Phys 300/301
Physics: Algebra/Trig
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11.0 Waves & Sounds

There are two fundamental waves of transporting energy and momentum: particles and waves. While they seem opposites, they are subtly intertwined – there are no waves without particles and no particles without waves. In this chapter, the focus will be on waves only. Near the end of the course, we'll discuss the duality theory.

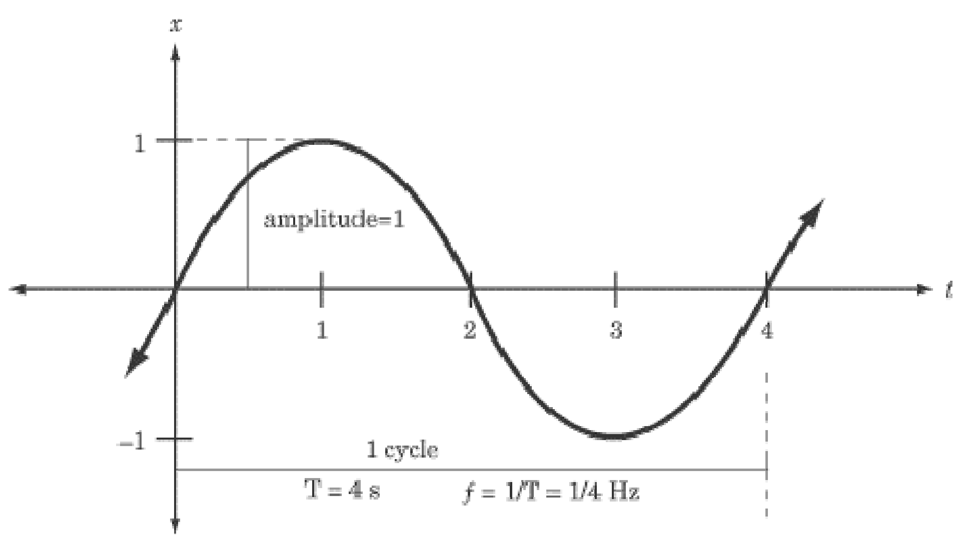
In general, a wave is a moving, self-sustained disturbance on a particular medium. That medium can either be a field or a substance. Here, we'll focus on the latter: Mechanical Waves.

11.1 Wave Characteristics

A traveling wave is a self-sustaining disturbance of a medium that propagates from one region to another, carrying both energy and momentum. Waves on a string, surface waves, fluid waves, sound waves, and compression waves are all types of mechanical waves. While the energy-carrying disturbance propagates through the medium, the individual parts of the medium do not advance. That is what distinguishes a wave from a flow of particles.

The two basic forms of waves we will discuss are longitudinal and transverse. When the sustaining medium is displaced parallel to the direction of propagation, the wave is longitudinal. If the edge of the spring is displaced up and down, the medium is displaced perpendicular to the direction of the disturbance and the wave is transverse.

Similarly to elastic waves, sound and other propagated waves are graphically shown by the graph:



The distance over which the wave executes one cycle of its basic repeated pattern is known as the wavelength. The Greek letter lambda, λ, is the symbol associated with wavelength.

Finding the velocity of waves is relatively simple. The number of waves that pass by in each second is the frequency, f, and the length of each wave is the wavelength, λ. Therefore, the rate, or speed, of each wave is given by the product of $f\lambda$.

$$v = f\lambda \tag{11.1}$$

The easiest wave to deal with is the harmonic wave. As you will see, all waves can be created through the superposition of harmonic waves.

The harmonic wave rises and falls sinusoidally without end. These waves are most interesting to view when they are reflected, absorbed, and transmitted. Suppose one end of a rope is held stationary while energy is given to the wave at the other end. When the wave reaches the stationary end, it is **reflected** back towards the source, and inverted. A reflected wave ideally carries away all the original energy, but since it is inverted, it is said to be 180° out of phase.

If energy is taken from the rope through friction or some other force, the wave is diminished and is said to be **absorbed**.

When a wave travels from one medium to another, there is a redistribution of the wave's energy. The distribution depends on the density of the medium that the wave is traveling into.

If the density of the second medium is greater than that of the first, the second medium acts as a stationary end, reflected an inverted wave. However, the second medium is also displaced and as a result energy appears as a transmitted wave. The speeds of the waves must be different due to the different densities of the mediums.

If the density of the second medium is lesser than that of the first, the second medium acts as a moving point and reflects the wave without a phase shift. The transmitted wave has a longer length; evidently, **the larger the density of the transmitting medium the smaller the length of the wave.**

11.4 Sound

The frequencies between 20 Hz and 20 kHz are the spectrum of sound heard by the average person. Acoustic waves, or sound waves, oscillate at every frequency, but our ears can only hear within that range.

