D. Wave Applications

The wave phenomena we studied in the previous chapter emphasized fundamental properties of waves. In this chapter, we focus more on applications. Some of the applications we encounter here will build on the basic physics of the previous chapter.

SONAR

SONAR stands for <u>SO</u>und <u>N</u>avigation <u>And R</u>anging. One can determine the depth of a body of water by sending sound waves to the bottom and timing how long it takes the sound to return. However, we must note that sound travels at different speeds in different media. In fact, even in the same medium such as air, the sound varies if the temperature of the air changes.

Table D-1 is a short list of sound speeds in a few media. The three main states of matter are accounted for: gas, liquid, and solid. Sound travels faster in lighter gases such as helium. Helium atoms are light and respond quickly. We commonly encounter a use for helium in party balloons. Helium's lightness causes balloons filled with helium to float upward in air.

Table D-1. Speed of Sound in Various Media.

	Medium	Sound Speed (m/s)
Gas	Air	340
	Helium	1000
Liquid	Water	1500
Solid	Wood (Typical)	4000
	Steel	6000

Sound speed is greater for liquids, where the molecules are closer together and they can transmit their vibrations more readily. The stiffness of solids allows for even more rapid propagation of sound waves.

The value for wood given in the table is typical of elm, maple, and oak. Steel is the stiffest of the examples in Table D-1 and therefore has the greatest speed of sound. Sound speed in steel is approximately 6000 m/s = 6 km/s (6 kilometers per second, which is about 4 miles per second).

Question: The circumference of the Earth is 40,000 km (25,000 miles). How long would it take to go around the world if you could travel at the speed of sound in steel?

Answer: How many kilometers per hour do you go if you travel at 6 kilometers per second? Multiply 6 km/s by 3600 to get 21,600 km/h and round this off to 20,000 km/h. Since you have to go 40,000 km, you get an estimate of 2 hours for your travel time!

Let's measure water depth by sound waves. See Fig. D-1 for a sketch of the general idea of SONAR. The sound is sent to the bottom of the water, bounces off the ground, and returns to the ship. The time it takes to return is then used to determine the distance. A travel time of 1 second indicates 1500 meters traveled since the speed of sound in water is 1500 m/s. For this case, the water is 750 meters deep, one half of 1500 meters since the sound needs to travel down and back. We have an echo effect, a result of the fundamental principle of waves called reflection. Fig. D-1. SONAR: Sound Waves Used to Measure the Depth of Water.



Recall that we encountered an experiment to measure the speed of sound on the UNCA Quad. There we knew the distance and time. We figured out the speed. Here we apply our knowledge of the speed and measure the time to determine the third variable, the distance.

If you are not too familiar with the metric system, remember that a meter is approximately a yard. A meter is actually a little longer than a yard, about 8% longer (8 centimeters or 3 inches longer). One hundred meters is the distance between the goal posts on a football field, a distance a little longer (8%) than the 100-yard playing field. A mile is 5280 feet or 1760 yards. In terms of meters, the value is approximately the same numerical value as that for yards: 1609 meters. Therefore, the speed of sound in water (1500 m/s) is almost one mile per second. Our body of water is 750 m deep or about a half-mile deep.

Ultrasound

Ultrasound refers to frequencies above the limit of human hearing. Rounded off, this limit is 20,000 Hz or 20 kHz. Ultra-high frequencies can be used to make images of internal body structure. The word ultrasonics is also often used to describe such high-frequencies.

Ultrasonic means "beyond sound," which can refer to passing the speed of

sound or to exceeding the frequency of the sound we hear. We use the latter definition in this section. The word supersonic we encountered in an earlier chapter is synonymous with ultrasonic.

Ultrasound penetrates the body and reflects off underlying structure. The waves that return are used to construct an image of the inner body. Such a medical image is called an ultrasound or sonogram. Ultrasounds are often used to take pictures of the fetus since common medical imaging using x-rays would be very harmful to the fetus. When you are x-rayed, a section of your body is chosen. A heavy cover containing lead may be placed over nearby parts of your body, and the technician may leave the room when the x-rays are emitted.

Sound waves allow the technician to look at parts of the fetus and capture images on a computer. Parts can be examined. Lengths of bones can be measured and compared with normal D-2 patterns. See Fig. growth for dimensions of a fetus from an ultrasound exam done at Asheville Women's Medical *Center* in 1983.

Medical researchers constantly improve imaging techniques and study their effects on the patient. As a general rule, you should always consult with your doctor about the possible side-effects for even supposedly safe treatments. While basic physics can tell us for example that ultrasound is very safe compared to x-rays, statistical medical observation over a long period of time is necessary to assess subtle or long-term biological effects to any diagnostic test or treatment. As with any developing field of research or science, the latest information can always modifv previously-held beliefs.

