Music and Sound

Reference Guide

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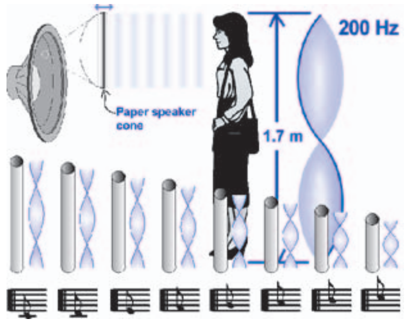
C-3 Natural Frequency and Resonance

Key Question: What is resonance and why is it important?

In this Investigation, students learn that the frequency at which objects tend to vibrate is called the natural frequency. They observe the natural frequency of a system and identify the relationship between amplitude and period. They experiment with different string tensions and discover the relationship between force and natural frequency, and length and natural frequency. Finally, they design and build their own oscillator and measure its natural frequency.



Preparation

Students should complete *Investigation C-1 Standing Waves* prior to this Investigation. In particular, review the results of their experiments from that Investigation, and introduce the terms natural frequency and resonance in that context.

Setup and Materials

Students work in groups of three to five at tables.

Each group should have:

- CPO timer and one photogate
- Physics stand
- Sound and waves generator
- A weight on a string
- Meter stick or tape measure
- Materials to build an oscillator (modeling clay, weights, balls, marbles, cardboard, string, rubber bands, elastic string, springs, stiff wire, glue gun and hot melt glue)

The Investigation

Time

One class period

Leading Questions

- How can you determine the natural frequency of a system?
- What is the relationship between force and natural frequency?
- How can you build an oscillator?

Learning Goals

In this Investigation, students will:

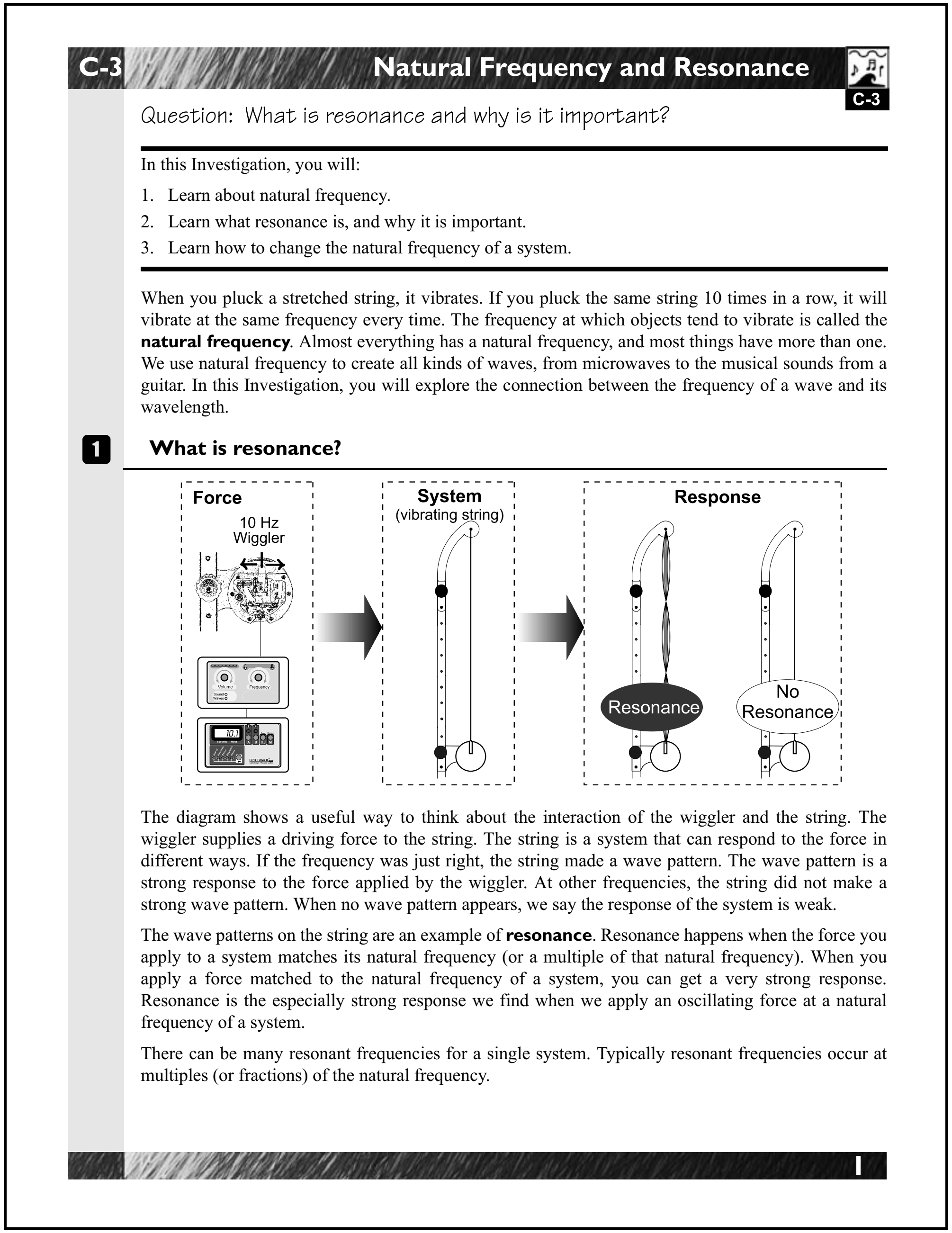
- Explain how natural frequency and resonance are related.
- Measure the natural frequency of a system.
- Describe the relationship between the force applied to a system, and the natural frequency of the system.
- Identify the relationship between mass, restoring force, and the natural frequency of a system.

