Traveling Waves on a String

Goals and Introduction

When a tension is applied to a string, the string is fixed at both ends, and is plucked, or disturbed from equilibrium with a repetitive application of a force, a traveling wave will be created on the string as it oscillates back and forth, trying to return to its equilibrium position. This wave is a *transverse* wave since the oscillation of the string is perpendicular to the direction in which we observe the wave to travel – along the string. The frequency (f) of these oscillations is related to the frequency of the applied force, but can also be related to the speed of the wave (v), and the wavelength (λ), where the wavelength of a transverse wave can be thought of as the distance the between crests along the wave at any moment.

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$$v = f\lambda \qquad \text{(Eq. 1)}$$

As the wave reflects from each boundary, the transverse waves will interfere with each other. If we were to “freeze” the string for a moment and look at it, we would see what would appear to be a fairly random, chaotic looking pattern of peaks and troughs of various heights. This pattern, however, can be mathematically explained as a summation of several “harmonic modes” of oscillation, similar to those described for sound in a tube open at both ends (See the lab document for Properties of Sound).

Each harmonic mode (labeled with a mode number, n) has a particular *harmonic wavelength*, λ. Given that the string has a certain length, L, there are particular wavelengths of sound that would fit perfectly along the string, while meeting the boundary condition that the string is not moving up and down at the ends. Locations where the string does not move in a particular mode are called *nodes*, while locations where the string appears to reach its maximum in a particular mode are called *antinodes*. These modes are sometimes called *standing wave modes* of oscillation since it appears that the wave is not moving along the string when it vibrates in one of these modes.

Mathematically, we can find the harmonic wavelength of each mode using the following mathematical relationship, where the $n = 1$ mode is called the *fundamental*, or *first harmonic*, the $n = 2$ mode is called the *second harmonic*, and so on. These can be found mathematically using the following formula.

$$\lambda_n = \frac{2L}{n} \qquad \text{where } n = 1, 2, 3, \ldots \qquad \text{(Eq. 2)}$$

If you would like to see a visualization of this idea and control which modes are present when a string vibrates, using a simulation, check out the interactive applet at the link below!

https://phet.colorado.edu/sims/normal-modes/normal-modes_en.html

Because the waves that make up these standing wave modes are traveling waves on the string, they move with a particular speed (in m/s), which depends on the tension in the string, F_T, and the mass per unit length of the string, μ. This speed can be found using the following formula, where the tension is measured in units of newtons (N), and the mass per unit length is measured in units of kilograms per meter (kg/m).

$$v = \sqrt{\frac{F_T}{\mu}} \qquad \text{(Eq. 3)}$$

It is possible to determine a *harmonic frequency* for each standing wave mode of oscillation using the harmonic wavelength for that mode and the fact that it must be true that $v = f\lambda$ for each mode. The result is seen in Eq. 3, for a string that is fixed at both ends..

$$f_n = \frac{nv}{2L} \qquad \text{where } n = 1, 2, 3, \ldots \qquad \text{(Eq. 4)}$$

Interestingly, it is possible to get a string to vibrate in a single mode of oscillation by continuously plucking the string at a particular rate, or frequency, that is near a harmonic frequency for the string. In this scenario, the string is oscillation is said to be *driven* by the frequency of the applied force. Under these conditions, the string would appear to have very particular nodes and antinodes, allowing us to identify the wavelength of the mode by measuring the distance across several nodes (*d*), as seen Figure 1. Note that while it may appear that there are nodes where the string is connected to the fork and where the string is draped over the pulley, this is not exactly true. We should only count nodes we observe away from these locations when performing this experiment.

When we measure the distance between nodes, we are measuring half of the wavelength of that particular mode of oscillation (try this with the simulation in the link mentioned above by using 100% of only one mode at a time and verify that this makes sense. If it still does not make sense after that, ask your TA when you are at your lab meeting!).

