# VII. Vibrations, Waves and Sound

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## CONCEPT REVIEW

### Vibrational Motion

1. An object at rest with no net force acting on it is said to be at its equilibrium point. If a displacement from equilibrium causes a net force to act on the object in the direction *opposite* of the displacement, then the object will vibrate about the equilibrium point.

2. If the magnitude of the net force acting on the object is also proportional to the displacement (for example, twice the displacement increases the net force by a factor of two), then the motion of the object is referred to as simple harmonic motion. A graph showing the displacement of the object over time is the shape of a sine or cosine curve.

3. Simple harmonic motion is an example of periodic motion because the object returns to the same value of position and velocity repetitively and regularly during its motion. An oscillation is defined as one complete cycle of periodic motion, and the period of motion is defined as the time it takes to complete one oscillation.

4. Frequency (or counting frequency) is defined as the number of oscillations completed over one time unit: it is the inverse of period, which is the time of one oscillation.

5. A vibrating system will possess a natural frequency that depends on the particular conditions of the system. For a vibrating mass attached to a spring, the natural frequency will be a function of both the ‘spring constant’, or stiffness of the spring, and the mass. The natural frequency for other types of systems undergoing periodic motion (such as the simple pendulum) may depend on other variables of the system.

6. Periodic motions may have a number of parameters that may be set independently of the systems conditions. For simple harmonic motion, independent parameters are the amplitude of vibration and the phase angle, or starting point of the motion.

### *Wave Motion*

1. A medium is a system of particles connected by restoring forces. Therefore, a medium is able to sustain a vibration locally.

2. A disturbance created in one part of the medium travels through the medium instead of remaining local. A single, traveling disturbance is called a wave pulse. An oscillation that continues at one point of the medium results in a traveling periodic wave.

3. Periodic waves, like vibrations, will have a period and frequency. The distance that the original disturbance travels from the point of origin through the medium over one period of oscillation is the wavelength of the wave.

4. A wave is a localized disturbance that travels through space which transfer energy but not mass. The energy of a wave is proportional to the square of the amplitude.

5. The speed of a wave is constant and determined by the properties of the medium only, and not by the parameters of the wave. For a periodic wave, the speed of the wave (v) is also equal to the product of its counting frequency (f) and wavelength (_).

$$v = f \square$$

6. Two waves that meet in a medium pass will through each other. The waveform that is created while this is happening is the sum of the amplitudes of the waves at that point. This principle is called superposition.

7. For the special case of two periodic waves of the same frequency and amplitude that meet crest-to-crest and trough-to-trough (or in phase) then the resulting superposition is called constructive interference. The wave form has the same frequency as each original wave but twice the amplitude of either one. If two periodic waves of the same frequency and amplitude meet crest-to-trough (or out of phase) then the result is no wave form at all, which is destructive interference.

8. A periodic wave reflected from a boundary between mediums may create a particular pattern known as standing waves.

a) Standing waves are the result of superposition. The waves themselves are continually and are never actually standing still.

b) A standing wave pattern has particular points in the medium that maintain zero amplitude (nodes) and others that always vibrate with maximum amplitude ( antinodes).

c) Only wave forms of particular frequencies may be sustained as standing waves. The allowed frequencies will depend on the speed of the medium and boundary conditions.

## CONFLICTING CONTENTIONS

### 1. Vibrating Strings

“The speed of a wave depends on the properties of the medium. No matter what the medium, there is always a force-like property and a mass-like property,” Mr. Nicholls said.

“Force-like? Mass-like? I don’t get it”, Mary responded.

“Well, for example, sound waves travel through air,” he said. “We usually associate mass with a single particle, but air is made up of many particles, mostly molecules of nitrogen, oxygen, and water. Instead of talking about a certain mass of air, we consider the density of air, which is the mass per unit volume.”

“So sound travels faster through helium, which is lighter than air,” Beth interjected.

