Activity P41: Waves on a String
(Power Amplifier)

Adopted from PASCO Manual, but modified for College Physics II.

<table>
<thead>
<tr>
<th>Equipment Needed</th>
<th>Qty</th>
<th>Equipment Needed</th>
<th>Qty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Function Generator</td>
<td>1</td>
<td>Pulley Mounting Rod (w/ ME-6838)</td>
<td>1</td>
</tr>
<tr>
<td>Balance (SE-8723)</td>
<td>1</td>
<td>Rod (ME-8736)</td>
<td>1</td>
</tr>
<tr>
<td>Clamp, Table (ME-9376)</td>
<td>2</td>
<td>String (SE-8050)</td>
<td>10 m</td>
</tr>
<tr>
<td>Mass Set (SE-8705)</td>
<td>1</td>
<td>Super Pulley (w/ ME-6838)</td>
<td>1</td>
</tr>
<tr>
<td>Meter stick</td>
<td>1</td>
<td>Wave Driver (WA-9753 or SF-9324)</td>
<td>1</td>
</tr>
<tr>
<td>Patch Cords (SE-9750)</td>
<td>2</td>
<td></td>
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</tbody>
</table>

Important Instructions:

1. This experiment can also be done without using DataStudio. In this case you would need a function generator to operate the driver (SF-9324).

2. Some equipment listed above may have to be substituted with an alternative to obtain an arrangement similar to that is shown on p. 44.

3. On class web page you will find instruction sheet on Wave Driver SF-9324

Introduction

There are two models to describe how energy is transported from one point to another. One is the particle model and the other is the wave model. The purpose of this activity is to explore the wave model. To do so we will produce mechanical waves in stretch string fixed at two ends (standing waves). Electromagnetic waves do not require material medium to travel, but mechanical waves do. The speed of either kind of wave (electromagnet or mechanical) depends on two properties of the material in which they are travelling. For mechanical waves it is the inertial property (linear density $\mu = \text{mass per unit length}$) and the elastic property (the tension $T$ force in the material). For electromagnetic waves it is the permittivity $\varepsilon_0$ and permeability $\mu_0$.

It is not easy to setup equipment to see electromagnetic waves for the purpose of this experiment at this level, so we will use standing waves. When a stretched string fixed at two ends is plucked, waves are produced that travel from one end to the other. If the length of the string between the ends is an integral multiple of wavelength of the wave, the incoming wave from one end is reflected back from the other end and the wave interferes constructively to produce a standing interference pattern. Such a wave pattern is called standing wave. Your goal in this activity is to learn how standing waves are created, what are segments, nodes and antinodes, how to determine wavelength, frequency, and state the relationship between wavelength, frequency and speed and how can you use these to find the linear density of the string.

The purpose of this activity is to investigate standing waves in a string. What is the relationship between the tension in the string and the number of segments in the standing wave? What is the relationship between the frequency of oscillation of the string and the number of segments in the standing wave? How can you use these relationships to find the linear mass density of the string?

Background

When a stretched string is plucked it will vibrate in its fundamental mode in a single segment with nodes on each end. If the string is driven at this fundamental frequency, a standing wave is
formed. Standing waves also form if the string is driven at any integer multiple of the fundamental frequency. These higher frequencies are called the harmonics.

Each segment is equal to half a wavelength. In general for a given harmonic, the wavelength $\lambda$ is

$$\lambda = \frac{2L}{n}$$

where $L$ is the length of the stretch string and $n$ is the number of segments in the string.

The linear mass density of the string can be directly measured by weighing a known length of the string. The density is the mass of the string per unit length.

$$\mu = \frac{\text{mass}}{\text{length}}$$

The linear mass density of the string can also be found by studying the relationship between the tension, frequency, length of the string, and the number of segments in the standing wave. To derive this relationship, the velocity of the wave is expressed in two ways.

The velocity of any wave is given by $v = \lambda f$ where $f$ is the frequency of the wave. For a stretched string:

$$v = \frac{2Lf}{n}$$

The velocity of a wave traveling in a string is also dependent on the tension, $T$, in the string and the linear mass density, $\mu$, of the string:

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

Setting these two expressions for the velocity equal to each other and solving for tension gives:

$$T = \left(4L^2 f^2 \mu \frac{1}{n^2}\right)$$

If the tension is varied while the length and frequency are held constant, a plot of tension, $T$, vs. $(1/n^2)$ will give a straight line which will have a slope equal to $4L^2 f^2 \mu$. The slope of this line can be used to calculate the linear mass density of the string.

The equation for the tension can also be solved for the frequency:

$$f = \sqrt{\frac{T}{4L^2 \mu} \frac{1}{n^2}}$$

If the frequency is varied while the tension and length are held constant, a plot of frequency, $f$, vs. number of segments, $n$, will give a straight line. The slope of this line can also be used to calculate the linear mass density of the string.

**Overview**

- First, determine the linear mass density of the string directly (Pre-Lab).
- Next, determine the linear mass density of the string using the relationship of tension, length, number of segments, and frequency for standing waves on the string.
• In Part A use different hanging masses to change the tension of a string but keep the length and frequency constant. Plot a graph of tension vs. $1/n^2$ to determine the linear mass density of the string.

