

Lab Manual

Irina Golub

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Introduction

Look around:

- The radio receives signals by means of electromagnetic waves and emits waves that sound like music when they hit your ear.
- On the surface of a body of water you can see the waves.
- The human body creates waves (like heartbeats) and diagnostics of the body's physical condition involve many different kinds of wave phenomena.

Waves surround us.

All waves share certain physical comparisons.

Waves

Waves are periodic disturbances propagating in space and time.

To be able to deal with waves we introduce a number of definitions:

- The period T is the time it takes for a wave to repeat itself.
- The frequency f , defined as $f = 1/T$, measures the number of complete cycles the wave repeats in one second. The unit of frequency (1/seconds) is Hertz (Hz).
- The wavelength λ is the spatial separation between repeating points in a wave.
- The amplitude A of the wave is the maximum magnitude of the displacement.

If a long, stretched horizontal string is tight pulled up at some point and released, this part of the string will vibrate up and down. Bordering points will then follow the motion, and the original disturbance will propagate down the string as a traveling wave. Since the individual particles vibrate in a direction perpendicular to the direction of propagation, this wave is called a transverse wave. If the disturbance is periodic, i.e., repeated continuously, a wave points will move down the string. The following figure shows the disturbance along the string at a single instant of time, in this case for a sinusoidal wave. If the wave is moving to the right and a second picture is taken a quarter period, $T/4$, later, all points on the wave will have moved an equal distance to the right, as shown by the dotted curve. The frequency, f , of the wave is defined as the number of times per second the disturbance is repeated (thus $f = 1/T$). Note that the period of the motion is determined by the cause of the

initializing disturbance. During each period T , the wave travels a distance of one wavelength, λ ; therefore the velocity of the wave is given by

$$c = f\lambda.$$

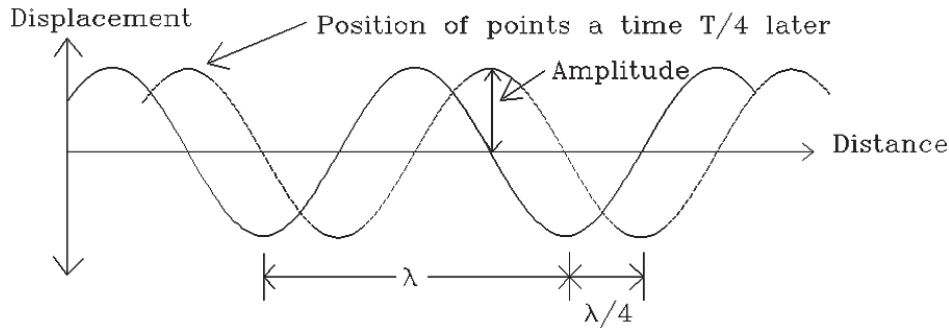


Figure 1: Propagation of a Transverse Wave

The figure below shows the vertical displacement of the string versus time at a fixed location along the string. The time interval between successive identical displacements of a given point is the period T of the wave. Remember that the wavelength of a traveling wave can only be determined when one observes the displacement as a function of distance at one instant in time. The period, on the other hand, is obtained when one observes the displacement of one point as a function of time at one location.

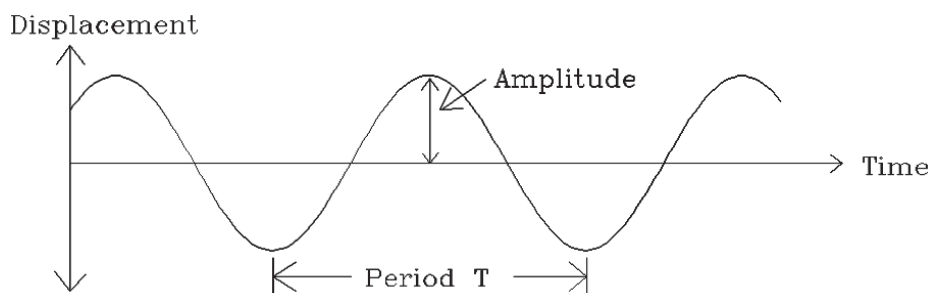


Figure 2: Vertical Displacement of a String

There are, in general, two types of waves: transverse and longitudinal. If the oscillation is perpendicular to the direction of propagation of the wave, then the wave is transverse. If a wave changes along the direction of propagation, it is called a longitudinal wave.