“Exactly,” the instructor said. “All things being equal, sound travels faster through helium than air because its mass-like property, it’s density, is less.”

“So is pressure the force-like property for a gas?” John wondered.

“No, although that is a good guess,” Mr. Nicholls responded. “It’s a property of matter called the bulk modulus. You can think of the bulk modulus as the ‘springiness’ of a material, such as air. It’s similar to the stiffness of a spring. So the larger the bulk modulus, the faster waves travel through the material.

“But we want to deal with waves we can see and measure, so today we are going to set up standing wave patterns in a string. I’ve attached a string about two meters long to this mechanical vibrator. The vibrator always produces waves with a frequency of 120 Hertz. It’s important to remember that the frequency in this experiment is always constant.

“I’ve attached the other end of the string to a weight hanger and hung it over a pulley. It is also important to remember that the two ends of the string will always be nodes of the standing wave vibration.

‘The mass-like property of the string is its mass divided by its length, which is called – surprise, surprise – its mass-per-unit-length. The force like property is the tension in the string. Watch what happens when I add some mass to the weight hanger.”

The teacher added mass to the weight hanger, and the class observed a series of loops in the string. There were certain parts of the string which were vibrating vertically with an amplitude of almost three centimeters, but other parts of the string didn’t appear to vibrate at all. The class counted six loops in the string.

“What do you think will happen if I add more mass to the weight hanger?”, Mr. Nicholls asked. “Will the number of loops increase, decrease, or stay the same?”

“Increase,” said Frank. “Since you are adding more weight, the tension will increase. That means faster waves, and that means more loops.”

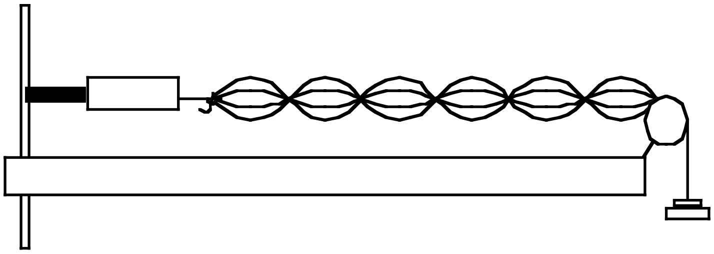
“No way,” said Daniel. “More weight means more mass. That slows down the waves, so there are fewer loops.”

“I wish you two would look at the equations once in a while,” Cathy added. “Faster waves mean fewer loops and slower waves mean more loops, not the other way around.”

“How can you tell?”, Mary asked. “The speed of a wave is the product of its wavelength and frequency. Since all three of them depend on each other, you can’t just take two of them at a time and ignore the third. Frequency will also have an effect on the wavelength when the velocity changes in the string.”

“I’m more concerned about the string stretching with greater tension”, Alonzo said. “If the string gets longer, then the mass per unit length will change. Will that be important?”

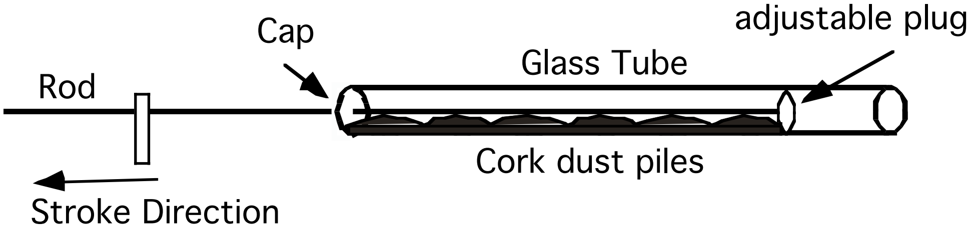
Now it's your turn.  What do you think?



2. The Speed of Sound in Metal

"I love this experiment," Mr. Nicholls told the class, "because it includes so many concepts about vibrations, waves, and standing waves.  I've clamped a metal rod, about 60 centimeters long, at its center.  One end of the rod has a circular cap on it that just fits into this glass tube.

