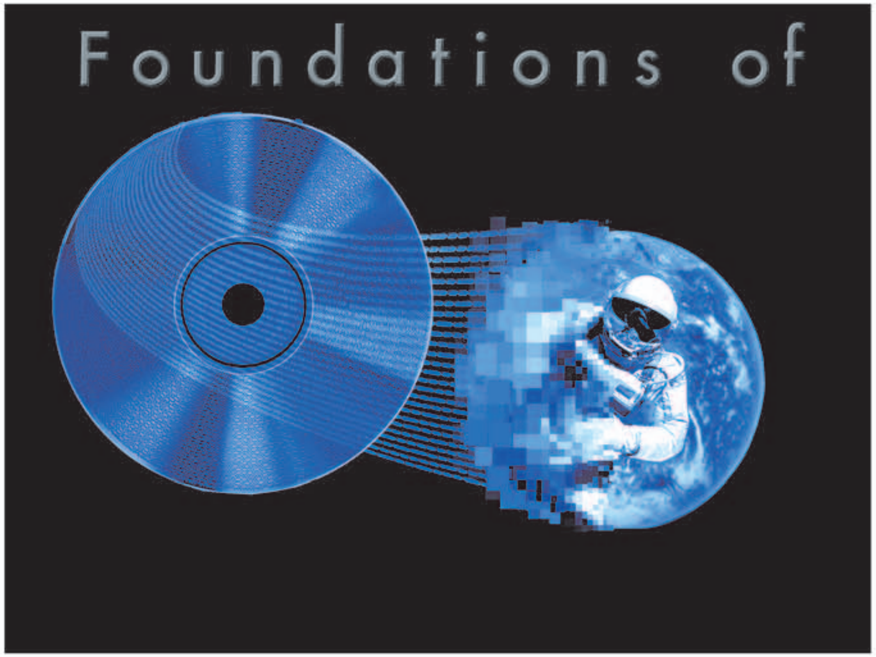

Physics

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About the Author

Dr. Thomas C. Hsu is a nationally recognized innovator in science and math education and the founder of CPO Science (formerly Cambridge Physics Outlet). He holds a Ph.D. in Applied Plasma Physics from the Massachusetts Institute of Technology (MIT), and has taught students from elementary, secondary and college levels across the nation. He was nominated for MIT's Goodwin medal for excellence in teaching and has received numerous awards from various state agencies for his work to improve science education. Tom has personally worked with more than 12,000 K-12 teachers and administrators and is well known as a consultant, workshop leader and developer of curriculum and equipment for inquiry-based learning in science and math. With CPO Science, Tom has published textbooks in physical science, integrated science, Earth and space science, and also written fifteen curriculum Investigation guides that accompany CPO Science equipment. Along with the CPO Science team, Tom is always active, developing innovative new tools for teaching and learning science, including an inquiry-based chemistry text.

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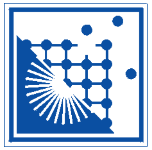

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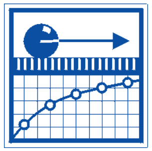

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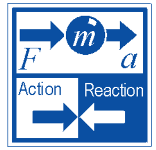

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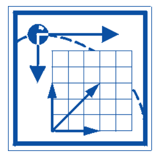

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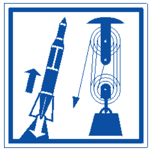

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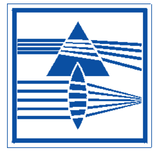

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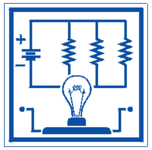

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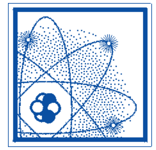
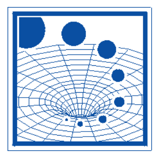




Unit 5

Waves and Sound

Chapter 13

Harmonic Motion

Objectives for Chapter 13

By the end of this chapter you should be able to:

1. Identify characteristics of harmonic motion, such as cycles, frequency, and amplitude.
2. Determine period, frequency, and amplitude from a graph of harmonic motion.
3. Use the concept of phase to compare the motion of two oscillators.
4. Describe the characteristics of a system that lead to harmonic motion.
5. Describe the meaning of natural frequency.
6. Identify ways to change the natural frequency of a system.
7. Explain harmonic motion in terms of potential and kinetic energy.
8. Describe the meaning of periodic force.
9. Explain the concept of resonance and give examples of resonance.

