Acoustic characterization of magnetic braking with a smartphone

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Smartphone sensors have shown to be adequate to perform physics experiments in introductory and first-year university physics courses.[1] The published work covers a wide range of topics within general physics such as linear[2] and circular[3] motions, oscillations,[4] beats,[5] acoustics,[6–8] and optics, among others. The microphone and speakers have been particularly useful for studying sound phenomena, such as the determination of the speed of sound,[6] the study of acoustic beats,[7] or the Doppler effect.[8]

In this work, we will use sound wave resonance in an air column to study the terminal velocity of a falling magnet inside a non-ferromagnetic pipe (made of aluminium). Magnetic braking is a widely used concept when the topic of Faraday's law of induction is introduced.[9] The magnetic braking of a magnet inside a non-ferromagnetic pipe (e.g., made of aluminium or cooper) follows a similar model as the body falling in the air. When the magnet is dropped into the vertical pipe, it experiences an upward force proportional to the increasing velocity. Very shortly, the braking force approaches the weight force, leading to a linear uniform motion with a constant terminal velocity.

The experiment

Figure 1 shows the experimental setup used for the experiment. On the left side of the figure, the mobile phone, the magnet, and the aluminium pipe are shown. The magnet diameter fits the inner diameter of the pipe but such that a fine air layer still exists between the pipe and the magnet. The length of the pipe is 1.524 m, and its inner diameter 0.021 m. The diameter of the magnet is 0.197 m and its height 0.058 m. A schematic representation of the pipe with a standing wave produced as the magnet falls is represented on the right side of the figure.

The smartphone is used here with a double purpose, that is, to generate the single-frequency sine sound wave and to record the standing sound wave produced between the open end and the closed end consisting of the magnet moving through the pipe. For the single-tone sound wave generation, the free Android app Physics Toolbox Suite has been used (Fig. 1). When the magnet goes down in the non-ferromagnetic vertical pipe, sound amplitude variations are produced. These variations are registered by recording the sound with the Voice Recorder app, commonly incorporated in Android smartphones.

The described system can be modeled by an open-end air column for which resonances take place according to the following expression:

$$L_n = \frac{\lambda_n(2n+1)}{4}; \quad \text{with } n = 0, 1, 2, 3\ldots \qquad (1)$$

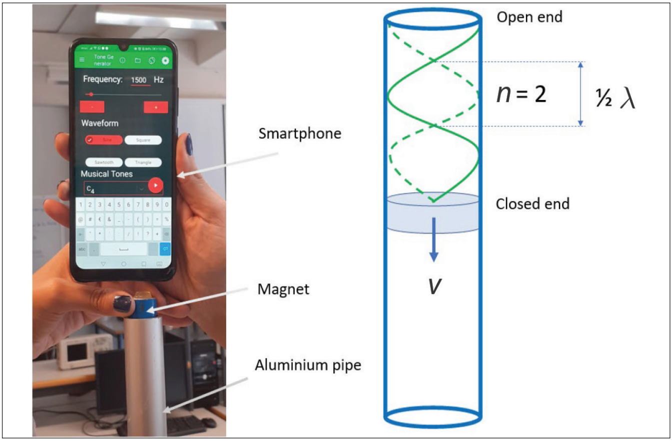

Fig. 1. Experimental setup on the left-hand side and schematic representation of the alumunium pipe, the magnet, and the standing wave on the right-hand side.

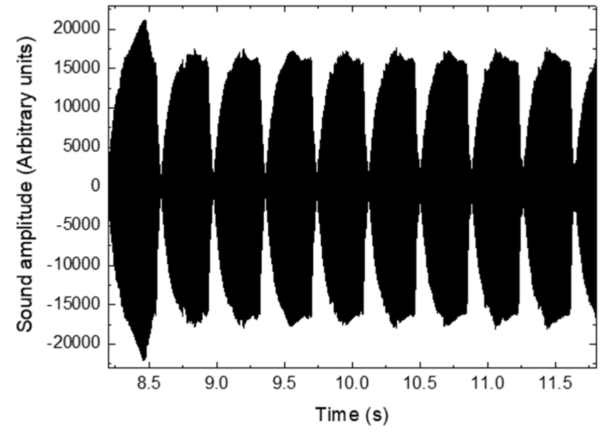

Fig. 2. Audio recorded with the smartphone while the magnet was falling inside the pipe. The graph represents the amplitude of the sound vs. time.