Key Vocabulary

natural frequency, resonance, oscillator, restoring force

1

Student responses are not required in part 1.



C-3 Natural Frequency and Resonance

Question: What is resonance and why is it important?

In this Investigation, you will:

1. Learn about natural frequency.
2. Learn what resonance is, and why it is important.
3. Learn how to change the natural frequency of a system.

When you pluck a stretched string, it vibrates. If you pluck the same string 10 times in a row, it will vibrate at the same frequency every time. The frequency at which objects tend to vibrate is called the **natural frequency**. Almost everything has a natural frequency, and most things have more than one. We use natural frequency to create all kinds of waves, from microwaves to the musical sounds from a guitar. In this Investigation, you will explore the connection between the frequency of a wave and its wavelength.

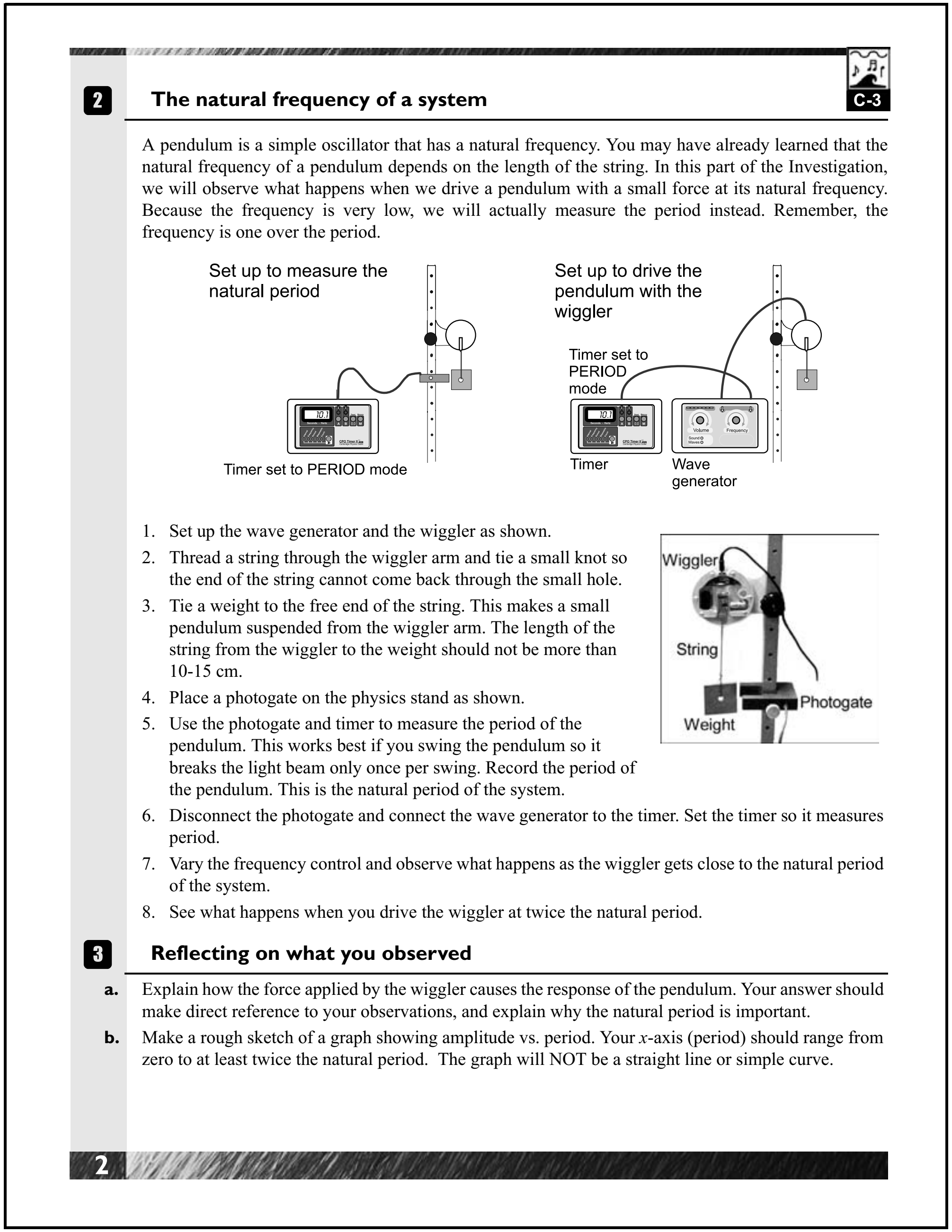
1 What is resonance?