An example of a longitudinal wave is a sound wave, in which there are periodically changing regions of low and high air pressure along the direction of wave propagation. A sound wave is normally initiated by a vibrating solid (such as a tuning fork), which alternately compresses and rarefies the air adjacent to it. The wave thus consists of

pressure variations in the air that are moving away from the fork. Since these variations oscillate along the direction of wave propagation, the sound wave is a longitudinal traveling wave.

The definitions of f , λ , and T , explained above for transverse waves, hold equally for longitudinal waves. The diagrams in the above figures also apply, so long as we understand “displacement” to mean the longitudinal (forward or backward) pressure or density variation of air from its undisturbed equilibrium value. The relationship between wave velocity and the other parameters is also still valid:

$$c = f\lambda$$

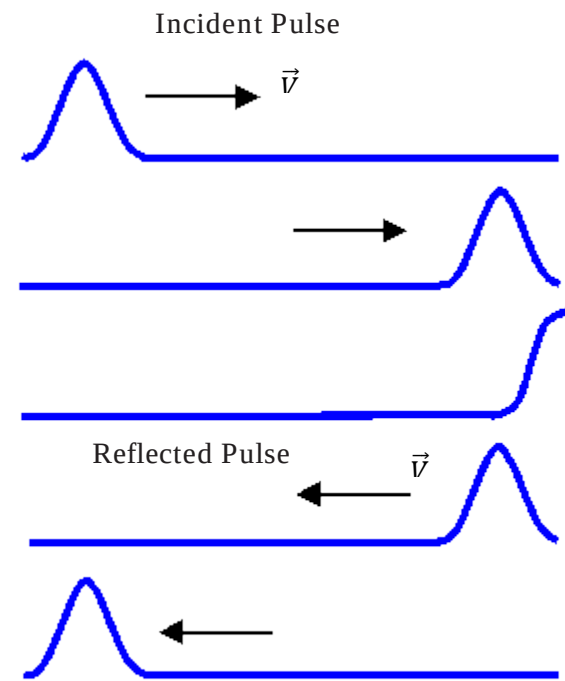
Standing Waves

If a string is tied between two fixed supports, pulled tightly and sharply plucked at one end, a pulse will travel from one end of the string to the other. When you pluck the string you put energy into an elastic medium, and this energy travels through the medium as a transverse pulse. Transverse means that the amplitude is at right angles to the direction of propagation. The speed of the pulse through the medium, in this case the string, is a function of the properties of the string. Specifically, it is a function of the linear density of and the tension in the string. Making the string tighter and lighter increases the pulse speed, and making the string looser and heavier slows the pulse speed down. The relation between pulse speed, tension and linear density is given by the following equation:

$$\sqrt{\frac{T}{\mu}} = v$$

where v is the pulse speed, T the tension in the string, and the string's linear density.

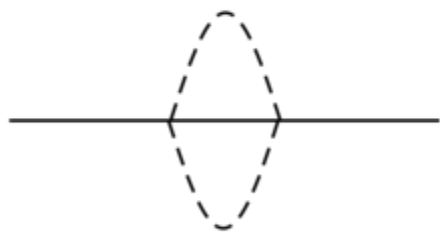
The pulse is reflected from where it is tied to the support. When a reflection occurs from a low density medium to one of higher density (essentially infinite if the string is tied securely), the reflection inverts the pulse and it travels back down the string in the reverse direction. By Newton's third law of action and reaction, when the pulse hits the wall it exerts an upward pull on it if the pulse has a positive amplitude. The wall then exerts a downward pull on the string and the reflected pulse is inverted, giving it a negative amplitude. If the initial pulse has a positive (up) displacement and is traveling to the right, then the reflected pulse will have a negative (down) displacement and be traveling to the left.