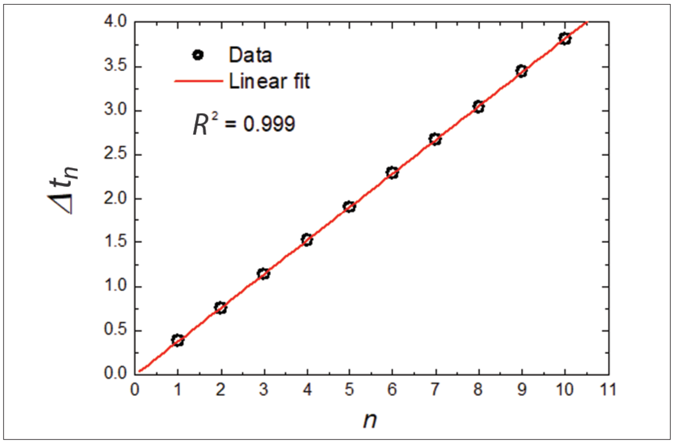

Fig. 3. Time elapsed from a node taken as reference to each of the of the consecutive nodes. The last 10 nodes out of 16 nodes given in the pipe have been used in the graph.

Every time the magnet reaches a resonant length L_n, that is, a length that equals an odd number of $\lambda_n/4$, a node is produced. Here, λ is the wavelength of the sound wave.

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Results

The nodes are detected in our experiment by the microphone and registered with the Voice Recorder application. For the best results, the room should remain silent during the experiments. Figure 2 shows the recorded “wav” file. The amplitude of the sound wave is plotted vs. time. The nodes are clearly visible along the curve.

Taking the length for a given node ($n = 0$) as reference,

$$L_n - L_0 = \frac{\lambda_n(2n+1)}{4} - \frac{\lambda_n}{4} = \frac{\lambda_n}{2} n. \tag{2}$$

And assuming that a linear uniform motion is reached very quickly after the magnet enters the pipe, the expression $L_n - L_0 = v(t_n - t_0) = v\Delta t_n$ can be substituted in Eq. (2) to obtain

$$\Delta t_n = \frac{\lambda_n(2n+1)}{4v} - \frac{\lambda_n}{4v} = \frac{\lambda_n}{2v} n, \tag{3}$$

where v is the velocity of the falling magnet and Δt_n the time elapsed from the moment a node taken as reference is produced to each of the subsequent consecutive nodes. The wavelength in Eq. (3) is calculated as $\lambda_n = v_s/f_n = 0.1818$ m, where $v_s = 345.48$ m/s is the speed of sound at 24 °C (room temperature) and $f_n = 1900$ Hz is the frequency set at the sound tone generator of Physics Tool Suite mobile app. The values of Δt_n calculated according to Eq. (3) are included in Table I as a function of the node number, n.

Figure 3 shows a linear fit applied to the time elapsed from the moment a node taken as reference ($n = 0$) is produced to each of the consecutive nodes (Δt_n) vs. $n = 1, 2, 3, 4, \ldots$. The last 10 nodes out of 16 nodes given in the pipe have been used to make the graph. The equation resulting from the fit is $\Delta t_n = (0.3819n - 0.0026)$ s with a coefficient of determination of $R^2 = 0.999$. According to Eq. (3), the slope is $\lambda_n/2v = 0.3819$, from which the velocity of the falling magnet can be calculated: $v = 0.2380$ m/s.

Table I. The first column shows a number identifying the consecutive nodes, the second the corresponding time elapsed, and the third the time elapsed relative to the node $n = 0$ taken as reference.

n	t_n (s)	$\Delta t_n = t_n - t_0$ (s)
0	10.126	0
1	10.597	0.387
2	10.877	0.755
3	11.262	1.139
4	11.646	1.523
5	12.030	1.908
6	12.415	2.292
7	12.799	2.677
8	13.166	3.043
9	13.567	3.445
10	13.934	3.812

Final remarks

For comparison, an alternative method has been used to calculate the velocity of the falling magnet. The total traveling time of the magnet through the pipe of length 1.524 m has been measured seven times with a stopwatch. The resulting average time is 6.477 s (the measured times were 6.48, 6.47, 6.48, 6.48, 6.48, 6.47, and 6.48 s). The resulting mean velocity using this method was 0.2353 m/s. The percentage difference between the velocities calculated with the different methods is 1.14%, which confirms the fact that the terminal velocity is reached soon after the magnet starts its travel inside the pipe.

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