Fig. D-2. Dimensions of Fetus (Author's First Daughter) from Ultrasound Exam.



View of Head

Distance: 61 mm

Single Fetus, 25th Week (7/29/83).

The smaller variety of bats, called microbats, use ultrasound to navigate. These bats are about the size of a small bird. They emit an ultrasound which reflects from objects. When they receive an echo, they know something is in front of them.

This is convenient for bats living in dark caves. Or maybe, if a cave is not available, the bats may find a home in an old dark abandoned house - perhaps the one on the hill near the graveyard. Or a bat may settle for your dark attic. The bat's ability to locate objects and prey by an echo is referred to as echolocation. Echolocation does not have to use ultrasound. Some birds use sounds in the audible range. Porpoises also use echolocation.

We will use a simple model to estimate the ultrasound frequency of bats as physicists often use simplified ideas to estimate things. Bats typically use pulses of ultrasound rather than a continuous emission. The high frequency has very short wavelength. Recall that waves diffract around obstacles comparable in size to their wavelengths. So if you want to get a good bounce off a very small object, use a very short wavelength. Then, the structure is "large" compared to the wavelength and reflection predominates instead of diffraction. The ability to get a reflected wave from a small object in order to acquire its image is called resolution.

Bats use short wavelengths to obtain good resolution. This is especially important if you like to dine on insects. And most bats

Body Section	Size
Width of Head	61 mm
Humerus (upper arm)	43 mm
Femur (thighbone)	46 mm

do. However, three of the hundreds of species of bats prefer blood. These are called vampires!

We can use the relation $v = \lambda f$ to find out how high the frequency has to be in order to image an insect. Let's suppose that a bat wants to have a moth for dinner. Estimate the size of a moth. How about 3 cm (three centimeters)? That's a little more than an inch. To get a significantly smaller wavelength than this, let's pick 1/10 of this value. That gives a wavelength of 0.3 cm or 3 mm (3 millimeters). Think of 1 cm as the width of your little finger and 1 mm as the size of lead in a pencil. To use our relation $v = \lambda f$ properly we need to be consistent with our units for distance. If we stick with mm, then we express the speed of sound, 340 m/s, as 340,000 mm/s. Remember that 1000 mm gives one meter.

So if you travel 340 meters, this distance is also 340,000 millimeters. Since our analysis is an estimate, we can round off 340 to 300. Then $v = \lambda f$ becomes 300,000 mm/s = (3 mm) f. What must 3 bemultiplied by to get 300,000? The answer is 100,000. Therefore, f = 100,000 Hz (one hundred thousand hertz).

Bats actually use frequencies as high as this. See Fig. D-3 for a wave reflecting from a moth. Bats are not blind, so you shouldn't use the expression "blind as a bat." But echolocation enables the bat to detect a flying insect from afar.

Challenging Problem: Estimate the frequency for a medical ultrasound head if

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= 5 Megahertz = 5 MHz.

the resolution is 1 mm and sound speed in tissue is 500 m/s. Answer: f = 5,000,000 Hz

Fig. D-3. Reflected Ultrasound from Flying Insect.



The hearing ranges of some common animals reach well into the ultrasonic region. We are familiar with a dog's ability to easily hear high-pitched sounds. The silent whistle produces a tone of about 30,000 Hz (30 kHz), well beyond human hearing. Yet dogs respond to the whistle. The whistle is small since the wavelength is very short. We will study waves in pipes later. A general feature to remember is that small structures produce short-wavelength sounds, i.e., high pitches. Large vibrating mechanisms produce long-wavelength sounds, i.e., low pitches. That's why during Saturday-morning cartoons, the little

creatures speak in high-pitched voices and the large ones sound low and deep.

Fig. D-4 indicates the hearing ranges of some animals. Snakes do not do well. They lower frequencies. restricted to are Humans, with a hearing range of 20 -20,000 Hz, hear many more frequencies than snakes. Human speech falls mostly between 250 and 4000 Hz. In order to get an idea of what frequencies snakes can hear, have your friends talk to you with rags jammed in their mouths. This will filter out the higher frequencies. The other animals listed in Fig. D-4 surpass humans. Our friend, the bat, ranks the highest.

Fig. D-4. Some Animals and Very Approximate Hearing Ranges.



Bats: 1000 - 100,000 Hz

Cats and Dogs: 20 - 50,000 Hz

Elephants have a range from about 16 Hz to 12,000 Hz, but they are very sensitive at the lower end. For the other animals we have generously rounded off at the lower end.