The diagram shows a useful way to think about the interaction of the wiggler and the string. The wiggler supplies a driving force to the string. The string is a system that can respond to the force in different ways. If the frequency was just right, the string made a wave pattern. The wave pattern is a strong response to the force applied by the wiggler. At other frequencies, the string did not make a strong wave pattern. When no wave pattern appears, we say the response of the system is weak.

The wave patterns on the string are an example of **resonance**. Resonance happens when the force you apply to a system matches its natural frequency (or a multiple of that natural frequency). When you apply a force matched to the natural frequency of a system, you can get a very strong response. Resonance is the especially strong response we find when we apply an oscillating force at a natural frequency of a system.

There can be many resonant frequencies for a single system. Typically resonant frequencies occur at multiples (or fractions) of the natural frequency.

1



2 The natural frequency of a system

A pendulum is a simple oscillator that has a natural frequency. You may have already learned that the natural frequency of a pendulum depends on the length of the string. In this part of the Investigation, we will observe what happens when we drive a pendulum with a small force at its natural frequency. Because the frequency is very low, we will actually measure the period instead. Remember, the frequency is one over the period.

1. Set up the wave generator and the wiggler as shown.
2. Thread a string through the wiggler arm and tie a small knot so the end of the string cannot come back through the small hole.
3. Tie a weight to the free end of the string. This makes a small pendulum suspended from the wiggler arm. The length of the string from the wiggler to the weight should not be more than 10-15 cm.
4. Place a photogate on the physics stand as shown.
5. Use the photogate and timer to measure the period of the pendulum. This works best if you swing the pendulum so it breaks the light beam only once per swing. Record the period of the pendulum. This is the natural period of the system.
6. Disconnect the photogate and connect the wave generator to the timer. Set the timer so it measures period.
7. Vary the frequency control and observe what happens as the wiggler gets close to the natural period of the system.
8. See what happens when you drive the wiggler at twice the natural period.

3 Reflecting on what you observed

a. Explain how the force applied by the wiggler causes the response of the pendulum. Your answer should make direct reference to your observations, and explain why the natural period is important.

b. Make a rough sketch of a graph showing amplitude vs. period. Your *x*-axis (period) should range from zero to at least twice the natural period. The graph will NOT be a straight line or simple curve.

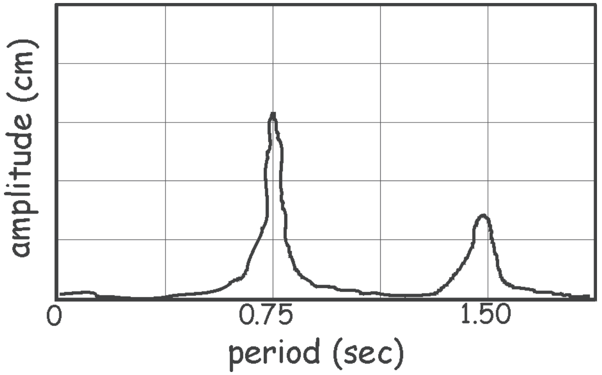
2

Student responses are not required in part 2.

