Low-Cost Timer to Measure the Terminal Velocity of a Magnet Falling Through a Conducting Pipe

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Dropping a magnet into a conductive pipe (made up of copper or brass or aluminum) is a very popular demonstration in many physics classrooms and laboratories. In this paper we present an inexpensive timer that can be used to measure the terminal velocity of the magnet falling through a conducting pipe. The timer assembly consists of Hall effect switches connected to a digital stopwatch. The timer assembly was then used to observe the variation in the terminal velocity of the falling magnet with respect to the thickness of the copper pipes.

Introduction

In some recent studies, the motion of a falling magnet through a conductive pipe is observed using pick-up coils,[1-4] strain gauges,[5] ultrasound position sensors,[6] or simply a balance.[7] Typically the apparatus is used to measure the terminal velocity of the magnet as it falls through the pipe and consists of a pick-up coil connected to a data-acquisition system[2,5] or a storage oscilloscope.[1,3] A recent paper[6] describes a novel method to make measurements using an ultrasound position sensor. In this paper, we present a compact and inexpensive apparatus (Fig. 1) that can be used to measure the terminal velocity of the magnet. The apparatus consists of a stopwatch (RACER make) interfaced to two Hall effect switches. These switches control the start/stop mechanism of the stopwatch. The distance between the switches can be adjusted depending upon the experiment under consideration.

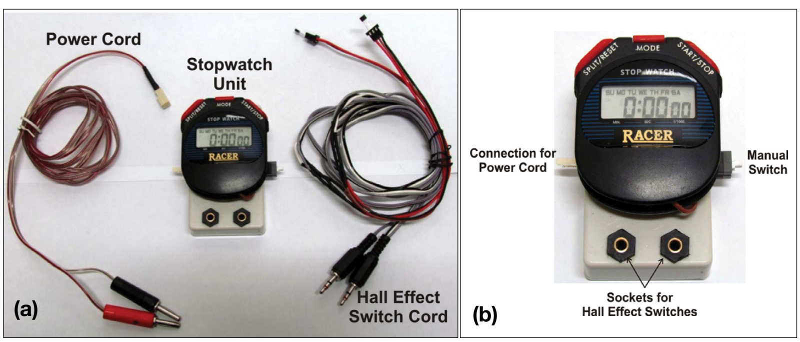

Fig. 1. (a) Photographs of timer assembly. (b) Stopwatch unit.

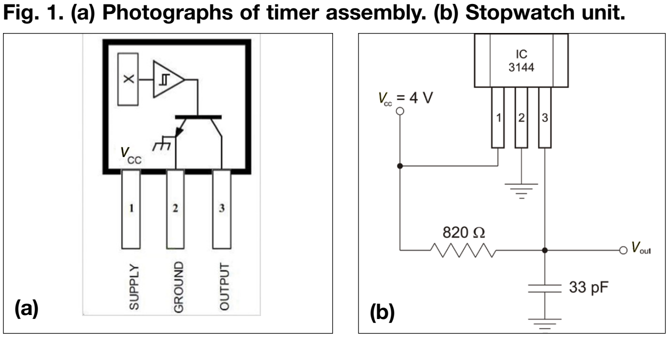

Fig. 2. (a) Pin-out diagram of IC3144. (b) Biasing circuit for IC3144.

Hall effect switch connections

The pin-out diagram of the IC3144 (Allegro Microsystems) and the biasing circuit are shown in Fig. 2.

Digital stopwatch connections

A handheld digital stopwatch (Racer make) is used. It is modified to start and stop automatically instead of pressing manually. Usually when the start/stop button is pressed, a pulse goes to the internal circuit. This pulse either starts or stops the stopwatch. In this system, start or stop signals are generated each time the magnet passes close to a Hall effect switch.

Interfacing Hall effect switches to stopwatch

Figure 3(a) shows the complete circuit diagram. A dc power supply is used to give 4 V to the circuit. Figure 3(b) shows the printed circuit board made using the software ExpressPcb. Point A (Fig. 4) of the stopwatch is connected to pin 3 (output of the IC) of the Hall effect switches. The negative terminal of the stopwatch battery, i.e., point B of the stopwatch, was connected to the negative terminal of the power supply through a manual switch.

Need for a manual switch [Fig. 1(b)]

When the dc power supply is switched on, a pulse is generated due to which the stopwatch starts. Here another pulse is required to stop the stopwatch. This can be achieved even by switching off the supply and then again switching it on. Instead a switch is connected in the circuit that provides this extra pulse to stop the stopwatch. Then the stopwatch can be reset using the RESET button.

