PHYSICS
DEMONSTRATIONS
IN
SOUND & WAVES

PART III

Demonstration No. 1

Standing Sound Waves: Resonating Air Column with Cork Dust

Length: 4:35 minutes / Location: 00:45 - 5:20 minutes

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discuss displacement nodes/antinodes first

Objective:
To build a physical model of a standing sound wave in an air column. By observing the motion of cork dust in an air column supporting a standing sound wave, evidence will be gathered concerning the motion of air molecules and the nature of the wave.

Using the Demonstration:
A standing sound wave pattern can be made visible in a couple of different ways. In this demonstration, it is dust which is used as an indicator to show the behavior of a standing sound wave in an air column. The dust responds to, and is pushed by, the displacement of the air molecules; thus making visible the displacement nodes and antinodes. In Demonstration No. 2, it is the gas itself which is used as an indicator and it therefore responds to the pressure nodes and antinodes.

In order to observe standing sound waves, a long glass tube which is 81 centimeters in length is used to contain a column of air. A speaker, driven by a variable frequency generator, supplies sound waves at one end of the tube; the other end is closed off. Longitudinal waves traveling within the air column are reflected at the closed ends. Interference between the waves traveling in opposite directions gives rise to standing sound waves. In order to get a visual picture of the standing wave pattern, fine cork dust is sprinkled inside the tube and evenly spread along its full length.

When sound of an arbitrary frequency is introduced into the tube, the cork dust remains largely undisturbed. However, when a frequency is found at which the air column is in resonance, the amplitude of the standing wave becomes large enough to cause the cork dust to be stirred up within the tube. The motion of the dust particles gives a good indication of the motion of the air itself, allowing one to visualize the standing sound wave within the tube.

When the resonant sound wave is first introduced into the air column, the cork dust is observed to be swept away from some regions, and to accumulate in well defined piles in other regions. One of the dust piles is seen to form at the closed end of the tube. Just as the fixed ends of a vibrating string are nodal points, we know that this has to be an area of zero air displacement due to the fact that the closed end prevents the neighboring air molecules from vibrating back and forth. Thus, areas were the cork dust collects must be displacement nodes, and it is here were the air is at rest. It follows that areas were the cork dust is swept away are displacement antinodes, and the air is vibrating with maximum displacement in these regions. It should be noted that the speaker end of the tube acts as a closed end, as dust collects at this nodal point.

Upon examining one of the areas where the cork dust accumulates, it is seen that the dust particles are pushed up from both sides to form a central ridge. The central ridge marks the exact position of the nodal point where the air displacement is zero. The air displacement starts to increase as one moves in either direction away from the central ridge.

These observations are used to construct a model of a standing sound wave. An animation of the air column depicts air vibrating with maximum displacement at the antinodes with less and less vibrational motion taking place as the nodes are approached. Its important to recognize that the air molecules are always vibrating in opposite directions on either side of a displacement node. As a result, the air molecules experience the greatest amount of compression and expansion at the displacement node, with no compression or expansion occurring at the displacement antinode. In other words, the pressure variation is greatest at points where the air molecules are at rest. Although it may seem somewhat contradictory to some students, the displacement node is in fact the location of a pressure antinode and vice versa.

In addition to revealing characteristics of the standing wave, the cork dust clearly displays the wavelength of the sound. With the distance from node to node equaling a half-wavelength, the four evenly spaced piles of dust which are observed indicate that 1.5 wavelengths are present within the tube. Measuring the length of the tube to be 81 centimeters, the wavelength of sound is found to be 54 centimeters at this particular frequency of 640 Hz. If the frequency is increased to where the next resonance is found, five evenly spaced piles of cork dust are formed. Here, the wavelength has become shorter as 2.0 wavelengths are present within the tube.

Teaching Notes:

- In order for students to better understand standing sound waves, the teacher may wish to refer to *Demonstrations in Sound & Waves: Part I - Longitudinal Standing Waves: Stroboscopic Analysis of Standing Wave Behavior.*
- When discussing nodes and antinodes for a standing sound wave, it is important to distinguish between displacement nodes/antinodes and pressure nodes/antinodes.
- With each vibrational cycle of the standing wave, the dust is continually being pushed into an area where the air displacement is less and less. As a result, a given dust particle is never fully pushed back to its previous position, but always makes progress toward the displacement node.
- The sine wave diagrams which are commonly used in texts to illustrate standing sound waves in an air column represent the displacement amplitude of the standing wave. The pressure amplitude will be 90 degrees out of phase (shifted one-quarter wavelength) with the displacement amplitude.

