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How acoustic resonance can reduce the average velocity in a falling body?

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Abstract: In this article, a simple experiment is described for correcting the misconception that acoustic pressure and levitation effects are hard to observe in school laboratories. Analysis of the free fall velocity of a toy parachute within a vertical tube, driven by sound in a range of frequencies around the resonant condition, exhibits the resonance frequency, the node pressure zones, and the optimal conditions to obtain acoustical levitation of a light body.

Keywords: resonant tube, acoustic pressure, high school demonstration.

PACS: 01.50.Lc; 01.50.My; 43.20.Ks; 43.25.Uv;

1. Introduction

Many high school students might find that concepts of Mechanics and Wave Physics are disconnected; this idea can create serious misconceptions in the study of further Physics topics. On other hand, many videos about acoustic levitation that can be found in Internet sites, such as You-Tube, have attracted the attention of many students [1, 2], but many pupils think that these acoustic experiments are hard to do, and to study, in common school laboratories.

In this article, we use a variation of the resonance tube experiment to analyze the effect of the acoustic field pressure in the average velocity of a free falling light object. Moreover, from the experimental procedure and the data obtained, it is possible identify the resonance frequency, the nodes and antinodes in the resonant tube, and the velocity of sound in air. Finally, an acoustic levitation demonstration is also possible using the same simple experimental set-up.

2. Experimental methodology

The well-known acoustic resonance tube experiment allows students to evaluate the resonance frequencies, wavelengths, and speed of sound in air [3-7]. We propose enhancing the classical acoustic resonance experiment with the following methodological variation, which smoothly concatenates topics in Mechanics with concepts of Wave Physics, like displacement, average velocity, terminal velocity, and mechanical equilibrium, to obtain acoustical levitation. Figure 1 shows the proposed experimental set-up. A transparent tube (made of acrylic, 7 cm in diameter, h_r=1.857 m in length) is oriented vertically, with the lower end placed over a loudspeaker cone (400 W, 7 cm in diameter); the speaker is connected in series to two function generators (Pasco). Both generators are in the maximum amplitude, also synchronized in the in the same output frequency, and wave form. Thus, the synchronization and serial connection permit to deliver more net voltage in the speaker; the result is the increment of the amplitude in the acoustical wave. However, this set-up configuration also can be changed using an only generator and an amplifier. A piece of common paper ($4\times4\text{cm}^2$) is used as a free falling body, since this object quickly obtains a constant velocity (the terminal velocity in air of a free-falling body). In addition, taking into account speed of sound in air is 343 m/s at 20°C, and at 1 atm [8], the 5th mode of resonance in the tube, closed at one end, open at the other, is 416.3 Hz. The experiments are done at frequencies around this 5th mode resonance, and at 0 Hz, in order to allow students the observation of multiple nodes. At each particular frequency, the piece of paper is drop at the upper end of the tube, and its fall is recorded on a CCD video-camera mounted on a tripod. The video can then be analyzed in a personal computer. For the benefit of teachers and students, a video of the experiment, at frequencies of 0, 370, 416, and 450 Hz, is available for download over the Internet [9].

Digital videos of the experiment where analyzed using the computer program Logger-Pro 3.4.6™. The cursor in this program allows setting up a general referential length-scale, and also to spot the position of the falling paper frame by frame, obtaining in this way, more than 180 points per video/experiment. The program generates data of position as function of time; this time vector is obtained automatically from the video information, because the time interval is constant frame by frame. From this data, graphics and a linear fit were obtained for numerical analysis.

Finally, as a demonstration of acoustic levitation (this is when the sample's weight is equal to the upward force due to interaction with the acoustic field, a 10 ×10 cm foamy plate (2.10 g) is carefully placed above the tube top, when driven at the resonance condition. The plate remains in stable suspension until the frequency is changed somewhat above, or below resonance.

