The Velocity and Magnetic Field Dependence on the Magnetic Friction and Terminal Velocity of the Magnets Moving on the Conductor Plane

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ABSTRACT

The velocity dependence on the magnetic friction and the magnetic field dependence on the terminal velocity of the magnets moving on the conductor plane were investigated. A mechanical friction effect was eliminated by attaching the magnet to a cart which moves almost frictionless on the plane. From the relation between the terminal velocity and acceleration of the cart, the magnetic friction acting on the cart was found to be linearly dependent on the velocity. The magnetic field dependence on the terminal velocity was also investigated under the various magnetic fields and fixed acceleration. The terminal velocity of moving cart decreases linearly with respect to the increasing relative magnetic field intensity.

Key Words: Magnetic Friction, Terminal Velocity, Conductor Plane

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INTRODUCTION

When a magnet and a conductor are in relative motion, currents are induced within the conductor due to the changes of the magnetic flux passing through the conductor. The induced current is called eddy current, its magnitude is proportional to the rate of change of the magnetic flux and its direction is determined by Lenz law (1). Due to the eddy currents, the magnetic field is produced around the conductor and exerts a magnetic force on the magnet moving near the conductor. The force acting on the magnet due to the induced eddy currents is known as eddy current brake or magnetic friction (2-4). The magnitude of the magnetic friction between moving magnet and conductor depends not only on velocity of the magnet but also the magnetic field intensity of the moving magnet.

Common ways to see the effect of magnetic friction on the motion of magnets are observing the decelerated motion of magnets when they slide down on an inclined conductor plate or when they fall down inside a long vertical conductor tube, such as a copper or aluminum tube (2, 3). However, these methods cannot provide detailed information about the interaction between the magnet and the conductor because of the mechanical friction between them in the sliding magnet method and because of the high acceleration of the magnet in the falling magnet method. To study the characteristics of the velocity change of the magnet caused by magnetic friction, the mechanical friction should be eliminated while the magnet is moving and the acceleration of magnet should be small enough to observe the deceleration of the magnet before it reaches terminal velocity.

The magnitude of the magnetic friction is known to be related to the magnetic field intensity induced within the conductor, which depends on the induced eddy currents. Since the induced eddy currents are proportional to the rate of change of the magnetic flux through the conductor, the magnetic friction is consequently dependent on the velocity ($\sim v^n$) of the magnet moving on the conductor plate (1).

In this study, the velocity dependence on the magnetic friction and the magnetic field dependence on the terminal velocity were investigated under the conditions of minimized mechanical friction and small acceleration. The acceleration of the magnet was controlled by changing the inclined angle of the conductor plane and the various magnetic fields were obtained by changing the numbers of magnets used. The terminal velocity of the magnet with respect to the magnetic field intensity was obtained from the measured velocity of the moving magnet by extrapolation of a fitted curve.

MATERIALS AND METHODS

The equipment used for the experimental setup consists of a 2.2m low friction aluminum dynamics track (ME-9779 (5) of the company PASCO), a motion sensor (PS-2103A (6), PASCO) connected to a computer system, an aluminum cart (ME (7), PASCO), and a lab jack to change the incline of the track. As shown in Figure xx of the assembled setup, the track is fastened to one side of a table and the lab jack placed in a distance of about 1.5m. Lowering or raising the lab jack changes the inclined angle of the track. As the second variable, the number of magnet on the cart was varied. As the first experiment to determine the extent of mechanical friction of the cart moving on the track, a measurement was carried out without magnets at an inclined angle of 1.93°.

Using this setup, the velocity of the cart moving down the track was measured by the motion sensor and recorded over time at inclined angles of 1.15°, 1.91°, 3.05°, 3.82°, and 4.58° with a fixed number of yyy magnets. The data were collected and processed using xxx. The initial velocity of the cart was zero. The terminal velocity of the cart was obtained by fitting the measured data using the solution of an equation of motion for an object moving under a constant acceleration and drag force. In a second set of experiments, the number of magnets was varied from one to six and the cart run at the same inclined angle.