Demonstration No. 2

Standing Sound Waves: Resonance with Illuminating Gas in a Flame Tube

Length: 4:43 minutes / Location: 5:35 - 10:18 minutes

Objective:
To examine the pressure characteristics of a longitudinal standing wave in a gas column. Using a series of flames acting as pressure gauges along the gas column, pressure nodes and antinodes are observed at various resonant frequencies.

Using the Demonstration:
The previous demonstration utilized particles in a resonance tube to indicate the displacement of the air medium. By utilizing a series of flames on a resonance tube, this demonstration presents the other major attribute of a standing sound wave--pressure. The pressure characteristics of a standing longitudinal wave are made visible in dramatic fashion by using a piece of apparatus known as a flame tube, or Ruben's tube.

The flame tube consists of a 1.0 meter metal tube which is closed at one end, with the other end tightly covered with a flexible rubber membrane capable of vibrating. A speaker connected to an audio oscillator of variable frequency is used to set up vibrations in the flexible membrane. Flammable gas (LP) is fed in at low pressure, and as it fills the tube, passes out through regularly spaced small holes along the top. With no sound being generated by the speaker, igniting the gas produces a long line of flames which are of uniform height.

When the speaker is driven at a very low non-resonant frequency, the inaudible sound waves travel through the gas in the tube. The flames act as individual pressure gauges, responding to the pressure of the gas in the tube. The fluctuating height of the flames shows that the sound waves are in fact composed of pressure variations in the gas. With the speaker turned off, the flames burn with a medium height, indicating the normal pressure of the gas. When the speaker is turned on, the flame height alters above and below this position, giving evidence that the pressure within the sound wave is varying above and below the normal pressure.

As the frequency is increased, the pressure variations occur more rapidly until we see only the maximum flame height position which corresponds to the maximum pressure; the minimum flame height and minimum pressure still present, but no longer discernable. When the speaker is driven at a resonant frequency, a standing wave is formed within the gas column. The standing wave causes the series of flames to take on a smoothly flowing wave-like pattern. At points along the column where the flames are of maximum height, a pressure antinode exists, and the pressure varies between its maximum and minimum values. At points where the flames are of minimum height, a pressure node exists. At these points the pressure does not vary at all, but remains constant at the normal pressure of the gas in the tube. Just as with a standing wave on a vibrating string, the pressure nodes and antinodes remain stationary along the gas column; with the distance between adjacent antinodes (or nodes) equaling a half-wavelength. Its interesting to note that at the ends of the tube, pressure antinodes exist (displacement nodes). Although the closed ends of the tube prevent the neighboring gas molecules from being displaced, the pressure variation, above and below the average, is maximum at the end points. If the sound intensity is varied from zero, to a level which is very loud, the pressure nodes remain at their constant value; whereas the pressure antinodes change amplitude directly with the sound intensity.

By initially driving the speaker at a low frequency and slowly increasing it, one finds the various resonant modes of vibration for the gas column. The first resonant mode which can be produced is found to consist of a standing wave with pressure antinodes at each end and a pressure node at the center. At this first resonance, a half-wavelength perfectly fits the length of the gas column. By increasing the frequency, we pass from the first resonance to the second. The second resonant mode is made up of three pressure antinodes and two nodes. One full wavelength perfectly fits the length of the gas column. At a particular higher frequency, a third standing wave pattern is produced. This pattern continues, and due to the boundary conditions imposed by the closed ends, a half-wavelength is added with each higher resonance.

Teaching Notes:

- This demonstration can be used at a more fundamental level to simply give a strong visual of the wavelength of sound, and the frequency vs. wavelength relationship.