Terms and vocabulary words

harmonic motion	cycle	period	frequency	amplitude
hertz (Hz)	damping	periodic motion	periodic force	resonance
phase	phase difference	equilibrium	restoring force	stable equilibrium
unstable equilibrium	oscillator	natural frequency	steady state	piezoelectric effect

13.1 Harmonic motion

As you watch moving things, you see two different kinds of motion. One kind of motion goes from place to place without repeating. This is called *linear motion*. The concepts of distance, time, speed, and acceleration come from thinking about linear motion.

The second kind of motion repeats itself over and over. This is called **harmonic motion** and is the subject of this section. The word “harmonic” comes from *harmony* which means “multiples of.” Harmonic motion has multiple cycles, repeated over and over. A pendulum swinging back and forth is a good example of harmonic motion (Figure 13.1).

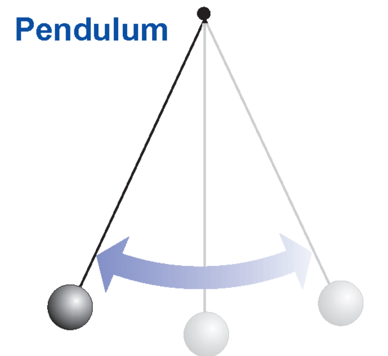


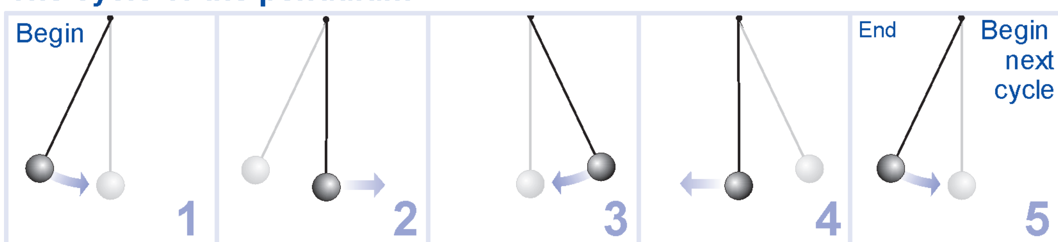
Figure 13.1: *A pendulum swings back and forth in harmonic motion.*

Cycles, systems, and oscillators

What is a cycle?

The **cycle** is the building block of harmonic motion. A cycle is a unit of motion that repeats over and over. All harmonic motion is a repeated sequence of cycles. The cycle of the pendulum is shown below.

The cycle of the pendulum



Finding the cycle

When investigating harmonic motion we start by identifying the basic cycle. A cycle has a beginning and an end. Between the beginning and end, the cycle has to include all the motion that repeats. The cycle of the pendulum is defined by where we choose the beginning. If we start the cycle when the pendulum is all the way to the left, the cycle ends when the pendulum has returned all the way to the left. The motion of the pendulum is one cycle after the other with no gaps between cycles.

Definition of an oscillator

A system in harmonic motion is called an **oscillator**. A pendulum is one example of an oscillator, a vibrating bead on a rubber band is another (Figure 13.2).

Figure 13.2: *A bead going back and forth on a stretched rubber band is a good example of an oscillator in harmonic motion.*

Harmonic motion is very common

Music comes from oscillations

Sound is an oscillation of the air. Musical instruments and speakers are oscillators that we design to create sounds. If you gently touch a speaker making sound, you can feel the rapid in-out cycles. The oscillation travels through the air to where it hits your eardrum. There is harmonic motion at every step, from the original musical instrument to the speaker to the detection of sound in your ear.

Oscillators are used in communications

Almost all modern communication technology relies on fast electronic oscillators. Cellphones use oscillators that make more than 100 million cycles each second. FM radio uses oscillators between 95 million and 107 million cycles per second. When you tune a radio you are selecting the frequency of the oscillator you want to listen to. Each station sets up an oscillator at a different frequency. Sometimes you can receive two stations at once when you are traveling between two radio towers with nearly the same frequency.