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Courtesy www.ghananewsagency.org

The Doppler Effect

When waves are bounced off moving objects, there is a shift in frequency. This phenomenon is named after physicistmeteorologist, Doppler. Back in 1840 there were no cars driving around every day in order to hear a passing car's horn shift in pitch. We have all heard such shifts. When a car blowing its horn comes toward you, the pitch is higher. When the car is leaving you, the pitch is lower. The effect is most dramatic when a car heading toward you, passes by you with the horn sounding. Measuring the shift in frequency can tell you how fast the car is moving relative to you. Police use the Doppler effect with an invisible form of light when they bounce

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Fig. D-5. The Doppler Effect.

radio waves off your car (RADAR). Bats experience frequency shifts when their high-frequency acoustic waves bounce off moving targets. This can help them determine the speed of flying insects. The delay of the echo gives the bat the distance to the prey.

Doppler had musicians help him with an experiment to verify that frequency changes due to motion. Some musicians played horns on a moving train. They chose a specific note. Other musicians on the ground could tell with their well-trained ears that the tone was higher as the train approached them, to their surprise. In music jargon, a raised pitch is said to be "sharp" or "sharper." A lowered pitch is said to be "flat" or "flatter." The musicians on the ground heard a tone that was too sharp as the source of sound approached them.

Fig. D-5 illustrates the Doppler Effect. Think of the horn as sending out a crest (compression) every so often. When the car approaches, it moves a little toward the last crest it sent out to the observer. Therefore, the distances between crests are shortened and the pitch is higher. When the car is moving away, the opposite takes place and longer wavelength means lower pitch.

No motion. Our hearer hears the reference pitch.

Approaching horn. The wavelength is shortened.



Receding horn. The wavelength is lengthened.

Wave Addition and Beats

We have seen the effects of adding waves in our previous discussion on interference. In our study of interference we considered two identical waves. When the waves were added in phase, we obtained constructive interference; when the waves were added out of phase, we found destructive interference. Now we are going to add different waves. To demonstrate the phenomenon of beats we need two waves that are almost the same. However, we will first take this opportunity to just practice adding different waves. This will help us develop the necessary skills to analyze depth waves in more later. After considering two examples of wave addition. we will proceed to discuss beats.

In Case I below (Fig. D-6) we add two square waves. Note that the second wave (lower diagram) is one half the wavelength of the first (upper diagram). Therefore, the second wave is twice the frequency of the first one. Remember our relation $v = \lambda f$. This tells us that the product of the wavelength and frequency is a constant, the speed of the wave in the particular medium. If you halve the wavelength, you double the frequency. Recalling the analogy with money, if you have 4 quarters, you have a dollar. If you halve the number of coins to 2, you double the amount of each coin. You need two fifty-cent pieces.

To readily find the sum wave, divide the waves into 4 parts or sections. In the first quarter, both top and bottom waveforms have displacement values of 1. Therefore, the sum displacement is 1 + 1 = 2. For the second quarter, we have the top wave at 1 and the bottom one at -1. The plus 1 and minus 1 cancel. We get 1 - 1 = 0. For the third quarter, we have -1 + 1 = 0. Finally, for the last quarter, we have 0 as being "in the black," while negative values mean we're "in the red" (in debt).



Fig. D-6. Wave Addition: Case I.

Case II is given in Fig. D-7. We are to add a square wave to a triangle wave. Note that the triangle waveform has one half the wavelength as the square wave, which is above it. The triangle wave therefore has twice the frequency. It goes through two complete cycles or patterns in the time it takes the top waveform to go through one cvcle of a crest and trough.

The first wave (upper one) is at +1 for the first half and -1 for the latter half.

Consider the first half of the triangle wave and add +1 everywhere. This is equivalent to raising the entire first half of the triangle up by 1. The second half of the triangle waves gets lowered by 1 since our square wave is at a minus 1 for the second half of its cycle. Study the sum displacement. Visualize the first half of the sum as a raised triangle. Visualize the second half of the sum displacement as a depressed triangle.



Fig. D-7. Wave Addition: Case II.

Sum Displacement Time

You can add any two waves if you have enough patience. Look at each unit of time above. Along the time axis (horizontal) there are 16 divisions in our graphs, for the waves under consideration. Consider the 3rd division along the horizontal axis. The upper wave has a value of 1 there and the lower wave has a value of 0.5 or 1/2.

value of 1.5 or 3/2 at the 3rd division. Since each vertical division is 1/2, you need to count up 3 divisions (or boxes) to find the 1.5 mark. You need to be a little careful at some places like the beginning. The square wave shoots up from 0 to 1. Well, since the triangle wave is 0 here, the sum wave will go from 0 + 0 = 0 to 1 + 0 = 1.