"The glass tube has a light sprinkling of cork dust in it and an adjustable plug at the other end. When I stroke the metal rod, you will hear a high-pitched hum.  The stroking sets up standing waves in the metal rod.  The disc on the end of the rod transfers the sound waves from the rod into the air inside the tube.  If I adjust the length of the tube just right by shifting the location of the plug in the other end, I can get standing wave patterns to form in the air inside the tube.  The cork dust shows me where the nodes and anti-nodes are by forming large piles of dust at the antinode locations and almost no disturbance in the dust at the nodes."



Mr. Nicholls took a piece of cloth with resin on it and began to stroke the tube lengthwise.  It sounded like a person scratching a chalkboard with his finger nails.  But, sure enough, the cork inside the tube began jumping around.  After eight or nine strokes, and a few adjustments of the moveable plug, the class could see that the mounds of cork dust, from node to node, were about four centimeters long.

"Can I take my fingers out of my ears, now?", Daniel asked.  "Sure," said Mr. Nicholls, "I'm done."

"Great," said Cathy, "So what are you going to show us next?  Something more about standing waves?"

"What a minute," he said, "I may be done, but you aren't.  I want you to calculate the speed of sound in the metal rod."

"How?", Alonzo asked.

"You tell me," the instructor said, "All you need to know are the length of the rod, the average separation distance between the cork nodes or anti-nodes, and the speed of sound in air, which is 340 m/s."

"But that's not fair!" Beth protested, "We don't know what's going on; you are supposed to tell us. You give us the lab hand-out." ("Which you don't read," Mr. Nicholls interjected.) "We make the measurements and write them down in the data table." ("Which don't mean anything to you because you didn't read the lab in advance," he added.) "And we calculate the speed of sound in metal, or whatever." ("Using equations which you don't understand and getting a number that has absolutely no meaning to you," he finished.)

"Now you are just being mean," Frank said.

"No, but I do want you to do some thinking in lab, just like in class time," he replied. "I'm not going to give you a lab hand-out with all the answers for this one, but I am going to help you think through this experiment. So by the time you are done, you will know exactly how the apparatus works and how you are able to calculate the speed of sound in a metal from the measurements.

"I'm giving you a list of questions with some possible answers. Reason through the correct answers, and the principles behind this lab will become clearer to you."

Here are Mr. Nicholls' questions. Can you explain how the apparatus works?

Also, if the length of the steel rod is exactly 59.8 cm and the average spacing from node to node of the cork dust in the air tube is 4.2 cm, can you calculate the speed of sound in steel?

QUESTIONS

a) Are the standing waves produced in the rod longitudinal or transverse? Are the standing waves produced in the air tube longitudinal or transverse?

b) The wave equation states that the velocity of a wave (v) is equal to the product of its frequency (f) and wavelength (_):

$$v = f\ \square$$

One of these three quantities is the same for the waves in the metal rod and the waves in the air tube. Which one is it: velocity, frequency, or wavelength? Can you explain why that quantity should be the same, based on how the waves are produced?

c) Based on your answer to the last question, is it important that both waves be of the same type (longitudinal or transverse) or can they be of two different types?

d) Let vm = fm _m be the speed, frequency, and wavelength of sound in the metal rod; and va = fa _a be the speed, frequency, and wavelength of sound in air.

One of these quantities is the same based on your answer to (b): either vm = va; fm = fa ; or _m = _a. Combine the two equations by eliminating the common variable. In other words,

If $v_m = v_a$, then $f_m \lambda_m = f_a \lambda_a$

If $f_m = f_a$, then $v_m / \lambda_m = v_a / \lambda_a$

If $\lambda_m = \lambda_a$, then $v_m / f_m = v_a / f_a$

Which of these expressions is the correct one? (Circle it.)

e) A standing wave must have nodes and antinodes. The distance from node to node in the air tube was measured. How is this distance related to the wavelength of the standing wave in air?

f) The standing wave in the metal rod must also have nodes and antinodes. A node has no amplitude of vibration; an antinode has the maximum amplitude of vibration. Is the clamped center of the rod a node or antinode? Are the two free ends of the rod nodes or antinodes?

g) Knowing where the nodes and antinodes are in the rod, calculate the wavelength of the standing waves in the metal rod, as you did for air in (e).