- It is very important to establish the fact that the maximum flame heights are in fact showing a maximum variation in pressure and not just a constant maximum pressure. The operation of the flame tube with a low frequency wave clearly shows that the flames are varying in height. At higher frequencies the variation in height is not perceivable, and the varying pressure (at all positions except pressure nodes) is seen as a constant flame whose height is proportional to the amplitude of the pressure variation.

- It is possible to operate the flame tube with maximum flame heights at either the pressure nodes or the pressure antinodes; as this is determined by the size of the sound pressure amplitude relative to the gas pressure. By either changing the gas pressure within the tube or the amplitude of the sound, the location of maximum flame height can be shifted from pressure node to pressure antinode. When the gas pressure within the tube is at a high level, the pressure nodes give a tall yellow flame; the pressure antinodes produce a short blue flame. However, when the gas pressure within the tube is at a reduced level, the tallest flames occur at the pressure antinodes.

- Musical instruments such as woodwinds, brass instruments, and the pipe organ, all produce sound from the vibrations of standing waves in a column of air.

Demonstration No. 3
Standing Sound Waves in Two-Dimensions: Illuminating Gas in a Resonating Cavity
Length: 3:00 minutes / Location: 10:35 - 13:35 minutes

Objective:
To observe the elaborate two-dimensional standing wave patterns formed by sound waves in a cylindrical cavity.

Using the Demonstration:
Standing sound waves can occur within the air of any cavity. When the cavity is something other than a long narrow tube, the standing waves take on fascinating patterns of surprising symmetry. In this demonstration, a hollow cylindrical container enclosing a volume of gas is used to extend the study of standing sound waves to two-dimensions.

Sound waves are introduced into the cavity by using a speaker mounted on the side of the enclosure. Driving the speaker with a variable frequency generator allows sound of various wavelengths to be used. Flammable gas (LP) which is fed into the container becomes the medium for sound waves to travel on within the cavity. As the gas fills the cavity, it escapes through an array of small holes in the upper surface. With no sound being generated by the speaker, the gas is ignited. A grid of small flames is formed, and apart from the convection currents which are produced, all flames are of uniform size.

When sound waves of proper frequency are introduced into the cavity, the flames take on an interesting pattern. The flame pattern which is seen is not related to vibrations on the metal surface, but instead, shows exactly how the gas inside the cavity is vibrating. With the sound waves experiencing multiple reflections inside the cavity, the reflected waves undergo an elaborate pattern of constructive and destructive interference. At resonant frequencies, the interference which takes place causes a standing wave pattern to be formed.

It is important to recognize that the flames are in fact "painting a picture" of the standing wave pattern which is present within the cavity. The flames, acting as pressure indicators, show where pressure nodes and pressure antinodes are present. In this case, the incoming gas flow is adjusted such that the tallest flames indicate locations of pressure nodes.

The dimensions of the cavity set restrictions, or boundary conditions, allowing only particular wavelengths to create a resonance condition. Unlike a long narrow gas column, higher resonant modes are not found at whole number multiples of the lowest resonant frequency, as the cavity does not produce a series of standing waves which are related in a simple way to the fundamental.

By continuing to increase the frequency, a wide variety of elaborate standing wave patterns are produced. The intricate pattern of nodes and antinodes shows the remarkable symmetry with which the gas vibrates in the cavity.

Teaching Notes:
- Simply by looking at the diverse collection of standing waves which are formed in the cavity, it is apparent that the resonant modes do not form a harmonic series as the standing waves are not related in a simple way to the fundamental. In an air column, a harmonic series is formed due to the fact that the standing waves are restricted to build in a simple way on the fundamental.

- The flame cavity gives a two-dimensional display of a three-dimensional standing wave. The flames show the standing wave pattern along the length and width dimension, but do not show the standing wave along the height dimension of the cavity.

Demonstration No. 4
Vibrations in a Two-Dimensional Surface: Chladni Plate
Length: 3:22 minutes / Location: 13:50 - 17:12 minutes

Objective:
Using fine sand to make nodal lines visible, standing waves are observed on circular and square metal plates which are set into vibration using a violin bow.

Using the Demonstration:
In the early nineteenth century, the German physicist Ernst Chladni performed interesting wave experiments by sprinkling sand on a thin plate and using a violin bow to induce vibrations. In this demonstration, two-dimensional vibrational patterns are observed for a solid plate using Chladni's technique.