Sound propagates through any medium which can respond elastically and transmit vibrational energy. Air, water, and most physical matter can all compress and therefore transmit sound waves. Space has no air and no propagating material, thus any movie which has noise in space is egregious wrong.

Instead of moving particles up and down in a sinusoidal wave pattern, sound waves compress the air and oscillate it with tiny amplitudes. This type of wave is known as a longitudinal or compression waves.

The Superposition of Waves

One characteristic of waves propagating through the same medium is that when they intersect they superimpose or combine with each other. Interestingly, the waves maintain their integrity after they interact, acting as if they had passed through each other. In the region where the waves interact, the resultant is the algebraic sum of the various contributions at each point. This is called the Superposition Principle.

Simply stated, when two waves superimpose, the amplitude of the resultant wave is the sum of the heights of the waves imposed. Any height above the x-axis is positive and any height below the x-axis is negative. The sum of any number of harmonic waves of the same frequency traveling in the same direction is also a harmonic wave of that frequency; the difference is the intensity of the wave. Conversely, when waves of different frequencies are added together, the resultant wave is not generally harmonic.

Intensity & Inverse Square Law

The intensity of the wave is defined as the average power divided by the perpendicular area across which it is transported.

$$I = \frac{P}{A} \qquad (11.2)$$

It has units of W/m^2.

The inverse square law explains how the intensity of the wave dissipates as it moves away from the source. As it moves into an increasing amount of spherical area, the sound dissipates inversely with the square of the radius. This is the Inverse Square Law.

11.6 The Speed of Sound

Simply put the speed of sound increases with temperature. The speed of sound itself does not depend on frequency or amplitude as commonly thought. If it did, at a concert, lower and higher frequencies would reach your ears at different times, causing a mumbled sound. Since the density of air increases as temperature does, it makes sense that the speed of the wave would slow. Over the usual range of temperatures, the speed of sound changes by approximately 0.6m/s for each degree of Celsius.

$$v_s = 331.5\,{}^{m}\!/_{s} + 0.6T \qquad (11.3)$$

Pitch

The pitch of a pure tone corresponds to frequency. Simply put, the higher the frequency, the higher the pitch of the sound; the lower the frequency, the lower the pitch of the sound.

11.8 Sound-Level

The sound-level of an acoustic wave is defined as the number of factors of 10 that its intensity is above the threshold of hearing ($I_o = 10^{-12}$ W/m^2). The name given to this level is the decibel. "Deci" indicates that the level is calculated in factors of 10, "bel" honors Alexander Graham Bell for his work with acoustics. The symbol for the decibel is dB.

The logarithmic base 10 function is used to calculate the intensity level because it is based on raising the power of ten to a certain value. The intensity level β in dB of any sound is:

$$\beta = 10\log_{10}\frac{I}{I_o} \qquad (11.4)$$

For example, a sound wave with an intensity of 10^{-6}W/m^2 (normal conversation) has an intensity level of 60dB.

$$\beta = 10\log_{10}\frac{10^{-6}W/m^2}{10^{-12}W/m^2} = 10\log_{10}10^6 = 10(6) = 60dB$$

From our definition, increasing the intensity by a factor of 10 raises the sound-level by 1 bel or 10dB. Increasing it by a factor of 100 raises the sound-level by 2 bels or 20dB.

11.10 Standing Waves

When a series of wave is excited in a finite medium, it generally encounters an end or boundary. At that point, some fraction of the energy of the wave is reflected back toward the source of the propagation. When this happens, the propagations interfere with each other and create what is known as a standing wave or a stationary wave. Within this standing wave are to patterns, nodes where the resultant is zero and antinodes where the resultant is at a maximum. Using these, we can measure the wavelength as twice the node-to-node distance.

Standing Wave on a String

When a standing wave is on a string we can find what are known as the resonant frequencies, or the frequencies which create a repeating pattern. Using the formula for a transverse wave on a string, we can calculate the resonant frequencies using the following:

$$f_N = \frac{N}{2L}\sqrt{\frac{F_T}{m/L}} \qquad (N=1, 2, 3\ldots)$$

Each frequency is the whole number multiple of the fundamental frequency. The lowest resonant frequency is given by $f_N = Nf_1$. The Nth harmonic will have N antinodes.

11.11 The Doppler Effect

As a wave is emitted, the motion of the source of the observer will close the gaps between successive wave fronts. This causes the frequency of waves to increase or decrease depending on the direction of observer or source motion. This change is a direct result of the space between the wave fronts increasing or decreasing. If the source is moving toward the observer or the observer moving toward the source, the space between the wave fronts decreases. Because of this, more waves reach the observer in a time interval, resulting in an increase in frequency. If the observer is moving away from the source or the source is moving away from the observer, the space between the wave fronts increases. This causes fewer wave fronts to reach the observer in a time interval, decreasing the frequency of the waves.