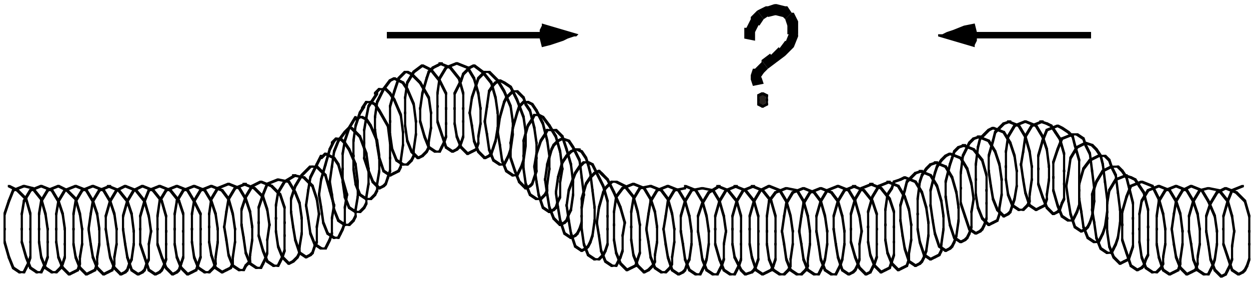
h) There are four variables in the expression you chose from (d). You know the speed of sound in air is 340 m/s. You determined the other two variables in (e) and (g). Solve the expression for the speed of sound in the metal.

## 3. Wave Collisions

Creativity and innovation are just as important in the advancement of science as logic and reason. This is especially true on the unexplored frontiers of science where very little about the behavior of the universe is known and the possibilities of what Nature might do are endless. Therefore, it is sometimes a useful 'mental exercise' to consider all of the possibilities of a situation even when you already know the right answer, since what may seem silly now (by knowing the right answer) may be exactly how the universe behaves in some other situation. (See chapter 10 on Modern Physics if you have any doubts about this.)

For example, consider two wave pulses traveling in opposite directions on a spring. According to the principle of superposition, the two waves will pass through each other, unaffected by the encounter. The displacement of the spring at any given instant will be the sum of the amplitudes of the two wave forms at each point on the spring.

But now consider what might happen when two wave pulses traveling in opposite directions on the spring encounter each other. Imagine at least three different possible behaviors of the wave forms when they meet, and describe what you would observe if that possibility correctly described the behavior of wave forms instead of the superposition principle.



QUALITATIVE REASONING

1. Piano Wires

The 88 keys of a piano are able to produce sound waves over many octaves by striking wires under tension with a hammer. The high frequency (high pitch) notes are produced by striking short, thin wires; the low frequency (low pitch) notes are produced by striking long, thick wires that are often wrapped with another wire to make them even thicker.

a. Relate the length and thickness of the wires to the types of sound they produce. In other words, why are thin and short wires used to make high frequencies; and why are long and thick wires used for low frequencies? Think in terms of both the vibrations that are produced and the wavelengths that travel through the air to your ear.

b. Suppose that a piano wire needs to be replaced, but the appropriate type of wire is not available. For example, suppose a wire that is used for notes slightly lower than the note produced by the broken wire must be used to replace the old one. If the broken wire is replaced with the new wire, how must the tension be different in the newly-installed wired compared to the old wire to make it produce the right note?

2. Organ Pipes

An organ pipe can either be open on both ends or open on one end and closed on the other. Organ pipes of the same length and made of the same material will produce different notes as a result. Which pipe can produce the lowest possible pitch (also known in music as the fundamental)?