Using a circular metal plate which is mounted at its center, a violin bow drawn across the plate's edge sets it in vibration and sound is heard. The bowing action creates a two-dimensional wave in the plate, which travels outward from the bowed point and is reflected again and again at the edges of the plate.

By sprinkling fine sand onto the surface, features of the vibrating plate are revealed. The sand collects along the nodal lines, regions where no vibration is taking place; and is thrown away from the antinodes, the points or lines of maximum vibration. The sand makes visible the two-dimensional standing wave pattern which is formed by interference between the reflected waves.

If the bow is drawn such that a greater amount of pressure is applied to the plate, a higher frequency is heard, and the sand reveals a different resonant mode which has been excited. Various resonant modes are produced within the plate by damping. If while the plate is being bowed, it is touched lightly at some point, all modes of vibration are damped out except those having nodal lines passing through the point which is touched. By using this method, numerous modes of vibration are excited within the plate, with a new and different standing wave pattern produced with each mode.

A square plate is used to produce a set of resonant modes which are quite different from those of the circular plate. Because waves can reflect off the four edges of the plate in many different ways and with multiple reflections, numerous standing wave patterns are possible. The standing wave patterns are all very different from one another in appearance, and occur at frequencies which are not simply whole number multiples of the lowest resonant mode. The way in which the plate vibrates, and the elegant patterns produced, are governed by many things: the nature of the material, the thickness and shape of the plate, how it is supported, how it is driven, and how it is damped.

Teaching Notes:
- An important question which should be raised for discussion is: what conditions have to be met in order for a standing wave to be formed on such a two-dimensional surface?
- In the demonstration, the plates are center clamped resulting in a node always being produced at that point. Off center clamping will produce a whole different set of standing wave patterns.
- Many of the higher frequency resonant modes are produced by using damping, and forcing a node immediately next to the spot where the plate is bowed.

Demonstration No. 5
Resonance/Real-Time Strobe Holography: Resonant Modes of a Vibrating Bell
Length: 3:32 minutes / Location: 17:28 - 21:00 minutes

Interesting, but needs an intro.

Objective:
To observe the various modes/standing wave patterns of a resonating handbell. The modes are visualized through a technique in which light from the vibrating bell interferes with light from its holographic image.

Using the Demonstration:
The modes of vibration for any object always consist of standing waves. For many sound sources, observing standing wave patterns can require elaborate methods. In previous demonstrations, standing wave patterns were made visible using cork dust, flames, and fine sand. In this demonstration, resonant modes of a vibrating bell are visualized using the technique of real-time interferometric holography and a strobed laser.

This method involves first making a transmission hologram of the bell when it is not vibrating. After being developed, the hologram is repositioned in its exact original position on the optics table. The set-up is then viewed such that one sees the actual bell positioned directly behind the developed hologram.

With both the bell and hologram illuminated with laser light, light which is reflected from the bell interferes with light from the holographic image. The interference pattern, made up of bright and dark fringes, is extremely sensitive to small displacements on the bell's surface. By simply lightly touching the bell, the surface is deformed enough to cause dramatic changes in the interference pattern. Indeed, the interference pattern is sensitive to displacements on the bell's surface which are on the order of the wavelength of light. (In this case, red light emitted by a helium-neon laser.)

By using a directional speaker to drive the bell, one can observe how it behaves when driven at resonant frequencies. Vibrations of extremely small amplitude become visible when light from the vibrating bell interferes with the stationary holographic image. Because the bell vibrates very rapidly, seeing the vibrational pattern requires the laser light to be strobed on and off, creating a slow motion effect.

At various resonant frequencies, different vibrational modes become visible. The pattern which is seen is in fact that of a standing wave, formed by waves traveling in opposite directions on the bell's surface and undergoing interference. The dark and bright fringes create a contour map of the bell's surface, revealing the exact way in which it vibrates. At the center of concentric fringes, the surface vibrates with maximum displacement and an antinode exists at this point. Moving outward from the antinode, each successive ring (fringe) marks a region of smaller and smaller displacement. Stationary nodal lines are observed to run both vertically and horizontally between antinodes.