Oscillators are used to measure time

The cycles of many oscillators always repeat in the same amount of time. This makes harmonic motion a good way to keep time. If you have a pendulum that has a cycle one second long, you can count time in seconds by counting cycles of the pendulum. Grandfather clocks and mechanical watches count cycles of oscillators to keep time (Figure 13.3). Even today, the world's most accurate clocks keep time by counting cycles of light from a cesium atom oscillator. Modern atomic clocks are accurate to within one second in 1,400,000 years!

Natural cycles involving the Earth

Earth is a part of several oscillating systems. An *orbit* is a type of cycle because it is repeating motion. The Earth-sun system has an orbital cycle of one year, which means Earth completes one orbit around the sun in a year. The Earth-moon system has a orbital cycle of approximately one month. Earth itself has several different cycles (Figure 13.4). The Earth rotates on its axis once a day, creating the 24-hour cycle of day and night. There is also a wobble of the Earth's axis that completes a full cycle every 22,000 years, moving the orientation of the north and south poles around by hundreds of miles. There are cycles in weather, such as El Niño and La Niña oscillations in ocean currents that produce fierce storms every decade or so. Much of our planet's ecology depends on cycles.

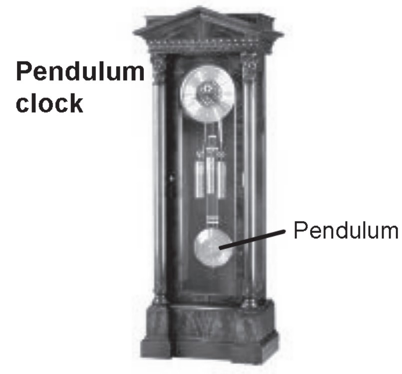


Figure 13.3: *A pendulum clock uses the period of a pendulum to count time.*

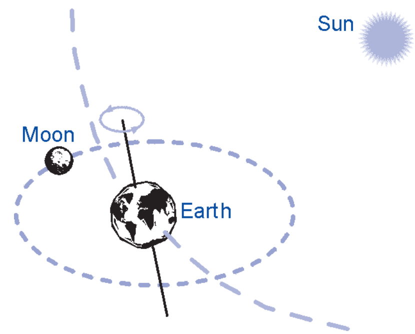


Figure 13.4: *The Earth, moon, and sun form a system with many cycles.*

Describing harmonic motion

Choosing a system

In science we often refer to "a system." A system is a group we choose that includes all the things we are interested in. Choosing the system helps us concentrate on what is important and exclude what is not important. For the pendulum, the system is the hanger, string, and weight. We do not need to include the floor or the table, since these are not directly important to the motion.

We choose a system depending on what we want to investigate. If we wanted to see how gravity affected the pendulum, then we would have to include Earth's gravity as part of the system.

Period is the time for one cycle

What makes harmonic motion useful for clocks is that each cycle takes the same amount of time. The time for one cycle is called the **period**. Some clocks have a pendulum with a period of two seconds. The clock's gears cause the minute hand to move one-sixtieth of a turn for every 30 swings of the pendulum. The period is one of the important characteristics of all harmonic motion (Figure 13.5).

Frequency is the number of cycles per second

Frequency is closely related to period. The **frequency** of an oscillator is the number of cycles it makes per second. Every day we experience a wide range of frequencies. Your heartbeat probably has a frequency between one-half and two cycles per second. A plucked rubber band might have a frequency of 100 cycles per second (Figure 13.6). The sound of the musical note "A" has a frequency of 440 cycles per second. The human voice contains frequencies mainly between 100 and 2,000 cycles per second. Frequency and period are inversely related. The period is the time per cycle. The frequency is the number of cycles per time.

Frequency is measured in hertz

The unit of one cycle per second is called a **hertz**. A frequency of 440 cycles per second is usually written as 440 hertz, or abbreviated 440 Hz. The hertz is a unit that is the same in English and metric measurement systems. When you tune into a station at 101 on the FM dial, you are setting the oscillator in your radio to a frequency of 101 megahertz (abbreviated MHz, which is 1 million hertz) or 101,000,000 Hz. You hear music when the oscillator in your radio is exactly matched to the frequency of the oscillator in the transmission tower connected to the radio station.

