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Vacuum cleaner isolates over 12 harmonics in the corrugated whistling tube

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Abstract

A vacuum cleaner is used to isolate over twelve harmonics in a corrugated toy whistling tube. The toy tube is first taped along a horizontal surface. Then a vacuum cleaner with a hose diameter approximately the same as that for the toy tube is turned on. As the vacuum cleaner hose approaches one end of the corrugated tube, individual higher harmonics are generated. From a sound recording, the frequencies of the harmonics can be measured with the free audio program *Audacity* and found to agree with theory to about 1%. An exciting class demonstration is included with a video accompanying this paper, Ruiz M J 2020 Video: Vacuum cleaner isolates over 12 harmonics in a corrugated whistling tube (http://mjtruiz.com/ped/hummer/).

Introduction

The singing corrugated whistling tube has been a popular physics demonstration for decades. An excellent review by Rajavel and Prasad [1] traces the historical research on corrugated pipes over generations. This comprehensive review discusses engineering papers relevant to industry such as heating ducts as well as publications on the toy whistling tube, which has had many names such as Hummer, Freeka, Whirl-a-Sound [2], Whirl-a-Tune [3], Voice of the Dragon, and

Magic Whistle [1]. When the swinging whistling tube appeared in the early 1970s, physicist Crawford [2] pointed out its usefulness for teaching harmonics. When the toy is swung, air is sucked up through the tube as air rushes by the swinging open end, similar to an updraft in a chimney as wind blows across the chimney top. As the toy is spun faster and faster, discrete resonances are excited with pitches higher and higher in frequency. One can obtain the second and higher harmonics with appropriate twirling speeds. With difficulty a student may be able to reach the seventh harmonic. The first harmonic is elusive. Crawford suggests that the very slow flow speed necessary to generate the first harmonic will not have the required turbulence [2]. However, Tonon *et al* indicate that the missing fundamental is mostly due to viscothermal losses dominating at low frequencies [4].

A little music theory [3] can assist in verifying that the fundamental (frequency $f_1 = f$) is missing. Whirling the tube first produces the second harmonic H2 ($f_2 = 2f$) and then the third H3 ($f_3 = 3f$), a frequency ratio of H3:H2 = 3:2. This ratio corresponds to a perfect musical fifth, i.e. going from H2 to H3 is the same musical interval from the first degree of the musical scale (Do) to the fifth degree (Sol). Such an interval marks the beginning of the song *Twinkle, Twinkle, Little Star*: Do, Do, Sol, Sol. The musical interval from H3 to H4 is a perfect fourth, which serves as the beginning of the *Bridal March* by Wagner, which most will recognize as 'Here Comes the Bride.' Finally, the sequence H2, H3, H4, and H5 played in succession on the hummer provides the first four notes of Stanley Kubrick's theme for his 1968 movie *2001: A Space Odyssey*, taken from the beginning of *Also sprach Zarathustra* by Richard Strauss (1896). Twirling the tube carefully will obtain the above musical intervals [3].

The vacuum cleaner demonstration

A vacuum cleaner can be used to obtain and maintain over a dozen individual harmonics in the corrugated tube. The inspiration for the use of the vacuum cleaner dates back to the 1980s when one of the authors (MJR) brought a toy tube to the home of John Stevens, Professor of Chemistry at UNC Asheville. A vacuum cleaner was heard in an adjoining room along with a shrill of pitches. Then the vacuum cleaner was abruptly turned off and about eight individual harmonics were heard descending as the vacuum cleaner motor reduced its speed to zero. The Chemistry Professor’s boys John G and Robby had placed the corrugated tube over a vacuum cleaner. See figure 1(a) for the vacuum cleaner demonstration performed in class by the authors. Ear plugs were first given to the students and worn by the instructors since the tones are loud. Then the hummer was held over a vacuum cleaner hose and the vacuum cleaner turned on producing a shrill sound. When the vacuum cleaner was turned off individual harmonics could be heard with successively lower pitches.