Generally, with each higher resonance, the number of antinodes increase and the surface vibrates in sections which become smaller and smaller. By vibrating in smaller sections, the metal surface can vibrate at a greater rate and higher frequencies can be attained.

Teaching Notes:

- It should be emphasized that the dark and bright fringes are not themselves nodes and antinodes, but rather, the fringes create contour lines of the bell's vibrating surface and can be interpreted much like a geographical map showing surface elevation. Antinodes are those areas which are seen to experience the greatest amount of change in surface elevation, whereas nodal lines show no change in elevation at all.

- The amplitudes of the observed oscillations are extremely small as the displacement between adjacent dark and light fringes is a mere half-wavelength of red light!

- The resonant frequencies of the bell range from 527 Hz to 7776 Hz.

Demonstration No. 6
Quality of Sound/Harmonics: String Vibrations on a Guitar
Length: 4:06 minutes / Location: 21:15 - 25:21 minutes

Good - Perhaps have students give a demon.

Objective:
To examine the harmonic composition (collection of standing waves) of a vibrating guitar string. In addition, the influence which harmonics have on sound quality is heard as a guitar string is sounded with all upper harmonics removed.

Using the Demonstration:
Standing waves of different frequencies can exist in the same medium simultaneously. This is a fortunate thing for those of us who enjoy music, as it adds richness to various sounds and prevents all musical instruments from sounding exactly alike. Every musical instrument has a characteristic sound with a unique tone quality. The quality, or timbre, of the sound is related to the unique collection of standing waves (harmonics) which an instrument produces. In this demonstration, the sound produced by a guitar string is examined in terms of its harmonic composition.

When the low E string on a guitar is plucked, it is heard to have a characteristic sound. An oscilloscope is used to show the complex waveform of the sound, which changes over the time the note is sustained. When the low E string is plucked and lightly touched at its mid-point, the frequency is heard to change by a factor of two, or one octave. By touching the string at its mid-point, the fundamental standing wave which has an antinode at this point is damped out. However, a standing wave with a node at the center of the string is not affected, and can continue to vibrate. This second standing wave is called the 2nd harmonic, and exists simultaneously on the string along with the fundamental. On the oscilloscope, the waveform of the 2nd harmonic is seen to be that of a pure sine wave.

If the string is plucked and lightly damped at a point which is one-third its length, the frequency of the sound changes to three times that of the fundamental. By touching the string at this point, all standing waves are damped out except for the standing wave which has a node at one-third the string's length. This 3rd standing wave is called the 3rd harmonic, and is set into vibration simultaneously along with the other standing waves when the string is plucked. The oscilloscope shows the waveform of the 3rd harmonic to also be that of a pure sine wave. It can be noted that its amplitude is somewhat less than that of the previous harmonic.

By continuing on and damping the string at one-fourth and one-fifth its length, higher harmonics are heard as these particular standing waves are isolated. The intensity of the sound is heard to become less and less as higher harmonics are picked out.

It becomes apparent that the sound produced by plucking the guitar string is composed of many different harmonics, all present at one time. It is the lowest frequency, or fundamental frequency, which determines the pitch of the note. Although the higher harmonics are all present when the string is plucked, the ear does not perceive them individually. The harmonics are responsible for giving the guitar its characteristic tone quality. These simple sinusoidal vibrations superimpose upon one another to form a complex wave which we recognize as the sound of a guitar.

Using an electromagnetic driver to induce vibrations in the guitar string, the fundamental frequency is singled out with no other harmonics present. The viewer hears what a note on a guitar sounds like when all upper harmonics are removed. Although it has the same pitch as when the string is plucked, its waveform is simply that of a sine wave, and one can no longer recognize the sound as being that of a guitar. The tonal quality lacks richness as the note is quite dull and mechanical sounding.

By using a different arrangement to drive one of the guitar strings, numerous upper harmonics are heard.

With the sound produced being up in the range of the 40th and 50th harmonics, one can get a feel of just how many harmonics the guitar string produces in order to create its familiar sound.