RESULTS

To determine the influence of mechanical friction on the results of the experiments to measure magnetic friction, the cart was run without magnets at an inclined angle, θ, of 11.36°. The plot of velocity over time is shown in Figure 2. The linear dependency of the velocity on time indicates that the cart without magnet has a constant acceleration, a. The slope of the data was determined as 1.91 which agrees well with the calculated theoretical acceleration value of $1.93(m/s^2)$ obtained using the equation $a = g\sin\theta$ with the gravitational constant $g = 9.8(m/s^2)$. Thus we can assume that the mechanical friction can be neglected in the whole experimental process.

Fig. 1 Experimental setup. ① aluminum dynamic track system(ME-9779, PASCO), ② motion sensor(PS-2103A, PASCO), ③ cart

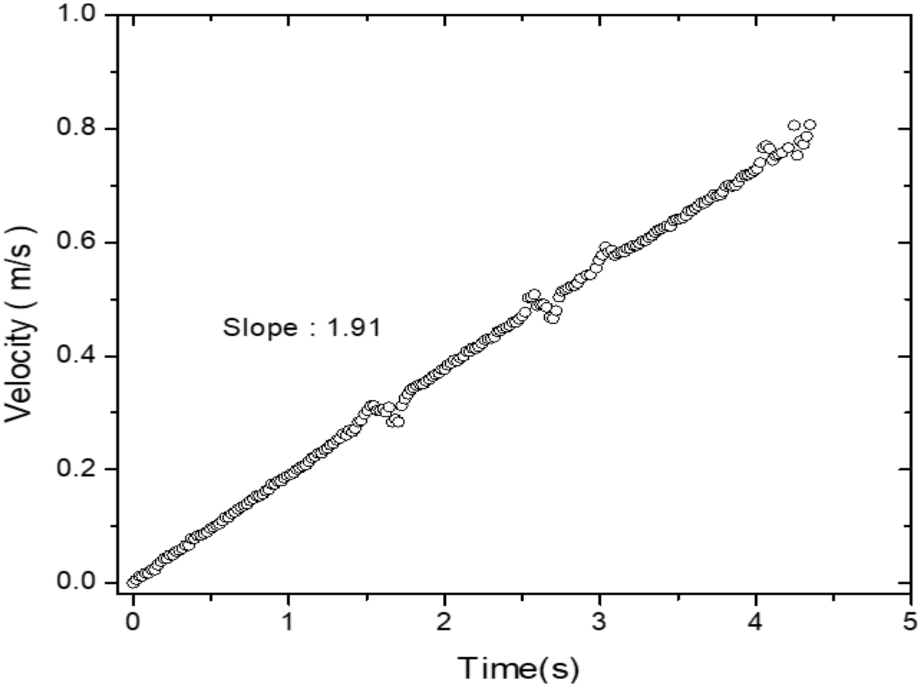

Fig. 2. The velocity of a cart without magnet sliding down the inclined track. The linear behavior of the velocity indicates the cart is in a constant acceleration motion with minimized mechanical friction.

Figure 2 shows the velocity changes of the cart with a fixed number of magnets moving on the aluminum conductor plane at different inclined angles. At the angle of 1.15° in Figure 3, the velocity initially increases, the rate of change gradually decreases and the velocity finally becomes constant, which is known as the terminal velocity. For larger angles, the magnets will reach the terminal velocity if the track is sufficiently long, which was not the case in these experiments. Therefore, we determined the terminal velocity via the following theoretical approach.

The schematic diagram of the cart with magnet sliding on the inclined conductor plate is shown in Figure 4. If we denote the magnetic friction as f_{eddy}, the equation of motion can be written as,

$$mg\sin\theta - f_{eddy} = m\frac{dv}{dt}$$

where $f_{eddy} = bv^n$ and b is a drag coefficient. If we assume t $f_{eddy} = b$, the equation of motion becomes,

$$mg\sin\theta - bv = m\frac{dv}{dt}$$

The solution is given as, (1)

$$v(t) = \frac{mg\sin\theta}{b}\left\{1 - \exp\left(-\frac{b}{m}t\right)\right\}$$