3

3a. The force applied by the wiggler has very little affect on the pendulum until it reaches the natural period. At that point, the pendulum begins to swing. Its amplitude increases with each swing until it hits the physics stand.

3b. Sample graph:



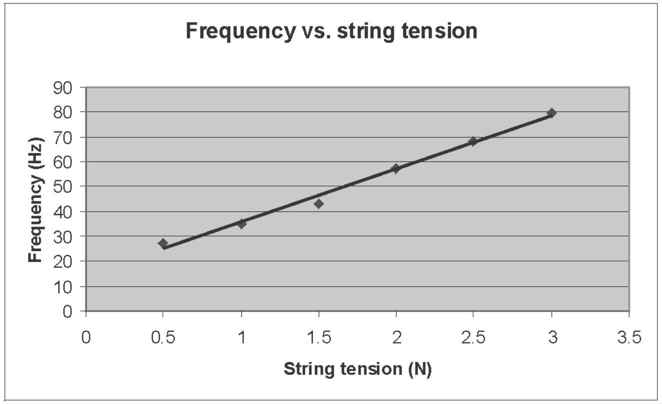
4 Investigation page shown on the next page

Table 1 data:

Harmonic	Tension (N)	Frequency (Hz)
3	0.5	27.2
3	1.0	35.1
3	1.5	43.3
3	2.0	57.1
3	2.5	68.0
3	3.0	79.6

5

5a. Graph of data:



5b. As we increased the tension in the string, the natural frequency increased. To tune a guitar, you tighten the string to raise the frequency and loosen the string to lower the frequency.

5c. As the string got tighter, we noticed that the amplitude of the waves got smaller. This makes sense because larger amplitude means the string is stretching more. The increased tightness made the string harder to stretch, which is why the amplitude went down.

For buildings, the stronger they are, the smaller the amplitude of any swaying motion from wind or earthquakes. To make a building sway less, you need to increase the force it takes to bend the building. This means adding steel or other kinds of reinforcing structures to increase strength.

C-3

4 Force and natural frequency

Sometimes you want large amplitude waves, as on a vibrating guitar string that is making sound. Sometimes you don't want large amplitudes, as in the motion of a tall building in an earthquake.

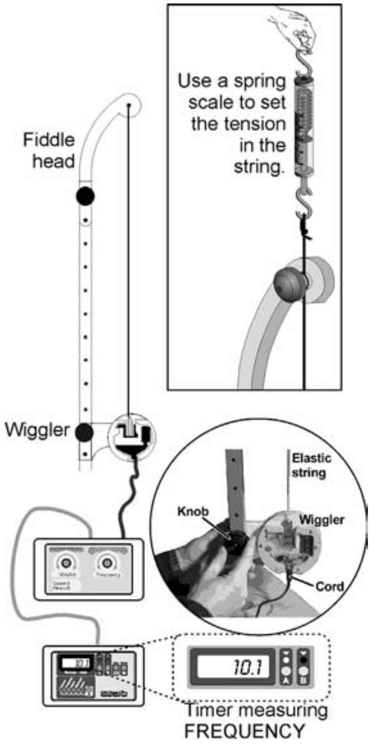
One way to change the natural frequency is to change the force it takes to move the system.

1. Loosen the knob on the fiddle head and attach a spring scale to the end of the elastic string.
2. While the knob is loose, stretch the string until the spring scale indicates the force that you want for the string tension.
3. Gently tighten the knob to hold the string without changing the tension.
4. Adjust the frequency of the wave generator until you have the third harmonic wave. Remember to fine-tune the frequency until the amplitude of the wave is as big as it can get.
5. Record the frequency in the data table.

Repeat steps 2-5 for each different string tension.

Table 1: Frequency vs. string tension data

Harmonic	Tension (N)	Freq. of 3rd (Hz)	Nat. freq. (Hz)
3	0.5		
3	1.0		
3	1.5		
3	2.0		
3	2.5		
3	3.0		