Teaching Notes:

- For the plucked guitar string, the waveform seen on the oscilloscope at the start of the note is observed to be very different from that later on. The reason for this is that the relative amplitude of the harmonics change over the time which the note is sustained.
- Those who play guitar know that the 12th fret marks the position at which the string should be damped to produce a strong, bell like, harmonic. The reason for this is that the 12th fret marks the centerpoint of the string, and when damped at this point, the 2nd harmonic is isolated. The 7th and 5th frets are also known to be positions at which the string should be damped to produce nice sounding harmonics, as they mark points which are 1/3 and 1/4 the length of the string.
- The manner in which an instrument is played strongly influences the sound quality. Plucking a string with a pick produces a very different sound than plucking it with one's fingers, due to differences in the relative amplitude of the harmonics.
- It is a rare occurrence for an object to vibrate with only one frequency. An ordinary sound, like that made by striking two wooden boards together, is a mixture of many frequencies which bear no real relationship to one another. There are no discrete harmonics, instead, the sound is made up of a continuous spectrum of frequencies. This kind of sound is referred to as "noise" in comparison with the more musical sounds which contain frequencies that are integer multiples of the fundamental.

Demonstration No. 7
Superposition Principle: Fourier Analysis & Synthesis of Complex Musical Tone
Length: 4:14 minutes / Location: 25:37 - 29:51 minutes

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excellent demo.

Objective:
To demonstrate that a complex wave can be broken down into a series of simple sine waves. The complex sound produced by a trombone is first analyzed into its harmonic components; having done this, the trombone sound is reconstructed using these same sine waves.

Using the Demonstration:
The superposition principle, together with Fourier's Theorem, shows that any complex wave can be synthesized by combining simple sine waves which are of the proper frequency, amplitude, and relative phase. The reverse process (analysis) is also found to be true, where even the most complex periodic waves can be broken down into a combination of simple sine waves.

In order to demonstrate this, the complex sound produced by a trombone is first analyzed, and then later synthesized. By recording a single note played by a trombone on a continuous loop audio cassette, a consistent and non-varying sound can be worked with. Seen on an oscilloscope, the waveform produced by the trombone is of a complex shape which is characteristic of its sound.

In order to perform an analysis of the complex sound, the note played by the trombone is fed into a waveform analyzer. The waveform analyzer breaks down the sound by using a series of electronic filters which pass only the specific frequency to which they are tuned. By sweeping the analyzer through a range of frequencies, one can find the basic components of the sound. The first and lowest component which passes through the filter is that of the trombone's fundamental frequency, or first harmonic. The oscilloscope shows that the harmonic is simply a pure sine wave. It should be noted that although the first harmonic is of the same frequency as the note played by the trombone, it does not in any way embody the full trombone sound.

If we slowly continue the sweep of the analyzer, we come across the second harmonic which also happens to be a pure sine wave. The oscilloscope shows the frequency, amplitude, and relative phase of this component of the trombone's sound. By continuing this process, a large number of harmonics are found hidden in the single note of the trombone. If we take note of the specific frequencies at which the harmonics occur, it quickly becomes apparent that they are all whole number multiples of the fundamental frequency. Thus, the trombone's complex waveform is no more than a harmonic series of simple sine waves.

The process is next reversed by using an electronic synthesizer to reproduce the sound of the trombone. The synthesizer produces a series of pure sine waves whose frequencies are whole number multiples of the lowest frequency. By setting the individual harmonics to the same amplitude and phase values which were found with the analyzer, the trombone sound can be reconstructed from the ground up. Starting with the lowest frequency sine wave, the fundamental, the pitch is established. As harmonics are added one by one, the sound and waveform come closer to resembling that of the actual trombone. The limits of the synthesizer prevent us from going higher than the 9th harmonic. In theory and practice, the greater the number of harmonics, the closer one comes to replicating the sound and waveform.

By playing the single note of the trombone into a spectrum analyzer, a histogram is charted which displays relative amplitude of individual harmonics versus frequency. As the analyzer sweeps through the range of frequencies, it is able to pick out the harmonic components of the instrument. Such a chart is called a "sound spectrum" and summarizes information which could be thought of as the instrument's "fingerprint". By running a sound spectrum on other musical instruments, one can see that the relative amplitudes of the various harmonics are quite different from one instrument to the next. Indeed, this is what gives each instrument its characteristic sound quality or timbre.