pulses move towards each other



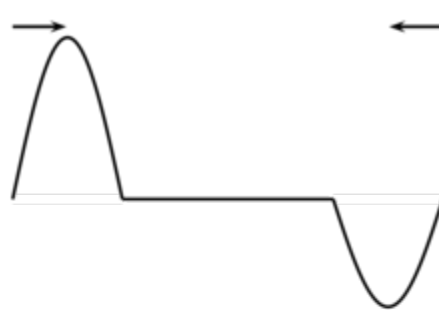
pulses destructively interfere



pulses move away from other



pulses move towards each other



pulses interfere



pulses move away from other



A particularly interesting example occurs when two waves of equal λ , f , and A are traveling along a taut string in opposite directions. (This occurs if the wave encounters a barrier that reflects the wave back in the original direction while the original wave is still propagating.) At some particular points on the string, the two waves will always be out of phase, one wave will try to move the point up and other wave will try to move the point down. The result is that the two waves will cancel each other at this particular point, and so that point will remain stationary. This condition is known as destructive interference, and the points at which this occurs are called nodes.

At other points on the string, the two waves will move up and down together so that the amplitude of the disturbance at these points will be twice what it would be if only one wave were present. This condition is known as constructive interference and the points at which this occurs are called antinodes.

As long as the λ , f , and A of the waves remain fixed, the positions of the nodes and antinodes will not change. The pattern produced in this circumstance is called a standing wave, since it looks as if it is stationary, although it is actually the sum of two waves traveling in opposite directions. The analytic description for the displacement versus position and time with one end fixed at $x = 0$ is given by:

$$A \sin\left(\frac{2\pi}{\lambda}x\right) \cos(2\pi ft)$$

A string with both ends fixed can be excited with standing waves as shown in the figure below. The fixed ends of the string cannot move, so the string must have nodes at these points. It is evident that the distance between the node at a fixed end and the first antinode is $\lambda/4$; and the distance between successive nodes (or antinodes) is $\lambda/2$.

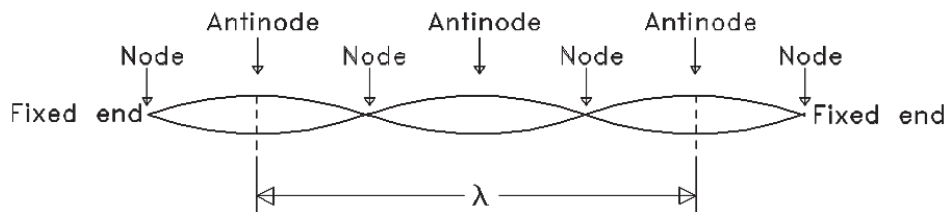


Figure 3: Standing Waves

The positions on the string where $A \sin\left(\frac{2\pi}{\lambda}x\right) = 0$ correspond to a node, so whenever $\left(\frac{2\pi}{\lambda}x\right)$ is a multiple of π , i.e.:

$$\frac{2\pi}{\lambda}x = n\pi$$

(x is a multiple of $\lambda/2$), we find a node. Midway between two nodes we will always find an antinode, a point where the string oscillates maximally.

A standing wave is a static, unmoving pattern. Even though a node is perfectly motionless, though, energy is flowing through it as a standing wave consists of interfering traveling waves.