Experiments

Working of the apparatus

In the presence of a magnet, the output of the first Hall effect switch becomes low. This triggers the stopwatch and the stopwatch starts. When the magnet passes by the second

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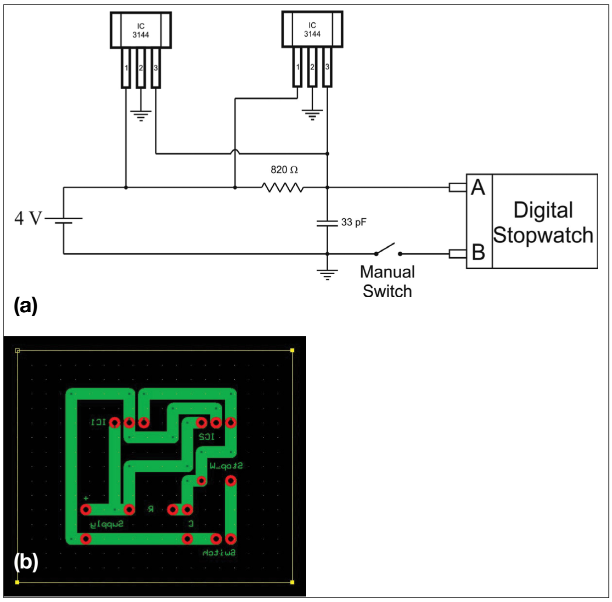

Fig. 3. (a) Circuit diagram. (b) The printed circuit board.

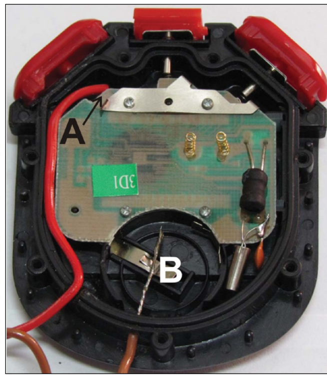

Fig. 4. Modified internal connections of the stopwatch.

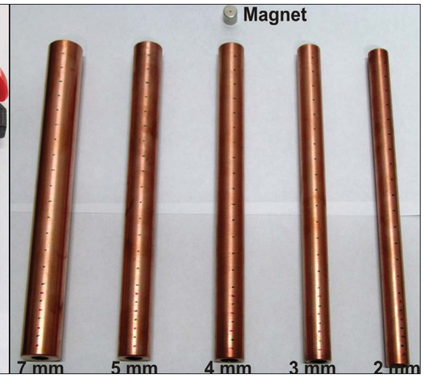

Fig. 5. The copper pipes and the magnet.

Hall effect switch, the output of this switch goes low and the stopwatch stops. Thus we get the time interval for the magnet to travel a distance between two Hall effect switches. The speed of the magnet is given by the distance between switches divided by the time interval displayed by the stopwatch.

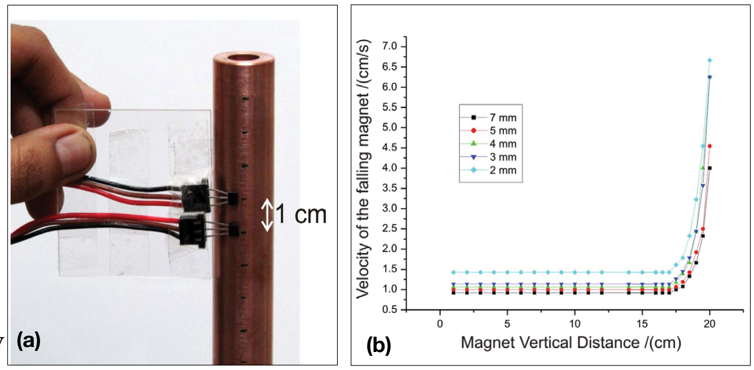

Fig. 6. (a) The apparatus. (b) Change in the velocity.

Experiments conducted using this assembly

This assembly is used to study the motion of a magnet falling inside copper tubes. A cylindrical neodymium magnet (9.9 mm in diameter, 10.0 mm in height, and 5.7 g) is used. Five copper pipes (each 20.0 cm long, 10.0 mm inner diameter) are used in the experiment. The outer diameters of these copper pipes are 14.0 mm, 16.0 mm, 18.0 mm, 20.0 mm, and 24.0 mm. Figure 5 shows the copper pipes with their wall thicknesses mentioned.