At long times, t, the terminal velocity, v_T, can be written as,

$$v_T = \frac{mg\sin\theta}{b}$$

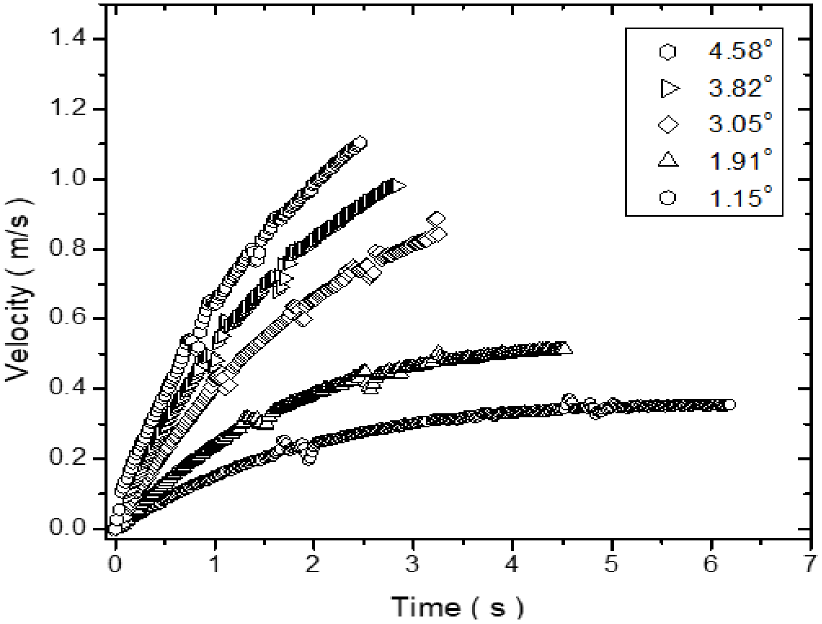

Fig. 3 The velocity of a cart with fixed number of magnet moving on the conductor plate of different inclined angles

In order to check if the velocity data in Figure 2 follow the above equation, data fitting was performed and the results are shown in Figure 5 indicating the respective terminal velocities for the different inclined angles.

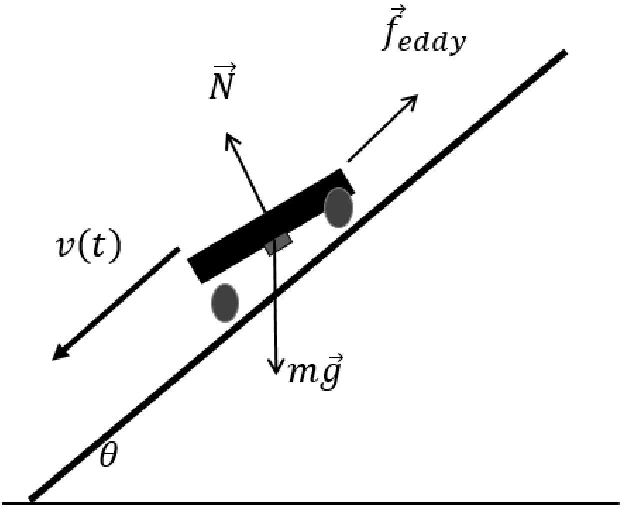

Fig. 4 The schematic diagram of the cart with magnet sliding on the inclined conductor plane

In Figure 5, the terminal velocities determined as described above are plotted over $\sin\theta$ indicating a proportional dependency. Therefore, the terminal velocity shows a linear relation with $\sin\theta$ if the magnetic friction depends linearly on the velocity of cart with magnet and the Figure 5 shows that the magnetic friction exerting on the magnet which is moving on the conductor plate is linearly proportional to the velocity of the magnet.