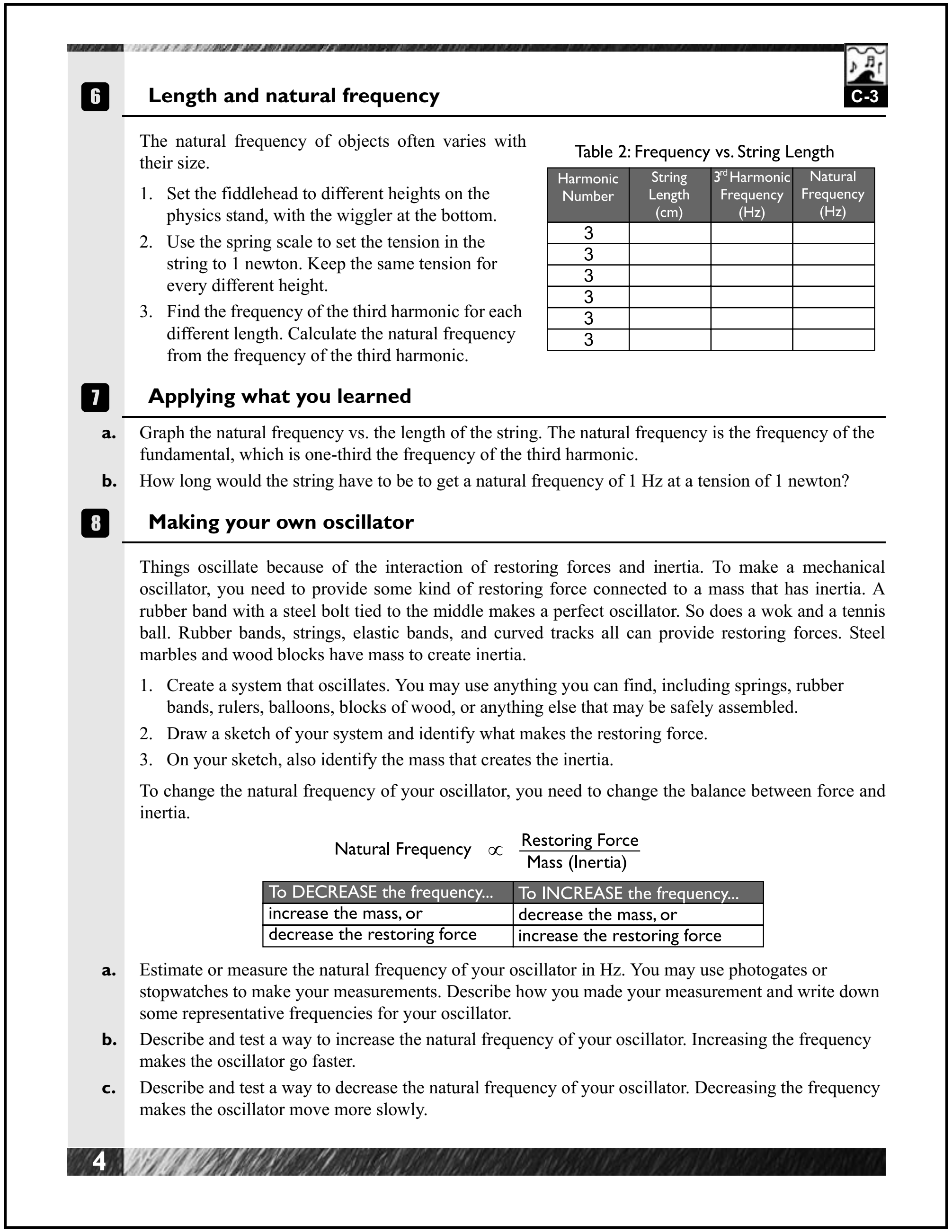


5 Applying what you learned

a. Make a graph showing how the natural frequency changes with the tension in the string. The natural frequency is the fundamental, which is one-third the frequency of the third harmonic.

b. What happens to the natural frequency as you increase the tension of the string? In your answer, discuss why this is useful in tuning a musical instrument such as a guitar or piano. You may need to do some research to investigate how guitars and pianos are tuned.

c. As the tension is increased, making the string stiffer, what happens to the amplitude of the wave? An earthquake is like the wiggler in that it makes the ground shake back and forth with a certain frequency. How do your results relate to making tall buildings sway less in an earthquake? In answering, you should consider what happened to the amplitude of the wave when you increased the tension in the string.



6 Length and natural frequency

The natural frequency of objects often varies with their size.

1. Set the fiddlehead to different heights on the physics stand, with the wiggler at the bottom.
2. Use the spring scale to set the tension in the string to 1 newton. Keep the same tension for every different height.
3. Find the frequency of the third harmonic for each different length. Calculate the natural frequency from the frequency of the third harmonic.