Hint: The end of a vibrating pipe must be either a node or an antinode of the standing wave being produced by the pipe. A closed end of a pipe must be a node; an open end must be an antinode. Draw wave forms as long as possible for each type of pipe meeting these conditions.

## 3. Does 'Who Moves' Matter?

The Doppler effect is a real or perceived change in the frequency of sound caused by a moving source of sound or a moving listener. If a sound source is moving towards a listener at rest, then the pitch heard by the listener is higher compared to what is heard if the sound source is also at rest because the wave fronts come closer together as the source moves. If the source of sound is at rest but the listener is moving toward it, then the listener will also hear a higher pitch than that produced by both listener and source at rest because the wave fronts reach the ear more frequently compared to the situation when the listener is standing still. Of course, the opposite effect will be heard if the source is moving away from the listener, or if the listener is moving away from the sound source: the pitch heard by the listener will be lower than that being produced by the source.

These experimental results can be summarized by the two following equations,

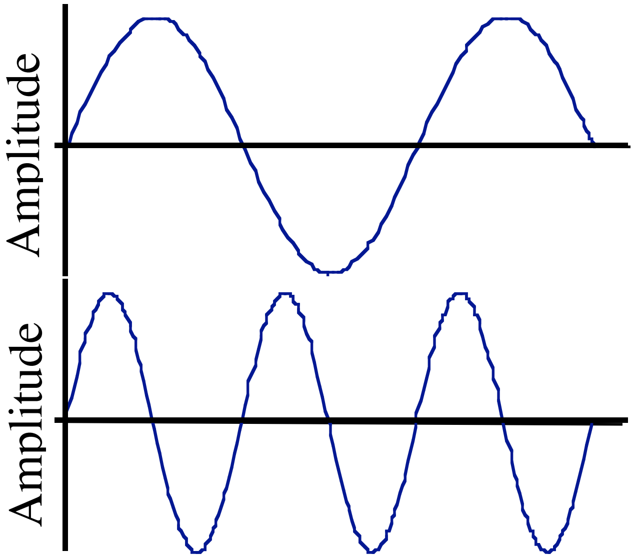
$$f = f_o \left[ (v + v_L) / v \right] \quad \text{and}$$
$$f = f_o \left[ v / (v - v_s) \right]$$

where f0 is the frequency produced by the sound source, v is the speed of sound in air, vs is the velocity of the source and vL is the velocity of the listener. A positive velocity, vs or vL always means that the source and listener are moving closer together.

Now here is the question: does the change in pitch depend on whether the source or the listener is moving? In other words, will the shift caused by a source moving 50 mph towards a listener at rest be the same as the shift in pitch caused by the listener moving 50 mph toward a source of sound at rest?

## 4. Adding Waves

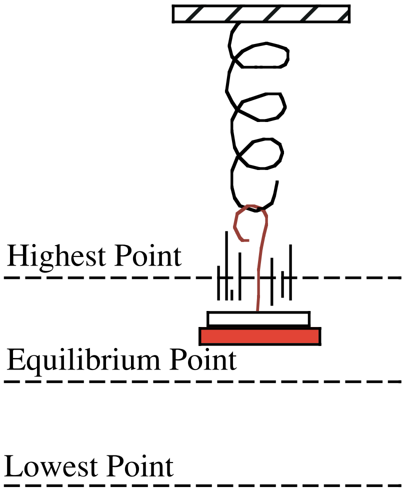
Below are pictures of two waves at a certain instant in time. What will the waveform look like if the two waves are superimposed? Draw or sketch your answer on paper.



## 5. Doubling effects on vibrations

The figure shows a 100 gram mass vibrating on a spring. The vibrational motion was begun by raising the mass 10 cm above its equilibrium point and letting go.