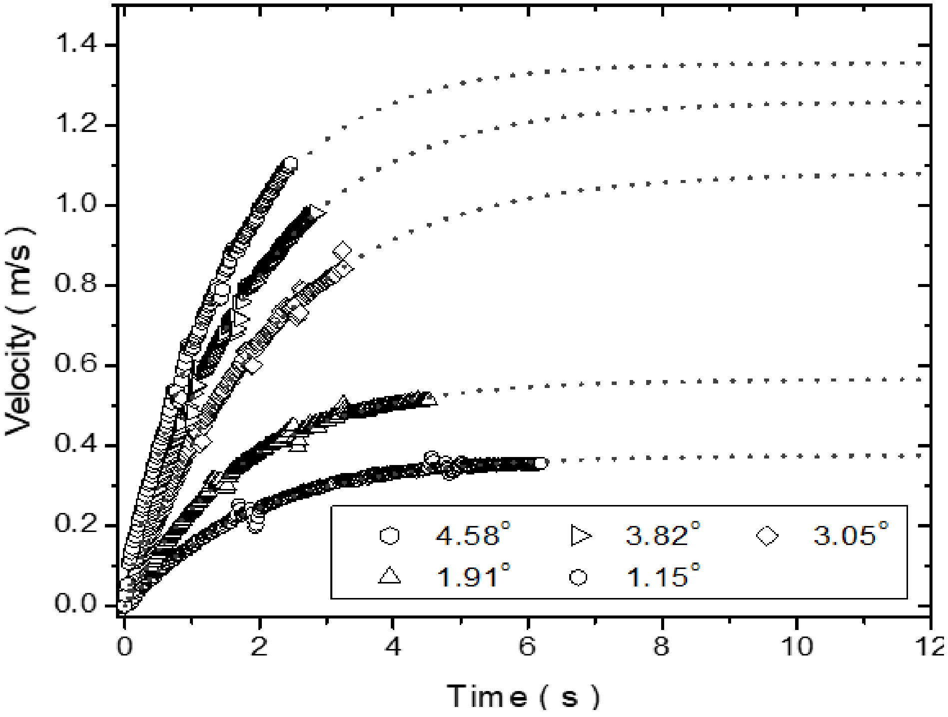

Fig. 5 The fitting result of the velocity data in Fig. 4

The magnetic field effect on the terminal velocity of the magnet was investigated by measuring the velocity changes of the cart with various numbers of magnets. The results are shown in Figure 7 as plots of velocity over time for the different loadings with magnets. As previously described, the data were used to fit the curves which are shown in Figure 7, and to determine the terminal velocities.

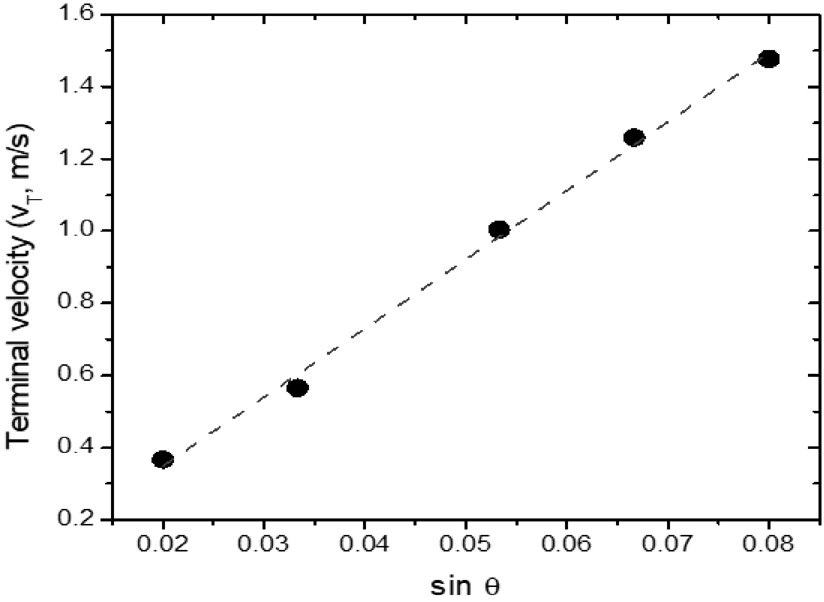

Fig. 6 The relation between the terminal velocity of cart and the inclined angle of conductor plane