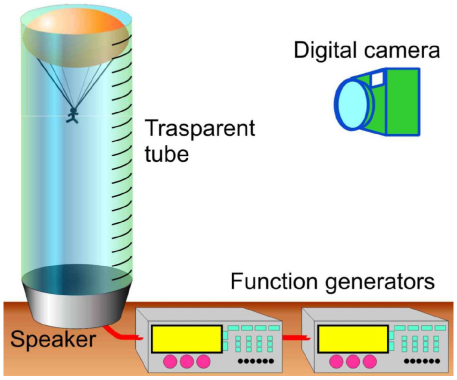

Figure 1. Sketch of the experimental set-up. A variation of the acoustic resonance tube experiment allows students to evaluate the frequency resonance, node positions, wavelength, speed of sound in air, and to demonstrate acoustic levitation.

3. Results and Discussion

Figure 2 shows distance-time curves from several experiments. Only some frequencies are presented, in order to avoid cluttering the figure. In Fig. 2, curve a) corresponds to the paper falling without sound (at a frequency of 0 Hz), while curve d) is with sound at the 5th resonance mode, with a frequency of 416 Hz; finally, the curves obtained at 370 and 450 Hz exhibit similar slopes, but lying in between the slopes obtained at 0 Hz, and 416 Hz. Linear fitting was done via the Least-Squared-Error (LSE) method. The physical interpretation of the fitting coefficients is as follows: the slope *m* is the average velocity, and the intercept *b* is the initial height of the object.

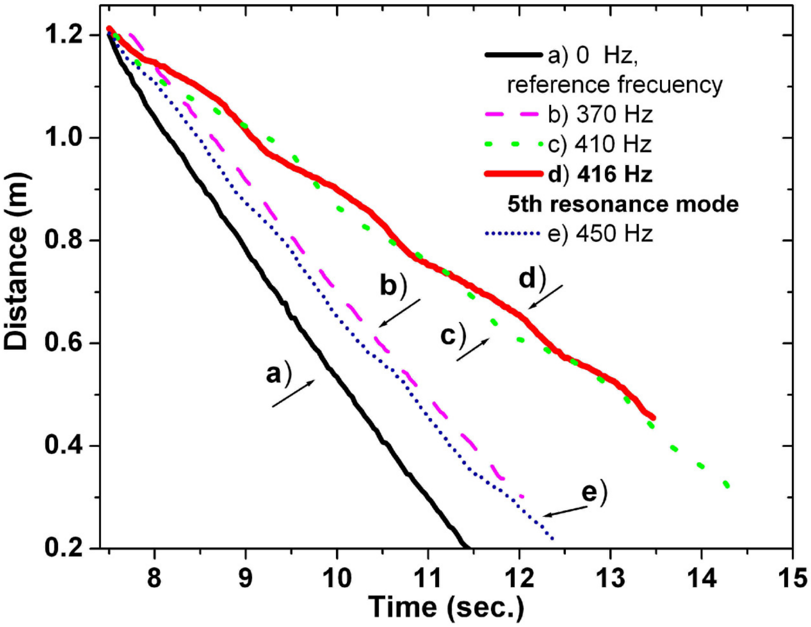

Figure 2. Curves of displacement as a function of time for a free-falling light object within a vertical acoustic resonance tube, at frequencies around the fifth resonance, and at 0 Hz as a reference.

Figure 3 shows the average free-fall velocity as a function of frequency. The curve presents a clear peak close to the expected resonance frequency. However, the error in the velocity is maximum at the resonance frequency, since the distance time curve of the falling paper is not completely linear, as can be observed from curves c) and d) in Fig. 2. The decrement of the average velocity at the resonance condition is a result of the increment of pressure at the nodes, which correspond to the velocity antinodes of the standing acoustic wave [10,11]. In fact, the falling paper minifies its velocity when the vertical acoustic force reaches a maximum. However, the body does not stop at the pressure node, because the inertia in the body is great enough, as to continue falling after this zone.