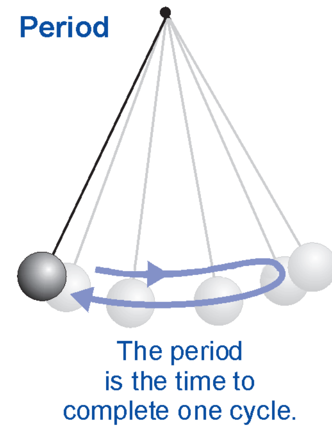


Figure 13.5: *The period is the time it takes to complete one cycle.*

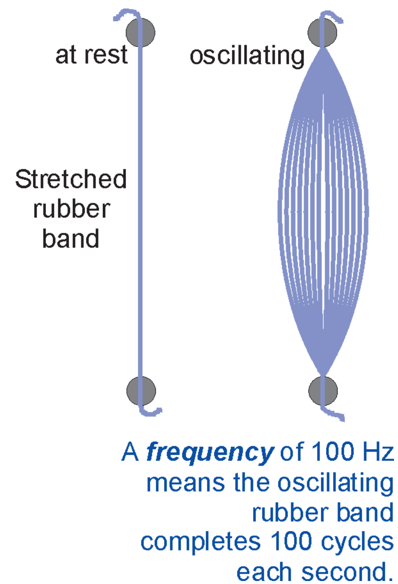


Figure 13.6: *The definition of frequency.*

Amplitude

Amplitude describes the size of a cycle

Another important characteristic of a cycle is its size. The period tells how long the cycle lasts. The amplitude describes how big the cycle is. With mechanical systems (such as a pendulum), the amplitude is often a distance or angle. With other kinds of oscillators, the amplitude might be voltage or pressure. The amplitude is measured in units that match the oscillation you are describing.

Measuring amplitude

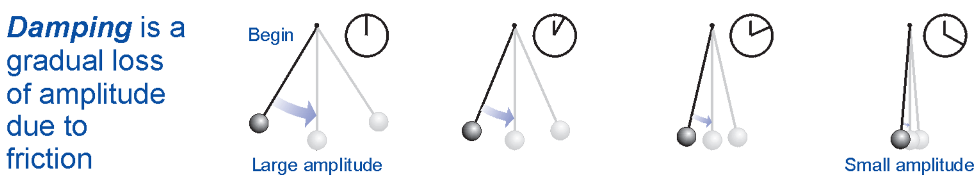
The amplitude is the maximum amount the system moves away from equilibrium. For a pendulum, the equilibrium is at the center. The amplitude is the amount the pendulum swings away from center (Figure 13.7). The amplitude is also half the total motion from one extreme to the other because a pendulum spends as much time to the right of center as it does to the left. It is often easiest to determine amplitude by measuring the total side-to-side motion and dividing by two.

Amplitude and energy

The motion of an oscillator has energy. Sometimes the energy is kinetic, as when the pendulum is swinging through the lowest point in its cycle and has its highest speed. At other times in the cycle the energy is potential, such as when the pendulum reaches the farthest point in the cycle and is raised above its equilibrium point. As you might suspect, the energy of an oscillator is proportional to the amplitude of the motion. Large-amplitude motions have higher energy than small-amplitude motions (Figure 13.8).

Damping

Friction drains energy away from motion and slows a pendulum down. Just as with linear motion, harmonic motion is reduced by friction. The effect of friction is to slowly reduce the amplitude of the system. If you start a pendulum swinging you will observe that the amplitude slowly decreases until the pendulum is hanging motionless. We use the word damping to describe the gradual loss of amplitude of an oscillator. Damping is due to friction acting to reduce motion.