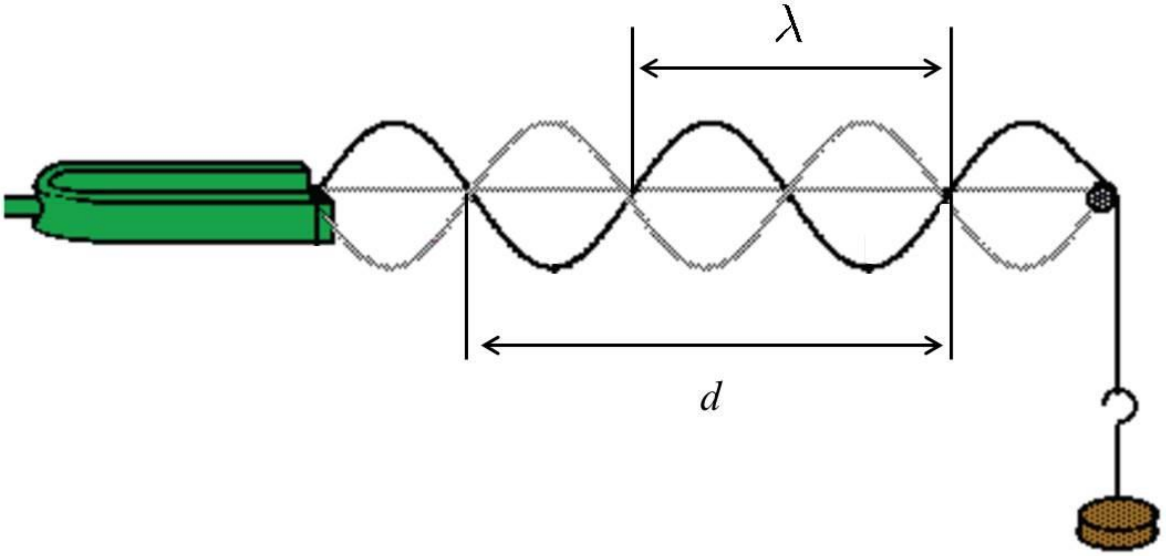

Figure 1

In today's lab, you will place a string under a tension and drive the oscillation by causing a large tuning fork to continually vibrate. You can then verify that the observed standing wave pattern has a frequency very near that of the tuning fork, as predicted.

Goals: (1) Observe the standing wave vibration of a string
(2) Predict, measure, and quantify the frequency of oscillation for an observed standing wave pattern
(3) Observe the effects of interfering with the standing wave vibration when contacting the string at nodes and antinodes separately

Procedure

Equipment – string, driving tuning fork assembly, pulley, meter stick, masses, mass holder, balance

1) Look at the tuning fork and **record** the frequency stated there. This will be the expected frequency of oscillation during the experiment.

2) Use the string and the balance to **measure and record** the mass of the string.

3) **Measure and record** the total length of the string.

4) Now, attach one end of the string to a post on the tuning fork and drape the other end over the pulley at the far end of the table. **Measure and record** the mass of the mass holder and then hang the mass holder from the free end of the string.

5) The tuning fork is driven by an electrical circuit that will be plugged into the wall of your lab station, DO NOT remove or change these wires. Your lab instructor may require you to flip a switch to "to turn on the wall", but be mindful of his or her specific instructions. Turn on the circuit by rotating the screw next to the tuning fork, which moves a peg inward to make electrical contact. The tuning fork may not start vibrating right away. If it does not, you can try giving the tuning fork a strong tap to get it started and it should continue from there.

6) Add mass to the mass holder to try and create a standing wave pattern, where you observe distinct locations behaving as nodes and others behaving as antinodes. **Record** the mass that you added to the holder. This mass can later be combined with that of the holder to calculate the tension in the string.

NOTE: It sometimes helps to move your head around the string while looking for the antinodes because they may not oscillate in the most convenient direction for viewing.

Question 1: How can the total mass hanging from the string be used to calculate the tension in the string? Think about the free-body diagram of the holder and additional mass and reference this in answering this question.

7) Remembering that where the string contacts the pulley and where the string connects to the tuning fork cannot be correctly considered nodes, **measure and record** the distance *d* between the two nodes that are furthest apart in your standing wave pattern. **Count and record** the number antinodes that appear between your endpoint-nodes.