Study of changing velocity when the magnet leaves pipe:

It is a common observation that the magnet falling through a copper pipe attains a constant velocity. But the velocity of the falling magnet increases again as it is about to leave the pipe. Figure 6(a) shows the placement of switches along the pipe. Both the switches are mounted on a transparent plastic piece at a distance of 1 cm. This piece is moved from the top in steps of 1 cm. Figure 6(b) shows a graph indicating the region (17.0 cm from the top of the pipe) for every pipe from where the velocity starts to increase.

To investigate the probable cause of this, we measured the change in the magnetic field using a gaussmeter. Figure 7(a) shows a graph of the magnetic field of the magnet with respect to the distance along the axis of the magnet. The curve is a theoretical fit to an inverse cube law (at large distances), with magnetic dipole moment 4.77×10^{-8} T·m^3.

It can be seen from the graph [Fig. 7(a)] that the magnetic field of the magnet decreases to 98% of its maximum value at a distance of 3.0 cm from the center of the magnet [Fig. 7(b)]. This reflects in Fig. 6(b), which also shows that the opposing force experienced by the magnet starts to decrease from 17.0 cm onward. In other words, the velocity of the magnet

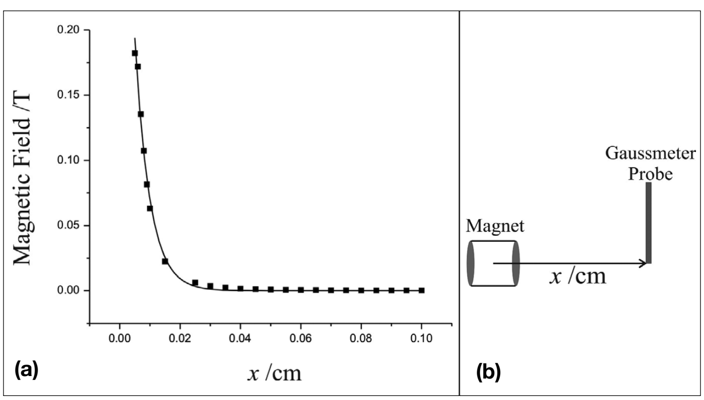

Fig. 7. (a) Magnetic field of the magnet with distance along its axis. (b) Schematic diagram of the magnetic field measurement.

Table I. Variation in the terminal velocity with wall thickness.

Pipe wall thickness (mm)	Terminal velocity (cm/s)
2	3.88 ± 0.02
3	3.05 ± 0.01
4	2.72 ± 0.01
5	2.61 ± 0.01
7	2.35 ± 0.01

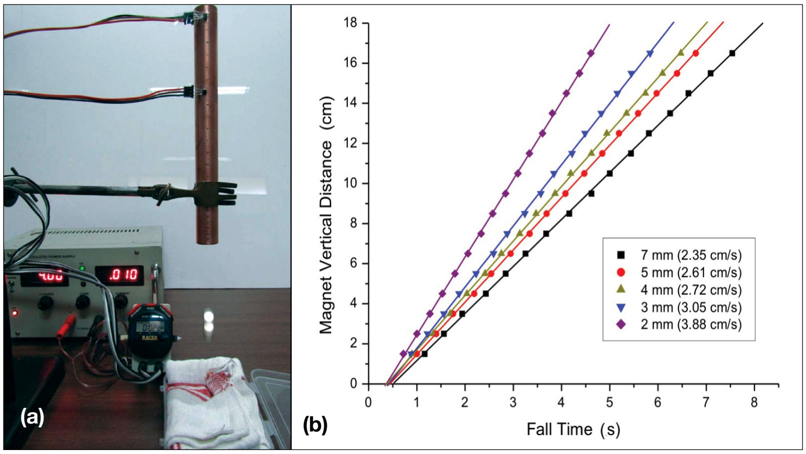

Fig. 8. (a) The apparatus. (b) Graph of fall time against the vertical distance of the falling magnet.

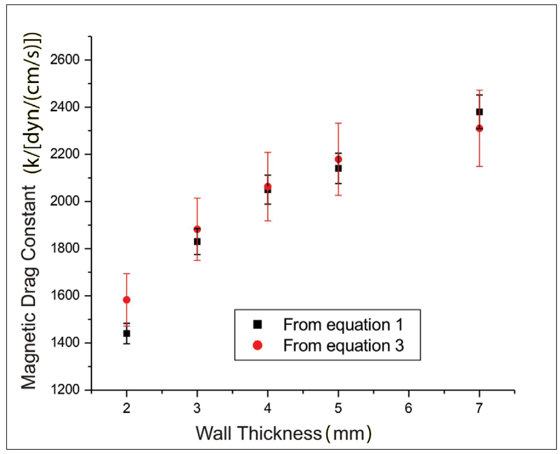

Fig. 9. Magnetic drag constant against pipe wall thickness.

starts increasing from this point onward. Hence a region above 3.0 cm from the bottom of the pipe is chosen for further experiments to ensure that the experiment is carried out in the region of terminal velocity.