The equations below are both for the velocity of the wave on the string, but to mathematically model the standing wave, we eliminate the horizontal velocity.

$$v = \sqrt{\frac{T}{\mu}} ; v = \lambda f$$

$$\sqrt{\frac{T}{\mu}} = \lambda f$$

In investigating the standing wave system, we can use we can use this equation to predict the linear density of the string using a graphical method. The slope of the line will be the linear density. The wavelength is the dependent variable and will be plotted on the y-axis.

$$\lambda = \sqrt{\frac{T}{\mu}} \left(\frac{1}{f}\right)$$

The slope of the line is $\sqrt{\frac{T}{\mu}}$, and knowing that the tension in the cord is the weight hanging from its end, the linear density can be calculated.

Standing waves can be created in a tube of gas using sound waves. In the part two of the experiment, a tuning fork vibrates over the open end of a tube containing air. The tube is sealed at the other end by the water. The motion of the fork causes longitudinal sound waves to travel down the tube. The sound wave is reflected back up by the air- water interface and the incident and reflected waves interfere with each other. The air at the closed end of the tube is cannot move freely, so in order for a standing wave to be produced, a node must exist at the there. The air in the open end of the tube is free to move; so when a standing wave is produced in the tube, the open end is an antinode.

Since the distance between a node and the nearest antinode in a standing wave pattern is $\lambda/4$, it should be evident that the shortest tube in which a standing wave can be established has a length of $\lambda/4$. A standing wave with wavelength λ can be established in longer tubes. All that is required is that a node exist at the closed end and an antinode at the open end – i.e. that the length of the air column is an odd multiple of $\lambda/4$. When a standing wave is produced in the tube, a resonance condition is established and the intensity of the sound will increase.

Part One: Standing waves on a String

PROCEDURE AND DATA ANALYSIS

We going to use the [online simulation](#) which represents Wave on the String.

The simulation allows changing the amplitude, frequency, set up the string with fixed end, loose end and no end.

You may adjust the frequency of the source and whether the ends of the medium are fixed or free. For some frequencies, you will not be able to establish a standing wave. The simulator builds up the standing waves slowly, so be patient before deciding whether a standing wave has been established, see what happens.

Part A: Fixed at both ends

1. Find the lowest frequency that will establish a standing wave. This is the fundamental frequency.
2. Determine the number of nodes, antinodes, and wavelengths for this frequency. Create a data table with 5 columns (frequency, 1/ frequency, nodes, antinodes, and wavelengths), and enter this data. Be careful with wavelengths; you should figure out how many wavelengths there are in the length of the string. Draw the standing wave and label the Nodes with “N” and Antinodes with “A”.
3. Increase the frequency until you find the next one that will establish a standing wave. Find the values listed in Step 2 for this standing wave, enter them into the data table, and draw and label the wave.
4. Continue increasing the frequency and entering the data for additional standing waves.
5. Plot the inverse of the frequency on the x-axis, against the wavelength on the y-axis and define the linear density.

If the maximum tension in the simulation is 10.0 N, what is the linear mass density (m/L) of the string?

6. The speed of a transverse wave on a string of length **L** and mass **m** under tension **T** is given by the formula

$$v = \sqrt{\frac{T}{\frac{m}{L}}}$$

Part B: Free at both ends

Select “Both ends free”, and repeat steps 1-4. You should have a new data table for this data. Include pictures of each wave with labels.

Part C: Free at one end

Select “One end free”, and repeat steps 1-4. You should have a new data table for this data. Include pictures of each wave with labels.

Compare and discuss the result in part A , B , and C .

Part Two: Standing Sound Waves

We going to use the [online simulation](#) is a demonstration to measure the speed of sound in air. The simulation allows changing the Water level, and frequency of the fork. You may adjust the frequency, the water level, and see what happens.

In the second part, we measure the wavelength of standing longitudinal waves.

Sound waves (longitudinal waves) are set up in a long open tube, which is partly filled with water,. In the simulation you can change the height of the water and produce a sound wave using a tuning fork. There are three tuning forks, a 440 Hz , 512 Hz and 660 Hz. You should perform the experiment with all of them. As you change the level of water in the tube, you find some water levels at which an amplitude of the wave significantly large (it is mean the sound from the tuning fork becomes significantly louder). This occurs whenever you have created a standing sound wave in the glass tube. By measuring the distances between water levels that achieve successive sound maxima, you can determine the wavelengths of the sound waves.