• In Part B use the wave driver to vary the frequency but keep the length and tension constant. Use DataStudio or ScienceWorkshop to control the frequency of the wave driver. Plot a graph of frequency vs. $n$ to determine the linear mass density of the string.

• Compare the values of linear mass density for all three methods.

SAFETY REMINDER

• Follow all safety instructions.

Pre-Lab

Direct Calculation of the Linear Mass Density

1. Measure the mass of a known length (about 10 m) of the string.
   
   length = $L =$ ______________ meters
   
   mass = $M =$ ______________ kilograms

2. Calculate the linear mass density by dividing the mass by the length ($\mu = \text{mass/length}$):
   Record this value in Table 3 of the Lab Report.

Part A: Change Tension – Keep Length and Frequency Constant

In Part A of this activity, use different hanging masses to change the tension in the string but keep the length and frequency constant. Use the function generator to keep the wave driver frequency constant.

PART IA: Computer Setup

1. Setup the equipment as shown in the Figure. The function generator should be set to sine wave at 60Hz. Keep the amplitude small initially.

2. Tie one end of a 2-m long piece of string to a vertical support rod that is clamped to one end of a table. Pass the other end of the string over a pulley that is mounted on a rod that is clamped to the other end of the table. Attach about 500 g to the end of the string.

3. Place the wave driver under the string near the vertical support rod. Insert the string in the slot on the top of the driver plug of the wave driver so the wave driver can cause the string to vibrate up and down. Use patch cords to
connect the wave driver into the output jacks of the Power Amplifier.

4. Use the meter stick to measure the length of the section of the string, L, that will be vibrating (the part between the driver plug of the wave driver and the top of the pulley). Record this length in the Lab Report section, Table 1.

5. Put enough mass on the mass hanger to make the string vibrate in its fundamental mode (one antinode in the center) at a frequency of 60 Hz. Adjust the amount of mass until the nodes at each end are “clean” (not vibrating). Record the initial mass in the Lab Report section, Table 1. (Be sure to include the mass of the hanger.)

6. Now change the amount of mass on the mass hanger until the string vibrates in each of the higher harmonics (for 2 segments through 8 segments) and record these masses in Table 1 section. Hint: Decrease the mass to increase the number of segments.

7. Calculate the tension for each different mass used (tension = mass in kilograms x ‘g’ where g = 9.8 newtons per kilogram).

8. Plot a graph of Tension vs. 1/n^2. Determine the slope of the best-fit line on the Tension vs. 1/n^2 graph.

9. Using the slope, length, and frequency, calculate the linear mass density of the string. (Hint: The slope is equal to \( \frac{T}{4L^2\mu} \). Solve for the linear density.) Record the value in the Lab Report section, Table 1.

10. Calculate the percent difference between this value and the directly measured value and record it in the Lab Report, Table 3.

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**Part B: Change Frequency – Keep Tension and Length Constant**

**PART IB: Computer Setup**

1. Use the same setup as in the first part of this procedure.

2. Put 500 g on the mass hanger. Calculate and record this Tension in Table 2.

3. Vary the output frequency of the Signal Generator until the string vibrates in one segment (the fundamental frequency).

4. Find the frequencies required for the higher harmonics (n = 2 through 7) and record these in the Lab Report section, Table 2.

5. Plot a graph of Frequency vs. Segments.

6. Using the slope, length, and frequency, calculate the linear mass density of the string.

   (Hint: The slope is equal to \( \frac{T}{4L^2\mu} \). Solve for the linear density.) Record the value in the Lab Report section, Table 1.

7. Calculate the percent difference between this value and the directly measured value and record it in the Lab Report, Table 3.
Lab Report – Activity P41: Waves on a String

Data

Table 1: Change Tension – Constant Frequency and Length

Frequency = ___ Hz
Length = ___ m

<table>
<thead>
<tr>
<th>Segments, n</th>
<th>Mass (kg)</th>
<th>Tension, T (N)</th>
<th>1/n²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
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<tr>
<td>2</td>
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<td>8</td>
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</table>

Linear mass density = ________ kg/m

Table 2: Vary Frequency

Tension = ___ N
Length = ___ m

<table>
<thead>
<tr>
<th>Segments, n</th>
<th>Frequency (Hz)</th>
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<tbody>
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<td>6</td>
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<tr>
<td>7</td>
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Linear mass density = ________ kg/m

Table 3: Results
<table>
<thead>
<tr>
<th>Method</th>
<th>Linear mass density</th>
<th>% difference</th>
</tr>
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<tbody>
<tr>
<td>Direct</td>
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<tr>
<td>Tension vs. 1/n^2</td>
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<td></td>
</tr>
<tr>
<td>Frequency vs. n</td>
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</tbody>
</table>

**Questions**

1. As the tension is increased, does the number of segments increase or decrease when the frequency is kept constant?

2. As the frequency is increased, does the number of segments increase or decrease when the tension is kept constant?

3. As the tension is increased, does the speed of the wave increase, decrease, or stay the same when the frequency is kept constant?

4. As the frequency is increased, does the speed of the wave increase, decrease, or stay the same when the tension is kept constant?

5. Suppose that String #1 is twice as dense as String #2, but both have the same tension and the same length. If each of the strings is vibrating in the fundamental mode, which string will have the higher frequency?