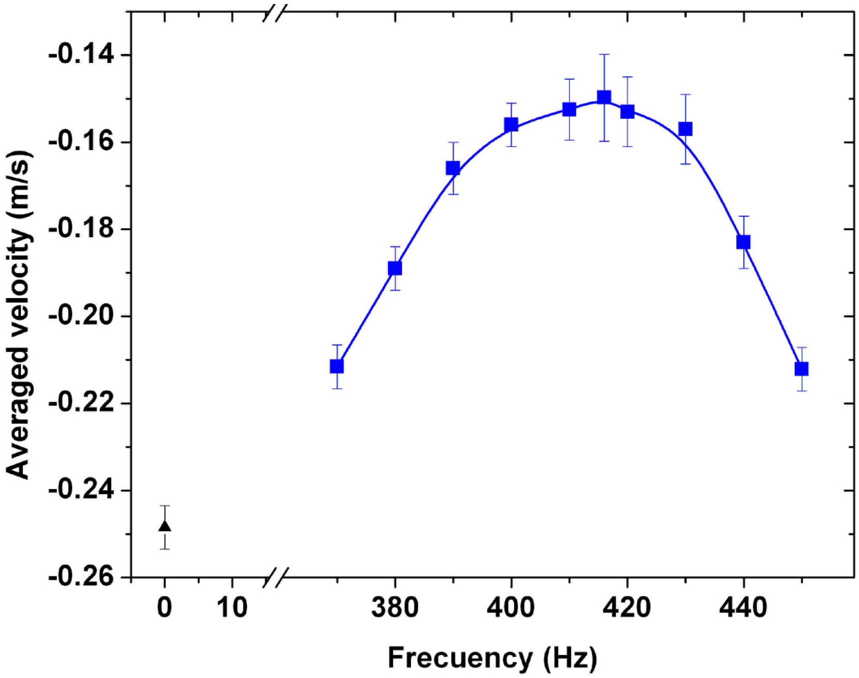

Figure 3. The average velocity of the falling body, as a function of frequency, exhibits the acoustic resonance in a vertical resonance tube.

Table 1 shows linear fit coefficients (slope, and intercept) and regression error (percent correlation factor) at four representative frequencies: 0 Hz as reference condition without sound, 370 Hz below resonance, 416 Hz the resonance frequency, 450 Hz above resonance. From Fig. 2, and Table 1, it can be observed that the linear intercept is in good agreement with the physical length of the tube; i.e. the average height h_a is 1.8 m. On the other hand, it can be observed that the maximum velocity occurs at 0 Hz, with the loudspeaker turned off, producing no sound; in fact, the velocity observed in this case, might correspond with the terminal velocity of the falling paper, given that its geometry promotes high friction from the surrounding air. At frequencies below resonance, the average velocity decreases as a result of the wave/paper interaction, neglecting that the paper changes the length in resonant-tube. The average velocity is minimal at the resonance frequency, where well defined nodes of pressure are responsible for the slower motion of the falling paper. Finally, an increment in the average velocity is again observed at frequencies above resonance.

Frequency (Hz)	Slope (m/s)	Intercept (m)	Percent correlation factor
0	-0.248	1.78	99.8%
370	-0.212	1.79	99.9%
416	**-0.125**	**1.81**	**99.8%**
450	-0.212	1.79	99.8%

Table 1. Linear fit parameters and regression correlation factor at four representative frequencies.

Moreover, the curve obtained at resonance presents clear maxima and minima around the linear fit line. In fact, this curve can be represented approximately as the sum of linear and sinusoidal functions. It is possible then, to find the nodes using the following mathematical model:

$$y = A\sin(\omega t + \varphi) + mt + b\,. \tag{1}$$

The *m* and *b* parameters have been calculated via LSE linear fitting. Thus, subtraction of this part allows us to find the frequency ω, phase φ, and amplitude *A* via simple calculus. In such way, a best fit curve is obtained as follows:

$$y = 0.015\sin(4t + 5) - 01252t + 2.146\,, \tag{2}$$

where the correlation factor improves from 0.9982 for the linear fitting, to 0.9995 for the sine-plus-linear fit. Figure 4 shows a detailed view of the experimental data, and the proposed sine-plus-linear fit.

