wanted to make a clock with a pendulum, you would have to find a way to keep adding energy to counteract the damping of friction so the clock's pendulum would work continuously.



Graphs of harmonic motion

Graphing harmonic motion It is easy to recognize cycles on a graph of harmonic motion. Figure 24.6 illustrates the difference between a graph of linear motion and a graph of harmonic motion. The most common type of harmonic-motion graph places time on the *x*-axis (horizontal) and position on the *y*-axis (vertical). The graph below shows how the position of a pendulum changes over time. The repeating "wave" on the graph represents the repeating cycles of motion of the pendulum.



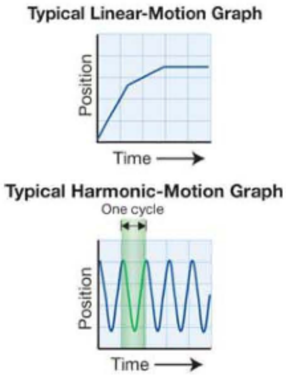


Figure 24.6: *A harmonic-motion graph shows repeating cycles.*

Finding the period In the graph above, the pattern repeats every 1.5 seconds. This repeating pattern represents the period of the pendulum, which is 1.5 seconds. If you were to cut out any piece of the graph and slide it left or right 1.5 seconds, it would line up exactly.

Using positive and negative positions Harmonic-motion graphs often use positive and negative values to represent motion on either side of a center (equilibrium) position. Zero usually represents the equilibrium point. Notice that zero is placed halfway up the *y*-axis so there is room for both positive and negative values. This graph is in centimeters, but the motion of the pendulum could also have been graphed using the angle measured relative to the center (straight down) position.

Showing amplitude on a graph The amplitude of harmonic motion can also be seen on a graph. The graph above shows that the pendulum swings back and forth from +20 centimeters to –20 centimeters. The equilibrium position is represented as the zero line. Therefore, the amplitude of the pendulum is 20 centimeters.

SOLVE IT!

Measuring Amplitude

Use a protractor to find the amplitude (in degrees) of the pendulum in the graphic below.

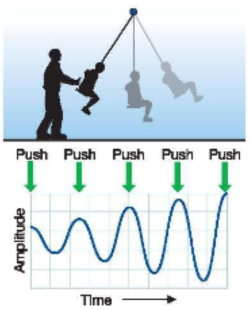
Natural frequency and resonance

Natural frequency An oscillator will have the same period and frequency each time you start it moving. This phenomenon is called **natural frequency**, the frequency at which a system naturally oscillates. Musical instruments use natural frequency. For example, guitar strings are tuned by adjusting their natural frequency to match musical notes (Figure 24.7).

Changing natural frequency The natural frequency of an oscillator changes according to its length. In the case of a vibrating guitar string, you can shorten the string to increase the force pulling the string back toward equilibrium. Greater force means greater acceleration, so the natural frequency is higher and the period is shorter. Lengthening an oscillator results in a lower frequency and a longer period.

How mass affects oscillators For oscillators with side-to-side movement, increasing the mass means the oscillator moves slower and the period gets longer. This is because of Newton's second law of motion—as mass increases, the acceleration decreases proportionally. However, for a pendulum, changing the mass does NOT affect its period (also because of Newton's second law). This is because the force of gravity keeps the pendulum moving through a center, or equilibrium, position. As in free fall, if you add mass to a pendulum, the added inertia is exactly equal to the added force from gravity. The acceleration is the same; therefore, the period stays the same.

Periodic force and resonance



A force that is repeated over and over is called a **periodic force**. A periodic force supplies energy to an oscillator and has a cycle with an amplitude, frequency, and period. **Resonance** happens when a periodic force has the same frequency as the natural frequency. For example, small pushes (a periodic force) to someone on a swing add together if they are applied at the right time (once each cycle). In time, the amplitude of the motion grows and can become very large compared to the strength of the force!

VOCABULARY

natural frequency - the frequency at which a system oscillates when disturbed.

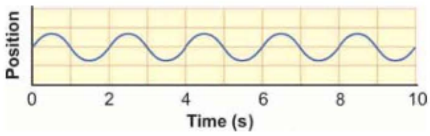
periodic force - a repetitive force.

resonance - an exceptionally large amplitude that develops when a periodic force is applied at the natural frequency.

Figure 24.7: *This guitarist is tuning his guitar by adjusting the natural frequency of the strings to match particular musical notes.*

24.1 Section Review

1. Which is the better example of a cycle: a turn of a wheel or a slide down a ski slope?
2. Describe one example of an oscillating system you would find at an amusement park.
3. What is the relationship between period and frequency?
4. Every 10 seconds a pendulum completes 2 cycles. What are the period and frequency of this pendulum?
5. What is the difference between a graph of linear motion and a graph of harmonic motion?
6. A graph of motion of a pendulum shows that it swings from +5 centimeters to –5 centimeters for each cycle. What is the amplitude of the pendulum?
7. What is the period of the oscillation shown in the diagram below?



8. Figure 24.8 shows a sliding mass on a spring. Assume there is no friction. Could this system oscillate? Explain why or why not.
9. Which pendulum in Figure 24.9 will have the longer period? Justify your answer.
10. Why does mass NOT affect the period of a pendulum?
11. Resonance happens when:
    a. a periodic force is applied at the natural frequency.
    b. an oscillator has more than one natural frequency.
    c. a force is periodic and not constant.
    d. the amplitude of an oscillator grows large over time.

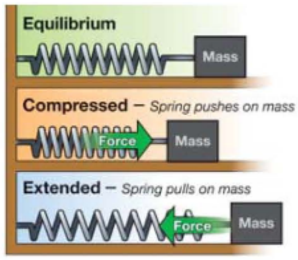


Figure 24.8: *Question 8.*

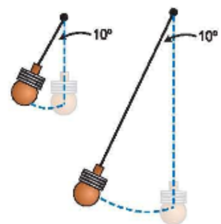


Figure 24.9: *Question 9.*