As before, from the wavelengths of the standing waves and the frequencies, you can compute the velocity of propagation of the sound waves for each case. This should equal the speed of sound in air.

PROCEDURE AND DATA ANALYSIS

1. Record the wavelength for all tuning forks. To improve your data, try to average over several measured values. Also don't forget to include uncertainties.
2. Calculate the speed of sound for all frequencies. Do you get the same value within uncertainty? Is your value for the speed of sound close to the standard value of 340 m/s? What could be reasons that you get a different value?
3. Give the main sources of error and make suggestions of how the result could be improved.

If you blow air along the top of an open soda bottle you can excite a standing wave in the bottle and you hear a sound. Explain what happens if you put some water into the bottle and then perform the same experiment!

Applications

Biological systems that create periodic pulses (like a beating heart) are optimized for a range of operating conditions. The variations in the operating parameters often provide an important diagnostic tool. For example, the period of beats in a human heart can vary; one may ask to what extent and how often the heartbeat rate changes. To identify patterns of heart rate, one makes use of a mathematical procedure called Fourier analysis. Besides the dominant frequency of the heartbeat (about 1 Hz), there are other frequencies that correspond to changes in the heart rate; Fourier analysis uses the heart rate to make a diagram of the amplitudes of the lower frequencies present in the heart rate.

This may at first sound a little bit complicated, but the basic idea is simple. In the experiment, we find only specific standing waves for each system. With the system parameters fixed, only certain frequencies are possible: most frequencies cannot achieve a standing wave. Obviously these frequencies are special and characterize the system! If you look now at a complicated oscillation of the system and take the Fourier spectrum, you find that only these special frequencies contribute. Other frequencies don't contribute at all. A beating human heart is, of course, much more complicated than the systems we deal with in the lab, but the basic ideas are the same!