(a) (b)

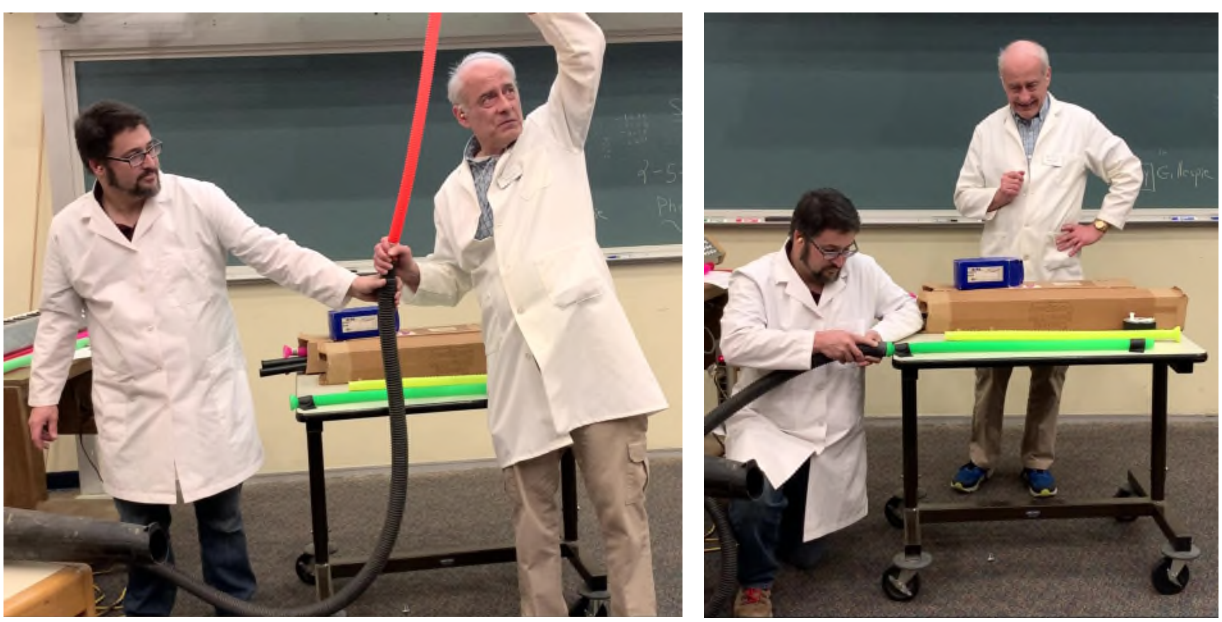

Figure 1. (a) Corrugated tube placed over vacuum cleaner hose. (b) Vacuum cleaner hose isolating higher harmonics as it is brought closer to the tube. Photos Courtesy Noah Michael

Bijesse.

In figure 1(b) the vacuum cleaner was brought closer and closer to one end of the tube isolating over 12 harmonics. As the sucking hose approached the end of the tube, higher and higher harmonics were obtained. Each harmonic is a standing longitudinal wave in an open pipe. The first three standing waves are represented in figure 2. Note that the first harmonic is not obtained with the corrugated tube in the demonstration, as explained in the introduction.