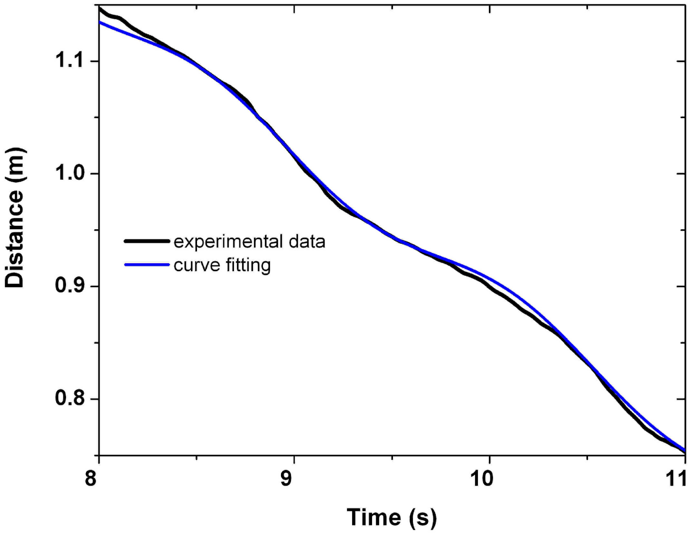

Figure 4. Curves of displacement as a function of time: linear-trigonometric fit, and experimental data at the frequency of the 5th resonance mode.

Thus, the wavelength can be calculated using eq. 2, from the intersections between the linear and the oscillating parts. The wavelength for the 5th resonance mode turns out to be 0.785 m. From here, the product of the resonance frequency and the wavelength gives the speed of sound in air as 326.6 m/s.

Finally, photographs a) and b) in Fig. 5 show the equilibrium of the foamy plate, 20 s, and then 2 min., after being left above the top end of the tube, in resonance condition. However, it was observed that the plate presented small vibrations, and also, that the acoustic levitation effect is lost out of the resonance modes.

In this experiment, we use a simple calculus to determinate the average pressure $\langle P \rangle$, which is the average force $\langle F \rangle$ over the area *A.* Considering stable and equilibrium in the foamy plate, the average force is the weight. So the average pressure to levitate the plate is

$$\langle P \rangle = \langle F \rangle / A = mg / A \qquad (3)$$

This is a pressure 2058 Pa, in the top of the tube to maintain is levitating a foamy plate.

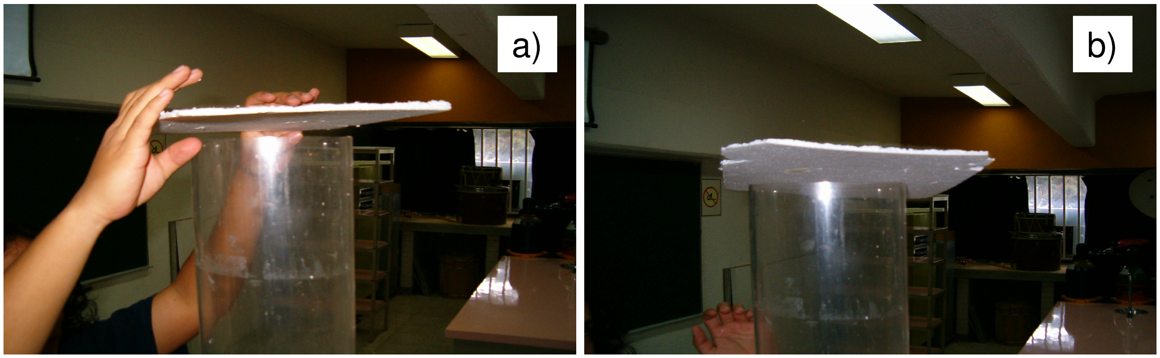

Figure 5. Acoustic levitation of a foamy plate when the tube is driven by sound at the 5th resonance mode. Photographs correspond to **a)** 20 s, and **b)** 2 min., after placing the foamy plate above the tube.

4. Conclusions.

A simple variation of the classical acoustic resonance tube experiment has been presented. This proposal allows of the opportunity to discuss mechanical and wave physics concepts; for example, terminal velocity and resonance, respectively. This experiment allows the quantification of sound wave parameters, such as wavelength and speed of wave propagation, much as in the typical experiment. However, driving at different frequencies, and further data analysis to obtain the average velocity of a free falling light object within the tube, leads to the concept, and the demonstration of acoustic levitation. Most of the equipment used in this demonstration can normally be found in many high-school laboratories; thus, a demonstration of acoustic levitation can be readily performed. In further work, we plan to present low-cost variations of this demonstration of acoustic levitation.

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