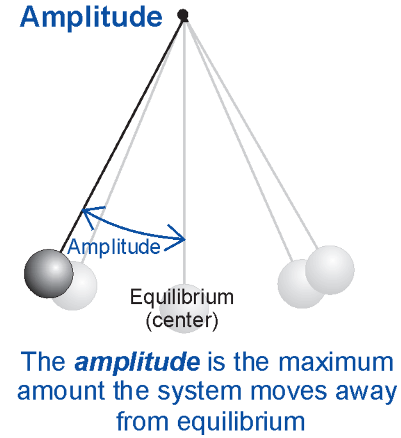


Figure 13.7: *The definition of amplitude.*

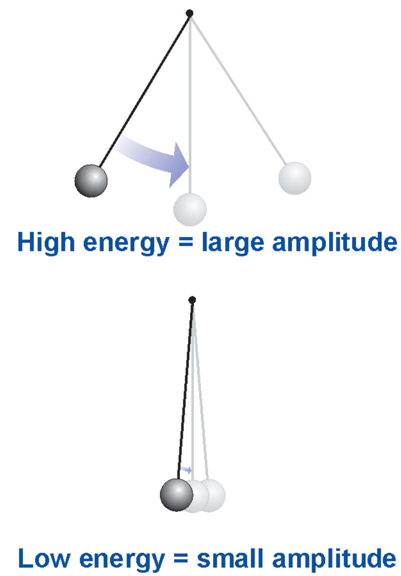


Figure 13.8: *The energy of an oscillator is proportional to its amplitude.*

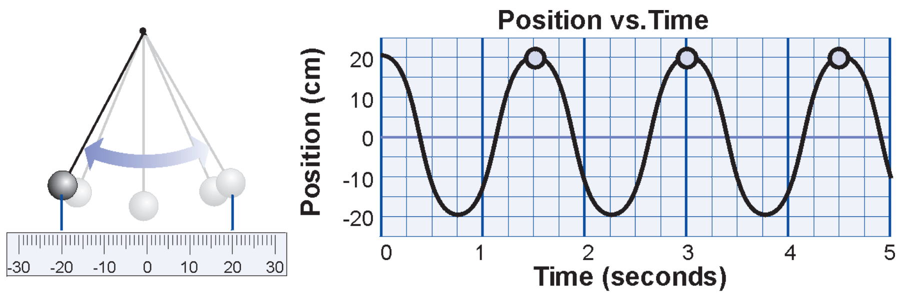
Harmonic motion graphs

Cycles and time

Harmonic motion graphs are easy to recognize because they show oscillation and cycles (Figure 13.9). Most graphs of harmonic motion show how things change with time. For example, the diagram below shows a graph of position versus time for a pendulum. The graph shows repeating cycles just like the motion. Seeing a pattern of cycles on a graph is an indication that harmonic motion is present.

Using positive and negative numbers

Harmonic motion graphs often use positive and negative values to represent motion on either side of center. We usually choose zero to be at the equilibrium point of the motion. The example graph below shows a pendulum swinging from plus-20 centimeters to minus-20 centimeters and back. The amplitude is the maximum distance away from center, or 20 centimeters.



Harmonic graphs repeat every period

Notice that the graph above returns to the same place every 1.5 seconds. No matter where you start, you come back to the same value 1.5 seconds later. Graphs of harmonic motion repeat every period, just as the motion repeats every cycle. Harmonic motion is sometimes called periodic motion for this reason.

Amplitude and period on a graph

To get the period from a graph, start by identifying one complete cycle. The cycle must begin and end in the same place on the graph (Figure 13.10). Once you have identified a cycle, you use the time axis of the graph to determine the period. The period is the time difference between the beginning of the cycle and the end. The amplitude is half the distance between the highest and lowest points on the graph. For the example in Figure 13.10, the amplitude is 20 centimeters.