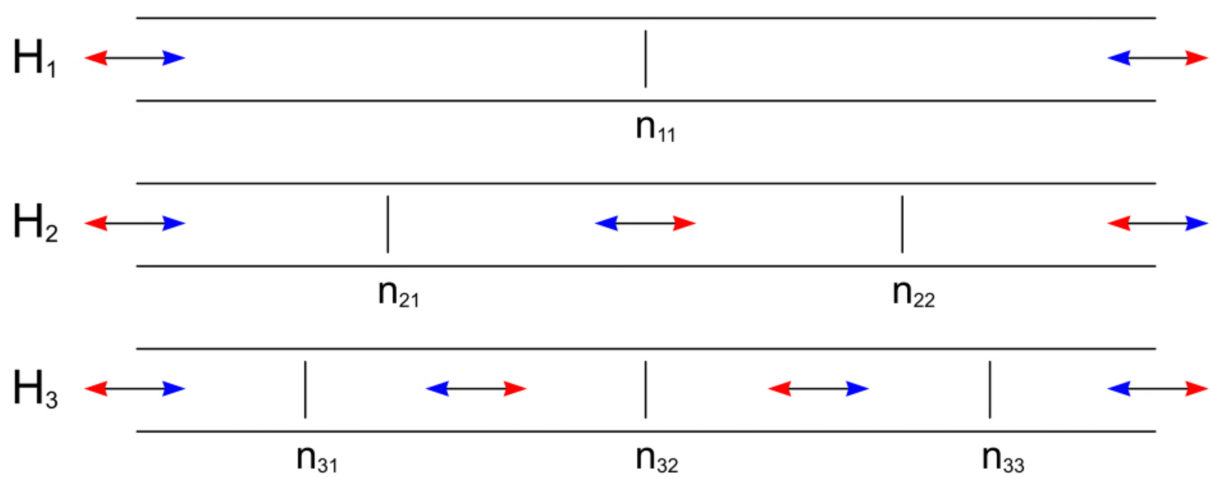

Figure 2. Representation of the first three longitudinal standing waves, harmonics H1, H2, and H3, in an open pipe. The locations labeled n are displacement nodes. The sole displacement node n_{11} for the first harmonic alternates between a compression (see blue arrows pointing inward) and a rarefaction (see red arrows stretching outward). For the second harmonic, when displacement node n_{21} is a compression, displacement node n_{22} is a rarefaction and vice versa.

The locations labeled n are displacement nodes. If one thinks of a longitudinal wave in a slinky, the slinky ringlet at a displacement node does not move. However, this ringlet undergoes compression (squeezing) and rarefaction (stretching). Therefore, these nodes are also pressure antinodes. The first harmonic, called the fundamental, has one displacement node designated by n_{11} in figure 2. This location alternates between compression (see the blue arrows pointing inward) and rarefaction (see the red arrows pointing outward). The second harmonic has two displacement nodes labeled n_{21} and n_{22}. When n_{21} undergoes compression (inward blue arrows), n_{22} undergoes rarefaction (outward blue arrows) and vice versa (red arrows). For the third harmonic, when both n_{31} and n_{33} undergo compression (blue arrows) there is a rarefaction in the middle node n_{32} (blue arrows) and vice versa (red arrows). One of the authors (MJR) has described an activity in this journal where a group of students dance the first two harmonics at the front of the class [5]. The dance demonstration is a nice complementary activity that can accompany the vacuum cleaner demonstration of this paper.

After class, the handle was cut off the tube so that the entire tube was corrugated, making the theoretical analysis easier. The experiment was ran again and recorded. The audio software *Audacity* [6] was then used to measure each harmonic. For details on using *Audacity*, see [7]. The results are plotted in figure 3. The vacuum cleaner was able to isolate 16 harmonics. The least squares fit gives a fundamental of $f_1 = 202\ \mathrm{Hz}$ with excellent correlation.