Table 2: Frequency vs. String Length

Harmonic Number	String Length (cm)	3rd Harmonic Frequency (Hz)	Natural Frequency (Hz)
3			
3			
3			
3			
3			
3			

7 Applying what you learned

a. Graph the natural frequency vs. the length of the string. The natural frequency is the frequency of the fundamental, which is one-third the frequency of the third harmonic.

b. How long would the string have to be to get a natural frequency of 1 Hz at a tension of 1 newton?

8 Making your own oscillator

Things oscillate because of the interaction of restoring forces and inertia. To make a mechanical oscillator, you need to provide some kind of restoring force connected to a mass that has inertia. A rubber band with a steel bolt tied to the middle makes a perfect oscillator. So does a wok and a tennis ball. Rubber bands, strings, elastic bands, and curved tracks all can provide restoring forces. Steel marbles and wood blocks have mass to create inertia.

1. Create a system that oscillates. You may use anything you can find, including springs, rubber bands, rulers, balloons, blocks of wood, or anything else that may be safely assembled.
2. Draw a sketch of your system and identify what makes the restoring force.
3. On your sketch, also identify the mass that creates the inertia.

To change the natural frequency of your oscillator, you need to change the balance between force and inertia.

$$\text{Natural Frequency} \propto \frac{\text{Restoring Force}}{\text{Mass (Inertia)}}$$

To DECREASE the frequency...	To INCREASE the frequency...
increase the mass, or	decrease the mass, or
decrease the restoring force	increase the restoring force

a. Estimate or measure the natural frequency of your oscillator in Hz. You may use photogates or stopwatches to make your measurements. Describe how you made your measurement and write down some representative frequencies for your oscillator.

b. Describe and test a way to increase the natural frequency of your oscillator. Increasing the frequency makes the oscillator go faster.

c. Describe and test a way to decrease the natural frequency of your oscillator. Decreasing the frequency makes the oscillator move more slowly.

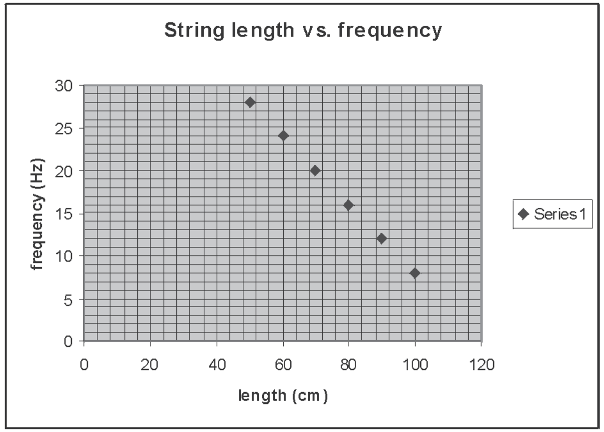
6

Table 2 data:

Harmonic	String length (cm)	3rd Harmonic frequency (Hz)	Natural frequency Hz)
3	100	24.3	8.0
3	90	36.1	12.0
3	80	48.1	16.0
3	70	60.4	20.0
3	60	71.7	24.0
3	50	83.9	28.0

7

7a.

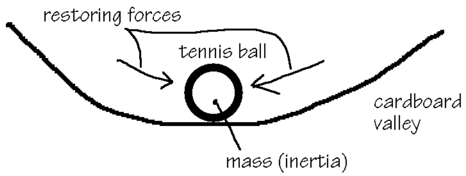


7b. The string would have to be 120 cm long.

1. 68 cm × 120 Hz = x cm × 180 Hz
   x = 68 cm × 120 Hz / 180 Hz = 45.3 cm
   You need a string that is 45.3 centimeters long.
2. If the frequency of the marchers matches the natural frequency of the bridge, the marchers could cause the bridge to vibrate very strongly, which might damage or break the bridge.
3. The frequency in **a** is lower than the frequency in **b**. This is because the tension in **a** is less than the tension in **b**. The greater the tension, the more forces is applied to the string. More force will cause a higher frequency. Less force means lower frequency.
4. 1 meter × 200 Hz = 0.8 meters × x Hz
   x Hz = 1 meter × 200 Hz/0.8 meters = 250 Hz
   Experiment **d** should have a frequency of 250 Hz.

8 Answers from page 4 of the Investigation (continued)

My oscillator looked like this:



The mass was the tennis ball.

8a. The frequency was 2 Hz. We used a stopwatch and counted cycles per second.

8b. We increased the natural frequency by making the walls of the valley steeper.

8c. We decreased the natural frequency by making the valley walls less steep, making the ball move slower.

Curriculum Resource Guide: Sound and Waves

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