See if you can determine the sum displacements for the cases in Fig. D-8.

Fig. D-8. Practice with Addition. Sketch in the Sum Displacement for Each Case.

Practice Case I.



Practice Case II.





We now turn to the subject of beats. Consider two pure tones very close in frequency. Let the sources of these waves start oscillating in phase. Our sources might be two electronic oscillators sending signals to amplifiers and then speakers. Since the waves do not have exactly the same wavelength, after several cycles, the peaks drift out of alignment. There comes a time when a crest from one is aligned with a trough from the other. The waves, starting with constructive interference, now experience destructive interference. However, after awhile, the waves are once again in phase. This drifting in and out of phase is heard as a pulsation, a pulsating tone. We call these pulsations beats.

An analogy of drifting in and out of phase can be found where two people are

walking with different step sizes. They can start off walking with each moving right foot forward. Shortly, the right foot of each will be doing something different. After awhile, when one person's right foot steps forward, the other person's left foot will be stepping forward. Then awhile later, we can find an instant when both right feet will step forward at the same time. Try observing this when you walk with a friend sometime.

Playing two sine waves (pure tones) with similar frequencies f_1 and f_2 results in beats. You hear the average frequency pulsating at a frequency given by the difference. You subtract the smaller frequency from the greater one to get this beat frequency.

Table D-2. Playing Two Similar Pure Tones with Frequencies f_1 and f_2 .

Frequency of Tone Heard	Average	$\frac{1}{2}(f_1 + f_2)$
Beat Frequency	Difference	$f_2 = f_1 \qquad \text{where} \ \ f_2 \geq f_1$

Let's do an example. Let one frequency be 440 Hz (f_1) and the other be 444 Hz (f_2). You hear the average. That would be $\frac{1}{2}$ (f_1 + f_2) = $\frac{1}{2}$ (440 + 444) = $\frac{1}{2}$ (884) = 442 Hz. This 442-Hz tone pulsates at a beat frequency of $f_2 - f_1 = 444 - 440 = 4$ Hz, i.e., 4 pulsations per second.

Musicians can use beats in tuning instruments. They know they are close when they hear their instrument "beating" with a reference tone. In fact, you don't even need talent to hear beats. Tuning without some reference, using a sense of *perfect pitch* is rare. Very few musicians

have so called perfect pitch, a gift where they can call out the name for any single note they hear and know if its pitch is off a little. On the other hand, matching two tones using beats requires one to adjust the instrument until the beats stop! When the beat frequency decreases, you are getting closer. For example, a beat frequency of 1 Hz (one beat per second) means you are piano however verv close. The is sufficiently complex that it takes a skilled piano tuner to tune all the strings properly. We will see why in a later chapter.

Basic Speaker Design

We started this chapter by looking at applications of the law of reflection. Then, the last phenomenon we investigated dealt interference. Speaker with desian incorporates the principles of reflection and interference. Diffraction is also relevant. The baffle we saw in the previous chapter is there to prevent waves from diffracting around to the other side where the waves destructively. interfere can Fig. D-9 illustrates how reflection plays a role in speaker design. The speaker is enclosed in a box so that the rear waves can reflect off the back wall. The reflection adds energy to the vibrating membrane.

Fig. D-9. Simple Speaker Design.

Air-Suspension Speaker



Speaker with Baffle. Half the Waves are Wasted.

Speaker with Enclosure to Reflect Rear Waves.

If a port or duct is added (see Fig. D-10) the mass of air in the enclosure begins to undergo vibrations as a whole, in addition to supporting the sound waves. This is an example of resonance. The mass of air in a large cavity can swish around. It does so at a low frequency since large air masses are actually displaced. This type of system is called a *Helmholtz resonator*. An empty gallon jug of apple cider is another example of a Helmholtz resonator. See Fig. D-11. Blow across the top to hear the low resonance frequency - a nice bass tone.

In the speakers of Fig. D-10, internal reflections (reflex) prevent half the waves from being lost. The other effect is the swishing of the air. Since the resonance frequency for the swishing air is low, you enhanced bass when get speaker frequencies are near resonance. In summary, the cavity reflex enhances the bass.

Fig. D-10. Bass-Reflex Speakers.



You might think the covering in front of a port is another speaker. It isn't.

Check out the following Helmholtz resonators: one from the late 1800s based on the original 1850 design and a modern one.

Fig. D-11. Helmholtz Resonator



Courtesy acultivatednest.com

--- End of Chapter D --