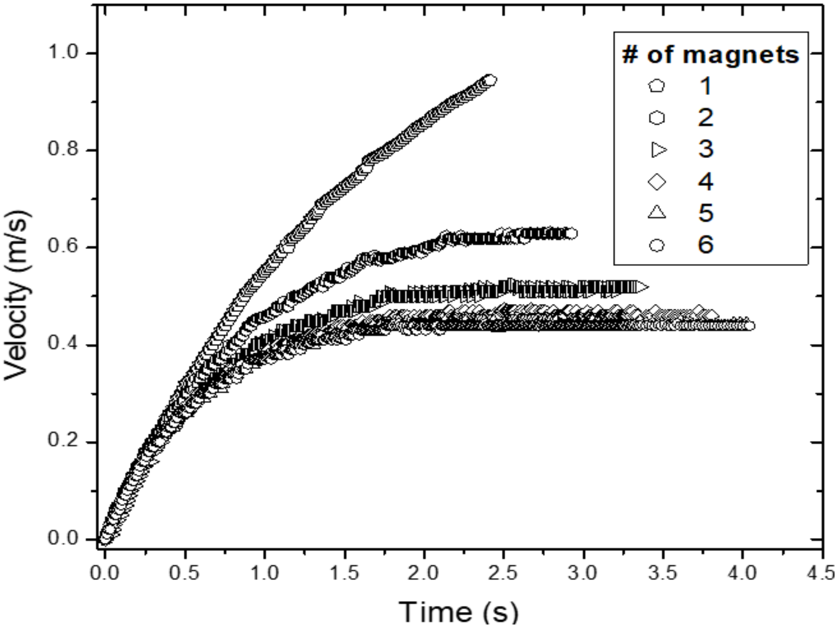

Fig. 7 The velocity of a cart with various number of magnets moving on the conductor plane of fixed inclined angles

As we expected, the magnetic friction increases and the terminal velocity decreases with increasing number of magnets. In addition, the decreasing rate of terminal velocity is not proportional to the number of magnets meaning that the magnetic field intensity does not increase linearly with the number of magnets. To determine the relationship between magnetic field intensity and terminal velocity, the magnetic field intensity changes with respect to the number of magnets will be examined in the following.