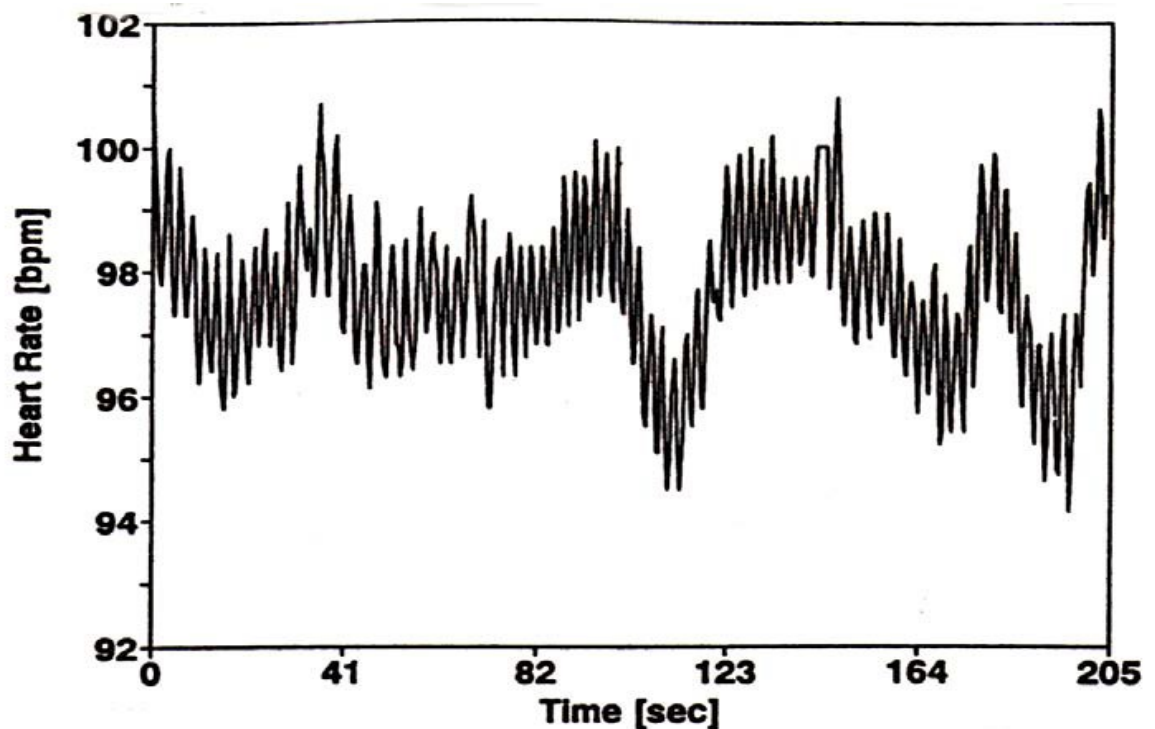


Figure 4: Heart Rate of an Adult

This picture shows the heart rate of a healthy adult over time. As one can easily see, the heart rate changes over time. The frequencies with which the heart rate changes can most easily be seen in the Fourier spectrum (sometimes called power spectrum) in the next figure.

One immediately sees a prominent change in the heart rate with a frequency of about 0.4 Hz. Therefore, roughly every 2.5 s the heart rate of this person changes. This frequency corresponds to the many little spikes we saw in the first diagram. (Another characteristic frequency is at about 0.02 Hz, corresponding to a change about every 50 s. We will not deal with this part here, even though it contains valuable information.)

Where does the change every 2.5 s come from? It turns out that the person took a breath about every 2.5 s. The heart then speeds up slightly to pump more blood

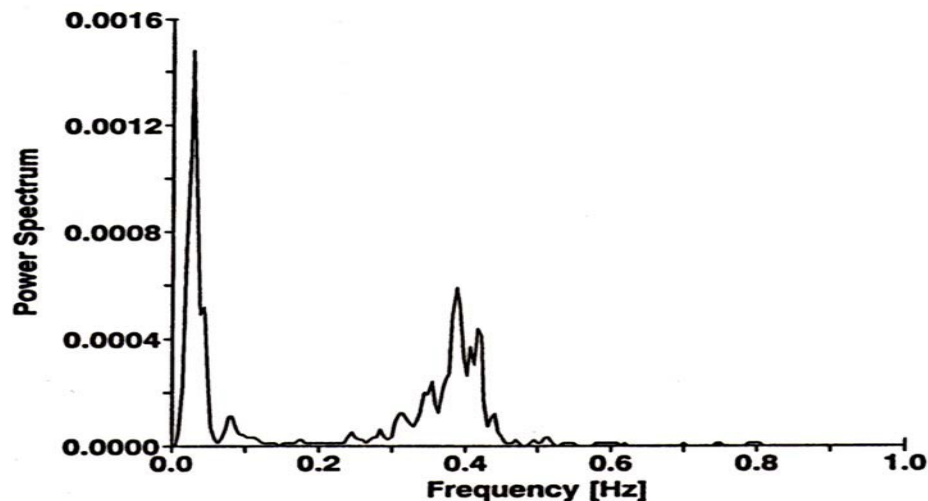


Figure 5: Power Spectrum of the Heart Rate

through the vessels of the lung, where the blood is oxygenated. Subsequently, it slows down again. (This particular frequency is called the respiratory frequency.)

The process of speeding up and slowing down is governed by the autonomic nervous system. Some diseases (e.g. diabetes) can damage the autonomic nervous system and therefore stop this adaptation of the heart rate. For example, as diabetes reaches its final stage the peak in the Fourier spectrum at the respiratory frequency vanishes.

This method has the nice feature that it is non-invasive, relatively simple, and shows dynamic processes rather than snapshot pictures.

Reference: Amos D. Korczyn: Handbook of Autonomic Nervous System Dysfunction.