8) Repeat steps 6 and 7 at least three more times, using a different amount of mass attached to the mass holder each time.

9) Try placing the tip of your finger on the string, first, where you observe an antinode, and second, where you observe a node. **Record** your observations of how the standing wave pattern was affected when you placed your finger at each location.

Question 2: Explain the effect that you observed when you placed your finger at an antinode. Explain the effect that you observed when you placed your finger at a node.

As always, be sure to organize your data records for presentation in your lab report, using tables and labels where appropriate.

Data Analysis

Use the mass and length that you recorded in steps 2 and 3 to calculate the mass per unit length (μ) of the string.

For each instance of recording the additional mass in step 6, consider the mass of the holder and calculate the total mass that was hanging from the string in each instance. Then, calculate the tension in the string in each case.

Use the mass per unit length and the tension in each case to calculate the speed with which waves travel on the string in each case.

For each instance of recording the distance between the nodes on either end (*d*) and the number of antinodes between (step 7), use these results to calculate the distance between nodes, or half the wavelength, for each standing wave mode that you measured. Then, express the wavelength of each standing wave mode that you observed.

Question 3: Why did we measure the total distance between the first and last nodes, and the total number of antinodes included between the first and last nodes, rather than just measure the distance between adjacent nodes to find half the wavelength? Explain why the method used here should result in a more accurate measurement of the wavelength.

Use Eq. 1 to calculate the frequency of the standing wave mode in each case where you performed steps 6 and 7. These will be your measured frequencies for each mode.

You can now proceed to the error analysis section where you will determine the percent error between the measured frequencies and the expected frequency from the tuning fork.

Error Analysis

Calculate the percent error between each measured frequency and the expected frequency from the tuning fork.

$$\%error = \frac{\left| f_{\text{experimental}} - f_{\text{accepted}} \right|}{f_{\text{accepted}}} \times 100\%$$

Question 4: How well did the experimental values match the expected frequency? What aspects of the measurement process do you feel contributed most to the differences you have calculated here?

Questions and Conclusions

Be sure to address Questions 1 through 4 and describe what has been verified and tested by this experiment. What are the likely sources of error? Where might the physics principles investigated in this lab manifest in everyday life, or in a job setting?

Pre-Lab Questions

Please read through all the instructions for this experiment to acquaint yourself with the experimental setup and procedures, and develop any questions you may want to discuss with your lab partner or TA before you begin. Then answer the following questions and type your answers into the Canvas quiz tool for "Traveling Waves on a String," and submit it before the start of your lab section on the day this experiment is to be run.

PL-1) Selena measures the total distance between the nodes on either end of a standing wave pattern to be 0.75 m, and she records that there were three antinodes between the endpoints. When she calculates half of the wavelength of the pattern, using these measurements, what is the result? Express your answer in meters.

PL-2) Selena measures the total distance between the nodes on either end of a standing wave pattern to be 0.84 m, and she records that there were four antinodes between the endpoints. When she calculates the wavelength of the pattern, using these measurements, what is the result? Express your answer in meters.

PL-3) Jerome measures the length of the total length of the string to be 1.15 m and the mass to be 4.0 mg. What is the mass per unit length of the string in kg/m?

PL-4) Jerome has added mass to the holder and created the standing wave pattern. He observes that the string appears to have nodes where it meets the pulley and where it is attached to the fork. When performing step 7, he should

A) measure and record the distance between any two adjacent antinodes.

B) measure and record the distance between the two nodes that are nearest the pulley and fork, but not at the pulley and fork.

C) measure and record the distance between the two nodes that are nearest the pulley and fork.

D) measure and record the distance between any two adjacent nodes.

PL-5) In this experiment, the standing wave pattern changes when more mass is added to the holder because

A) the frequency of the standing wave pattern changes.

B) the wavelength must remain the same for each standing wave pattern.

C) the product of frequency and wavelength must always be the same.

D) the velocity with which waves travel on the string changes.