Teaching Notes:

- In synthesizing complex waves, Fourier's Theorem shows that we only need to use frequencies which are integer multiples of the fundamental frequency. These frequencies are called harmonics of the fundamental frequency; the second harmonic referring to a wave whose frequency is twice that of the fundamental, the third harmonic referring to a frequency which is three times greater than the fundamental, and so on.

- Although the fundamental frequency is usually the strongest of the harmonic series, this is not always the case. For the trombone, the amplitude of the 2nd harmonic is significantly greater than that of the fundamental. With the oboe, the fundamental frequency is the weakest of the first 10 harmonics! Nevertheless, the perceived pitch is that of the fundamental!

- We perceive the trombone sound to be one large net effect, and it is difficult, if not nearly impossible, to pick out the sound of individual harmonics making up the series. However, when individual harmonics are added in one at a time (as during the synthesis segment of the demonstration), the ear is sensitive to the change and picks out the sound of the individual harmonic.

Demonstration No. 8
Frequency Spectrum of Sound: Audible and Ultrasonic Sound Waves
Length: 2:51 minutes / Location: 30:04 - 32:55 minutes

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less relevant

Objective:
To gain an understanding of the wide frequency spectrum of longitudinal waves. Using 1) a high frequency speaker, and 2) a piezoelectric crystal, a wide range of audible and ultrasonic sound waves are produced.

Using the Demonstration:
The vibrational frequency spectrum for longitudinal waves is divided into three general regions: infrasonic, audible, and ultrasonic. Using a speaker capable of high frequency vibrations, both audible and ultrasonic waves are produced. Starting at a frequency of 10,000 hertz, the high pitched sound is clearly perceived by the ear. As the frequency is increased, the sound seems to become noticeably fainter. Although the oscilloscope shows the amplitude of the sound to be remaining fairly constant, the ear becomes less responsive in this upper range.

At frequencies just under 20,000 hertz, the upper limit of human hearing is reached and the sound seems to disappear. The oscilloscope, however, shows that sound waves are still very much present. Sound waves which have a frequency above the audible range are called ultrasonic. Using the speaker and frequency generator, ultrasonic waves having a frequency of 50,000 hertz are detected as they propagate through the air and reach the receiving microphone.

In order to produce ultrasonic waves of extremely high frequency, a special transmitter is used. Inside the transmitter, electrical contacts are made to opposite faces of a quartz crystal. If an alternating voltage of very high frequency is applied to these contacts, the crystal vibrates at the same frequency as the applied voltage. As the crystal rapidly vibrates, it emits ultrasonic waves. In the demonstration, the alternating voltage source is provided by a commercial depth finder, producing ultrasonic waves of frequency 200,000 Hz.

With the ultrasonic transmitter turned on, the detector shows no sign on the oscilloscope of having received the waves. This is due to the fact that ultrasonic waves of very high frequency do not propagate well through air, as they are rapidly absorbed and dissipated by air molecules. However, if the transmitter and detector are immersed in water, the waves are able to reach the detector as indicated by the oscilloscope. A piece of wood is observed to be able to block the ultrasonic waves due to its porous composition. When a glass plate is positioned between the transmitter and detector, some of the waves are reflected, but many waves manage to pass through the plate and reach the detector. Clearly, ultrasonic waves of very high frequency propagate readily through liquids and certain solids.

Teaching Notes:

- The frequency spectrum of sound does not continue indefinitely. There is an upper limit of approximately 1 x 10^9 Hz, which is the upper limit set by material elasticity.
- By applying an alternating voltage to a crystal such as quartz (piezoelectric effect), it is possible to produce ultrasonic frequencies as high as 6 x 10^8 Hz. The corresponding wavelength in air is about 6 x 10^{-7} meters; a wavelength which is of the same order as visible light.
- Intense ultrasound of frequency 10 MHz is used to modify or destroy tumors in soft tissue. Ultrasonic waves are also used to reveal internal structures of the body.
- Many animals can hear ultrasonic frequencies. Dogs, for example, can hear sounds as high as 50,000 Hz and bats can detect frequencies as high as 100,000 Hz.