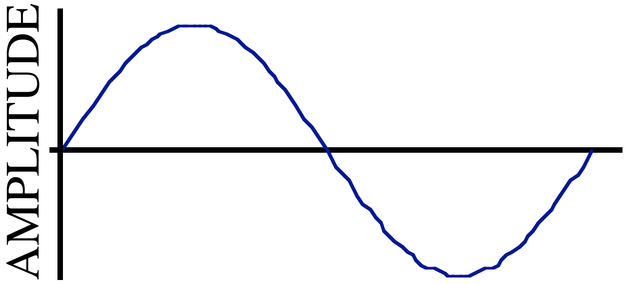
Suppose you grab the mass at the highest point of the motion and add another 100 grams to it, making a total of 200 grams on the spring. How would this change affect:



- the frequency of the motion?
- the period of the motion?
- the amplitude of the vibration?

## 6. Doubling effects on waves

Below is a figure representing a traveling wave, where the Y-axis represents the amplitude of the wave.



If the amplitude of the wave was doubled, what would be the effect on

- the frequency of the wave (or the pitch of the sound heard, if the waveform represents a sound wave)?
- the wavelength of the wave?
- the speed of the wave?
- the energy of the wave?

Try to be more exact than higher, lower, or the same. For example, would the frequency (or pitch) double, quadruple, be half as large, one-fourth as large, or not change compared to the original wave?

## CAN YOU EXPLAIN THIS?

### 1. The Sound of Silence

An audio generator is able to produce just a single frequency of sound. Two speakers are attached to an audio generator and are set about one meter apart, facing the same direction. As a person walks in a straight line in front of and parallel to the two speakers, there are certain spots where no sound is heard at all.

Can you explain this?

### 2. Step to the Beat

A platoon of soldiers is marching toward a pontoon bridge that crosses a river. The Sargent makes the soldiers stop marching as they cross the bridge. Why? What physics principle concerning vibrational motion is the Sargent trying to avoid?

### 3. Empty Headed

The human head is mostly empty space! The brain ends at about eye level; below that are the sinuses, nose, ear canal, mouth and throat, which are mostly air passages.

Why is that important in terms of sound production?

### 4. Big Ben

Try this yourself. Hang a metal coat hanger from a string and bang it against the edge of a table. You will hear a 'tinny' sound. Now wrap the ends of the string around your two index fingers and stick them in your ears. Bang the coat hanger against the table again, and it will sound like Big Ben.

Can you explain this? What principle of sound propagation does this demonstration illustrate?

Finally, if you pinch off some of the string with your thumb and middle finger on each side while keeping your index fingers in your ears, creating 'slack 'in the string, you will hear very little sound from the banging coat hanger. Can you explain why?

## 5. Out of Sync

This is a true story. I was walking on the sidewalk between two buildings on campus because I had left something in my office that I needed for class. Construction had begun on a new building, and a dump truck was emptying a load of dirt for the foundation. The door was swinging against the truck in a regular pattern, creating a ‘Bang! Bang! Bang!’ sound, only I was hearing the ‘Bang!’ sound when the door had swung the farthest away from the back of the dump truck, not when it actually struck the back of the truck.

Can you explain what I heard and saw?

Hint: The speed of light is much faster than the speed of sound.

BONUS: If the speed of sound in air is about 340 m/s, and if the period of the ‘Bang!’ was approximately one per second, how far away was I from the dump truck?

## 6. Bell in a Jar

There is a well-known demonstration of a ringing bell placed under a jar on a plate with a hole in the center. A vacuum pump is attached to the hole using a rubber tube, and all the air is slowly sucked out of the jar. As the air is removed, the sound of the ringing decreases until no sound is heard at all.

a. Can you explain, in terms of the principles of vibrations and waves, why no sound is heard when all of the air is removed from the jar?

b. Can you explain, in terms of the principles of vibrations and waves, why the intensity of the sound decreases while the air is being removed?

c. Sometimes you can still hear a faint ringing of the bell, even after the air is evacuated from the jar. Can you explain how the sound is ‘getting out’, even though the air is gone?