Harmonics in an Aluminum Rod

"A Golden Oldie"

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Surely I'm not the first physics teacher to have difficulty in getting students to "see" standing waves in closed tubes. Almost certainly many teachers use variations of the suggestion given here, but this little demo has simplified my teaching life and others might like to try it. When we're discussing the physics of musical sound, it's easy to show the standing waves present on stringed instruments with a wave driver and a flexible cord. But visualizing the nodes and antinodes present in a closed tube is another story. Then I learned that a standard aluminum rod (diameter 3/4 in, length 120 cm) typically used as a support bar on a lab table would produce tones if stroked in a certain way.

When I grasped the aluminum rod at its center with thumb and forefinger of one hand, added a bit of rosin, and stroked the rod with the thumb and forefinger of my other hand, I could generate a (quite loud) shrill tone. What delighted me still more was that I could produce even higher harmonics by holding the rod at one of the higher harmonic nodes. And then I found an easier way to excite the compressional standing waves—just strike the rod on its end with a hammer.

The first instructional problem is to get students comfortable with the idea of using transverse wave sketches to represent displacement compressional waves. Once they accept that transverse nodes and antinodes are easier to draw and no accuracy is sacrificed, they can begin to predict the positions for the nodes for various harmonics.

I start by comparing the rod to a tube open at both ends. When a standing wave occurs in the rod, the ends have maximum amplitude, just like the air in a tube open at both ends. It's easy for students to then predict that the node for the first harmonic, and the place to hold the rod, is at its center. This meets the constraint that the first harmonic be the simplest standing wave configuration with antinodes at both ends (Fig. 1). I hold the rod directly in the center (60 cm from the end) and give it a sharp tap on the end. Students are amazed at the sound produced. I ask them where I should hold the rod to produce the second harmonic and their immediate, but inaccurate, response is at 40 cm (one-third the length of the rod). I put my fingers there and bang the end, but there is no ringing tone. The problem, of course, is that they have simplistically assumed that if the first harmonic occurs where the rod is evenly divided into two parts about the one node, the second harmonic will occur for a configuration of two nodes separated from the ends and themselves by a third of the rod. After a little coaxing to make the decision on the basis of the standing wave constraints for a rod, they make a drawing and do calculations, this time predicting correctly that the node will be at 30 cm (Fig. 2). Sure enough, when I hold the rod at that spot and bang the end, a continuous higher tone sounds (though the volume is less than the first harmonic). Students with good musical ears verify that the tone is one octave above the fundamental.

Now I put small pieces of fluorescent tape on the rod at 30, 60, and 90 cm. After holding the rod at the 30-cm mark and striking it once again, students are pleased to see that I can hold the 90-cm mark either alternately or at the same time, with no change in the tone coming from the rod. However, if I hold the rod at the spot used for the first harmonic, it becomes silent. At this point, students really begin to get the idea and they eagerly predict positions for nodes of the third harmonic: 20, 60, and 100 cm (Fig. 3). I place two more pieces of tape at the new positions and bang the rod once again while holding the 20-cm mark. A clear and still higher pitched tone is produced. The volume of sound is considerably less, but still audible to everyone in class, and I can hold the 60- or 100-cm mark with no change in the tone.

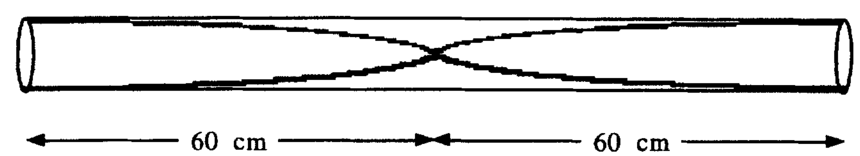

Fig. 1. Rod vibrating in first harmonic.

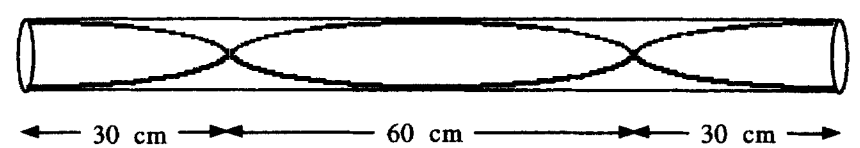

Fig. 2. Rod vibrating in second harmonic.

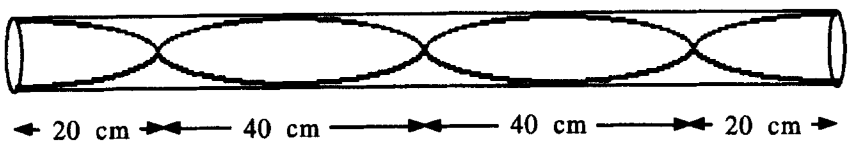

Fig. 3. Rod vibrating in third harmonic.

At this point a student will typically remark that one of the nodes for the third harmonic (the center one) is the same as the node for the first harmonic, and the question comes up about why the third harmonic wasn't produced the first time I held the rod by the center. I explain that it was, but that third-harmonic amplitude was so much less than the first that the first harmonic was overpowering. I then hold the rod as I did when I was producing the first harmonic and bang the rod one last time. Then, while the rod is ringing in the first harmonic, I pinch it at one of the other third-harmonic nodes; the sound of the first harmonic disappears, but careful listening verifies that the third harmonic is indeed ringing. I point out that in each demonstration of harmonics of the rod, not only is the desired harmonic present, but also *all* the higher-order even or odd harmonics are present (depending on whether the desired harmonic was even or odd). The portion of total sound coming from each of the higher-order harmonics of course gives the resonating medium its distinctive sound quality, making it easy to distinguish a guitar from a harp.

Editor's note: Students can do a quantitative check of the tone that is produced. The wavelength of the fundamental is twice the length of the rod. The (longitudinal) speed of sound in aluminum is about 5000 m/s. Therefore

$$5000 \text{ m/s} = (2.4 \text{ m}) f$$

$$f \approx 2000 \text{ Hz}$$

Musicians in your class can compare this with notes from a piano or a signal generator.

Vibrations in the rod can also be excited by holding it vertically and tapping the lower end on the floor. When striking the rod, you will usually excite a transverse vibration as well as the longitudinal. The speed of such a disturbance is about half that of the compressional wave. The tone, about an octave lower than the singing note, rapidly dies out.

Trick of the Trade

Carbon Electrodes Improvised

One of the more successful "inventions" I devised during my thirteen years of teaching physics and chemistry came about the day I needed carbon electrodes for an electrolysis experiment, but none were available in the school. With necessity at my heels, I took two pencils, cut off the erasers, and sharpened both ends. I twisted one pencil into one end of a piece (about 25 cm) of clear plastic tubing. Then I filled the tube to the brim with copper chloride (you could use silver nitrate or water) and squeezed out the bubbles (over the sink) using a flip-top squeeze bottle. Next I inserted the second pencil into the open end of the tubing, twisting as I inserted. (It's easier to remove the pencils if you twist rather than jam them in.) Next I attached two wires with alligator clips on the lead (graphite) of the exposed ends of the pencils (see sketch). The other end of the alligator clips went to a 6-V battery pack. I shaped the tubing into a "U" and rested it in a large beaker.

With your students, wait five, ten, twenty minutes. You will see the metal (copper or silver) plate out (or hydrogen bubbling) on the tip of one pencil (cathode) and bubbles forming at the anode. If you use copper chloride solution, you can smell the chlorine gas when you remove the pencil. Pencils can be sharpened and used over again. Tubing should be rinsed out with water.

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