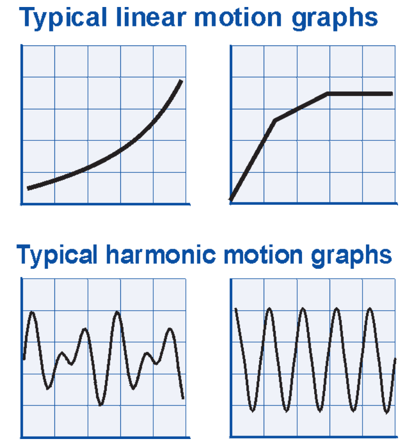


Figure 13.9: *Graphs of linear motion do not show cycles. Harmonic motion graphs show oscillation and cycles.*

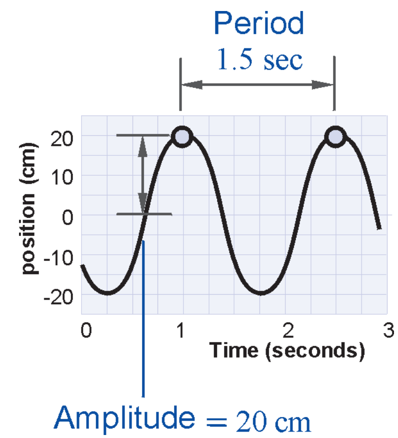


Figure 13.10: *Reading amplitude and period from a graph.*

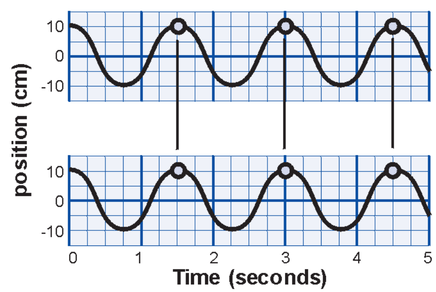
Circles and the phase of harmonic motion

Circular motion Circular motion is very similar to harmonic motion. For example, a turning wheel returns to the same position every 360 degrees. Rotation is a cycle, just like harmonic motion. One key difference is that cycles of circular motion *always* have a length of 360 degrees (Figure 13.11).

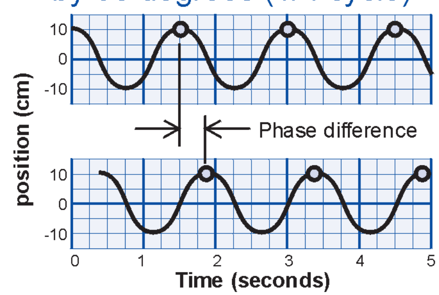
The phase of an oscillator Degrees are also convenient to describe where an oscillator is in its cycle. For example, how would you identify the moment when a pendulum was one-tenth of the way through its cycle? If we let one cycle be 360 degrees, then one-tenth of that cycle is 36 degrees. Thirty-six degrees is a measure of the phase of the oscillator. The word "phase" means where the oscillator is in the cycle.

What we mean by "in phase" The concept of phase is important when comparing one oscillator with another. Suppose you observe two identical pendulums, with exactly the same periods. If you start them together, their graphs would look like the diagram below left. You would describe the two pendulums as being *in phase* because their cycles are aligned and each one is always at the same place at the same time.

Two oscillators ***in-phase***



Two oscillators ***out-of-phase*** by 90 degrees (1/4 cycle)



Out of phase If you start the first pendulum swinging a little before the second one, the graphs look like the diagram above right. Although, they have the same cycle, the first pendulum is always a little ahead of the second. The graph shows the lead of the first pendulum as a phase difference. Notice that the top graph reaches its maximum 90 degrees *before* the bottom graph. We say the two pendulums are *out of phase* by 90 degrees, or one-fourth of a cycle.

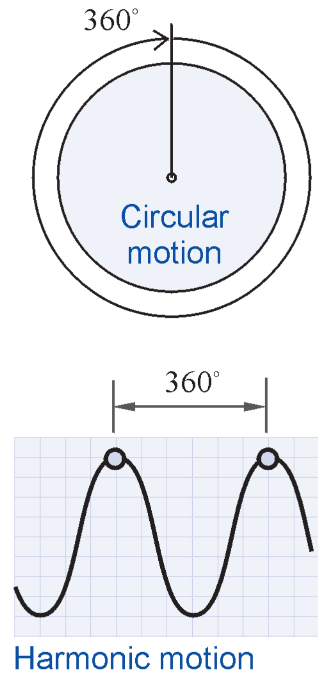


Figure 13.11: *A full turn of a circle is 360 degrees. One full cycle of harmonic motion is also 360 degrees.*