Determining the terminal velocity for all the pipes

One of the Hall switches is kept fixed at a distance of 1 cm from the top end of the pipe, and the observation for fall time is taken by sliding another Hall switch in steps of 1 cm.

The terminal velocity for each pipe is listed in Table I. The uncertainty in the terminal velocity was calculated from the slope of the graphs in Fig. 8(b). The uncertainty in slope was calculated using eyeballing method. The error bar in distance measurement was used as 0.1 cm and the error bar in time measurement was taken as 0.01 s.

Variation in the magnetic drag constant with respect to the wall thickness

When the magnet falls with a terminal velocity, we can write[3-5]

$$mg = kv_T,$$

where k is the magnetic drag constant:

$$k = \frac{mg}{v_T}. \tag{1}$$

The theoretical model presented by Donoso et al.[4] gives a relationship between the magnetic drag constant and inner and outer diameter of the conducting pipe. Equation (26) given by Donoso et al. needs a minor correction. The multiplying factor should be 18 instead of 36. Another correction is that the value of f [Eq. (11)][4] is $(5\pi/128)$ instead of $(5\pi/256)$. The equation then becomes

$$k = \frac{18\pi f \sigma \mu^2}{a^4}\left[\frac{a}{3}\left(1-\frac{a^3}{b^3}\right)\right], \tag{2}$$

where a and b are inner and outer radii of the pipes respectively, $f = \frac{5\pi}{128}$, $2a = 1.0$ cm,

Table II. Variation in magnetic drag constant with wall thickness.

Pipe wall thickness (mm)	Magnetic drag constant, *k* / [dyn/(cm/s)]	
	From Eq. (1)	From Eq. (3)
2	1440 ± 43	1583 ± 111
3	1830 ± 55	1882 ± 132
4	2050 ± 62	2063 ± 145
5	2140 ± 64	2179 ± 153
7	2380 ± 71	2310 ± 162

σ = conductivity of copper = $5.92\times10^7\ \Omega^{-1}\cdot\mathrm{m}^{-1}$, and μ = magnetic dipole moment of the falling magnet = $4.77\times10^{-8}\ \mathrm{T\cdot m^3}$. In Fig. 9, the magnetic drag constant k is plotted against the wall thicknesses of the copper pipes. Both the values of the magnetic drag constant [calculated using Eqs. (1) and (2)] agree quite well as seen from the graph.

Conclusion

The apparatus can be very suitable in performing time measurements for different experiments where the measured time interval is more than 0.06 s. The advantage of using this assembly is the low cost involved in building it. Though the apparatus is low cost, it gives a good repeatability of observations.

References

1. Jhules A.M. Clack and Terrence P. Toepker, "Magnetic induction experiment," *Phys. Teach.* **28**, 236–238 (April 1990).
2. Kenneth D. Hahn, Erik M. Johnson, Allen Brokken, and Steven Baldwin, "Eddy current damping of a magnet moving through a pipe," *Am. J. Phys.* **66**, 1066–1076 (Dec. 1998).
3. Cyrus S. MacLatchy, Philip Backman, and Larry Bogan, "A quantitative magnetic braking experiment," *Am. J. Phys.* **61**, 1096–1101 (Dec. 1993).
4. Donoso et al., "Magnet fall inside a conductive pipe: Motion and the role of the pipe wall thickness," *Eur. J. Phys.* **30**, 855-869 (2009).

5. See Ref. 3.
6. Joseph Priest and Bryant Wade, "A Lenz law experiment," *Phys. Teach.* **30**, 106–108 (Feb. 1992).
7. Petru S. Fodor and Tara Peppard, "Lenz's law demonstration using an ultrasound position sensor," *Phys. Teach.* **50**, 344–346 (Sept. 2012).
8. Gerald Feldman, "Dramatic (and simple!) demonstration of Newton's third law," *Phys. Teach.* **49**, 103–105 (Feb. 2011) and references therein provide information about other pedagogical uses and easily obtained versions of this demonstration.

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