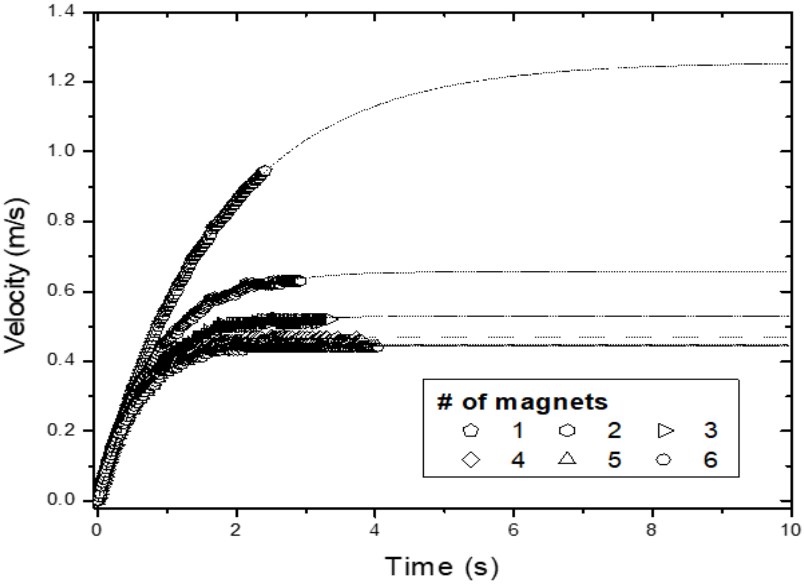

Fig. 8 The fitting result of the velocity data in Fig. 7

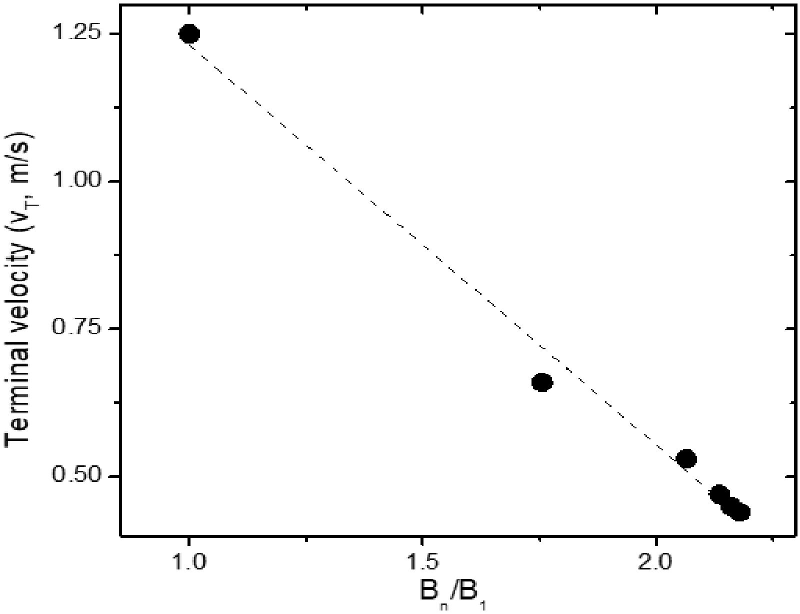

Fig. 9 The relation between the terminal velocity and the relative magnetic field intensity of the magnet attached cart

The relative magnetic field intensity B_r, which is defined as B_n/B_1 where B_1 and B_n are the magnetic field intensities of one magnet and n magnets, respectively, was obtained by measuring the magnetic forces between one and n magnets. Figure 8 shows the terminal velocity changes with respect to the relative magnetic field intensity. From the result, we can conclude that the terminal velocity decreases linearly with increasing relative magnetic field intensity.

DISCUSSION

The velocity dependence of the magnetic friction and the magnetic field dependence of the terminal velocity on the magnets moving on the inclined conductor plane were investigated by measuring the velocity changes of a cart with a number of magnets attached. The experimental setup minimizes a possible mechanical friction of a magnet moving on a surface by its attachment to a cart which itself shows only a negligible mechanical friction. The movement of the cart can therefore be regarded as the movement of a magnet on a conductor plane without an effective mechanical friction.

Under the condition of a fixed magnetic field, the velocity as a function of time can be described as $v(t) = v_T\left\{1 - \exp\left(-\frac{b}{m}t\right)\right\}$. The terminal velocity v_T was found to be proportional to sine value of the inclined angle of the conductor plane which implies that the magnetic friction is linearly proportional to the velocity of cart. The magnetic field dependence of the terminal velocity was investigated by measuring the velocity changes of the cart with various number of magnets and determining its relationship to the relative magnetic field intensity. The terminal velocity of constantly accelerated cart moving on the conductor plane decreased linearly with respect to the increasing relative magnetic field intensity.

REFERENCES

Fodor, Petru S, and Peppard, Tara. “Lenz’s law demonstration using an ultrasonic position sensor.” *Physics Teacher*, vol. 50, no. 6, 2012, pp. 344-346, https://doi.org/10.1119/1.4745685.

Ivanova, Dragia T. “Another way to demonstrate Lenz’s law.” *Physics Teacher*, vol. 38, no. 1, 2000, p. 48, https://doi.org/10.1119/1.880423

PASCO, “2.2 m Aluminum Dynamics Track.” https://www.pasco.com/products/lab-apparatus/mechanics/dynamics-systems/me-9779. Accessed 23 July 2020.

PASCO, “PASPORT Motion Sensor.” https://www.pasco.com/products/sensors/pasport/ps-2103. Accessed 23 July 2020.

Rossing, Thomas D. “Eddy currents and magnetic friction.” *Physics Teacher*, vol. 35, no. 3, 1997, p. 133, https://doi.org/10.1119/1.2344619.

Walker, J, Halliday, D, and Resnick, R. *Principles of Physics*. John Wiley & Sons, Inc., 2014.

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