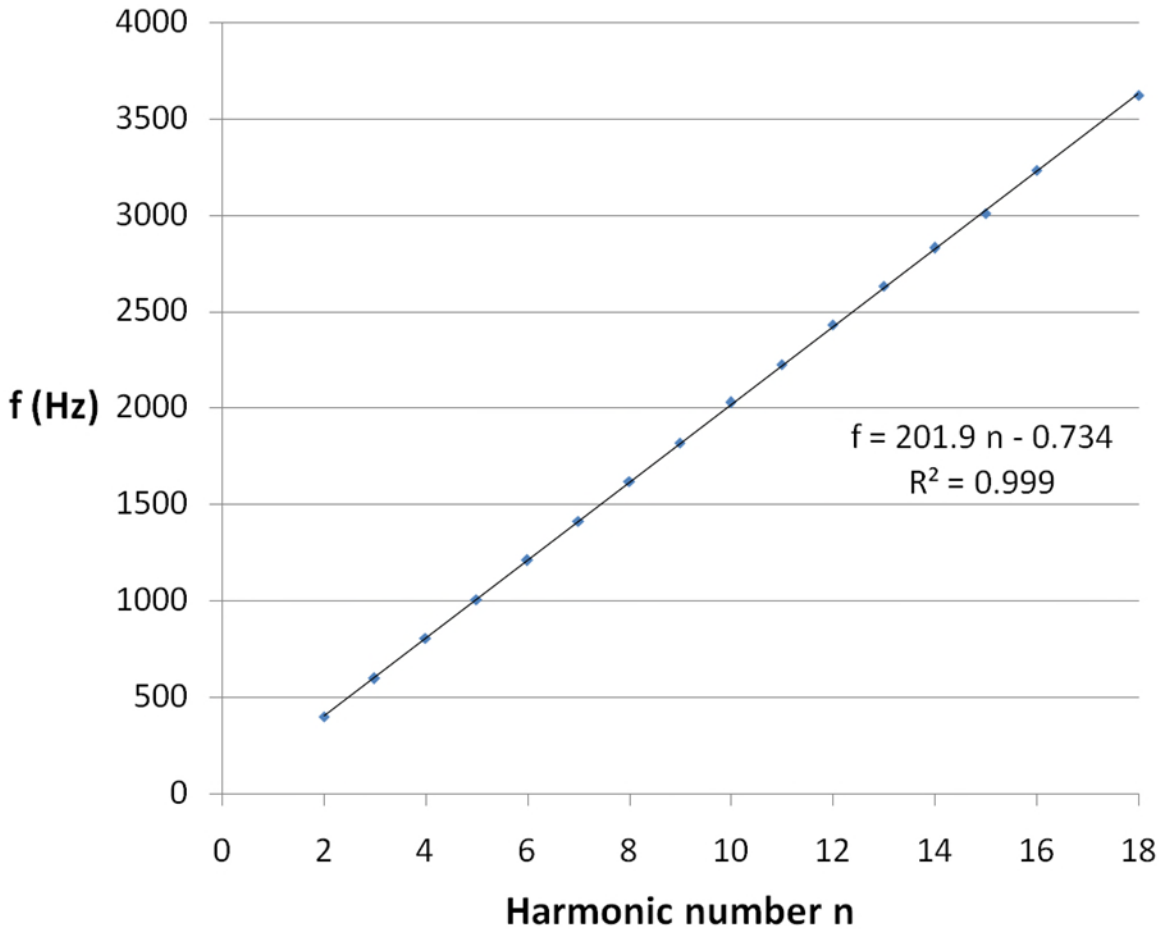

Figure 3. Plot of frequency measured with the software *Audacity* against harmonic number.

Theoretical analysis

The theoretical formula for the fundamental in a corrugated pipe is

$$f_1 = \frac{v_{eff}}{2L_{eff}}, \tag{1}$$

where v_{eff} is the effective speed of sound in the tube and L_{eff} is the effective length of the pipe. The effective length is found using the end-correction formula $L_{eff} = L + 2(0.61)r$ [8], where L is the physical length (76.3 cm) of the tube and r is the inner radius (1.3 cm). The formula using specifically $0.61r$ for each open end is valid when the diameter of the pipe is small compared to the wavelength of the sound [8].

The effective speed of sound in a corrugated tube is less than the speed of sound in a smooth tube. Years ago this observation led authors to study sound speed in periodic structures, a line of research that can be traced back to Newton [9]. The effective sound speed in a corrugated pipe can be written as $v_{eff} = \beta v$, where v is the usual speed of sound and $\beta < 1$. For our data $v = 345 \text{ m s}^{-1}$ since the ambient temperature was $T = 23\ °C$.

Kristiansen and Wiik analyzed corrugated pipes similar to the ones in figures 1(a) and (b) using models and experimental measurements [10]. They state that the 'lowering of the acoustic resonance frequencies by about 9% from what was calculated for a smooth pipe was evident in all our measurements involving fully corrugated pipes' [10]. Therefore, their work suggests that setting $\beta = 0.91$ is a reasonable assignment. Two additional studies with singing toy corrugated tubes [11, 12] also found $\beta = 0.91$.

Using $v_{eff} = 0.91v$ with $v = 345 \text{ m s}^{-1}$ and $L_{eff} = L + 2(0.61)r$ with $L = 76.3 \text{ cm} = 0.763 \text{ m}$ and $r = 1.3 \text{ cm} = 0.013 \text{ m}$, equation (1) becomes

$$f_1 = \frac{v_{eff}}{2L_{eff}} = \frac{0.91v}{2\left[L + 2(0.61)r\right]} = \frac{0.91(345)}{2\left[(0.763) + 2(0.61)(0.013)\right]} = 202 \text{ Hz}. \qquad (2)$$

Since some of the values used in the above calculation have only two significant figures, it is better to report the theoretical result as 200 Hz and that the agreement with the experimental value of 202 Hz is at about 1% uncertainty.

Concluding remarks

A dramatic lecture demonstration is presented where a vacuum cleaner isolates over a dozen harmonics on a corrugated toy tube. Earplugs should be worn by the instructor and students since the tones are loud and many are high pitched in a region where the ear is very sensitive to sound. The demonstration performed live in class is included in a video abstract [13]. In our class, we stop at this point since our course is more conceptual than mathematical. However, by recording the data of the demonstration, students can measure frequencies with the free software package *Audacity* and plot the results in a spreadsheet similar to figure 3. They can then use the theoretical equation (2) to see how theory compares with experiment. Agreement should be at the 1% level. Regardless of including the theoretical analysis, the demonstration itself is very interesting to watch and memorable for the students.

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