“Magnetic damping”: Quantitative experiments with MBL sensors

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Abstract

We propose a sequence of experiments with the goal of exploring electromagnetic induction phenomena and “magnetic friction” forces. The experiments have been tested with high school students in the context of a program of cooperation between our Physics Department and the Regional School District. The experiments involve permanent magnets and conductors (a coil of wire or an aluminium plate) in relative motion. Motion and current-voltage online sensors allow real time measurements of position, velocity and induced voltage and provide graphs of these quantities vs time.

The role played by the intensity of the induced current in determining the damping of oscillations due to the “magnetic braking” is stressed. To this aim the coil is connected to an external circuit with a variable resistance and students can observe how the damping of the oscillations increases when the circuit resistance decreases and can relate the variation of the mechanical energy of the system to the production of thermal energy in the circuit.

1. Introduction

Electromagnetic induction is a significant subject in college and undergraduate physics courses and it is extremely difficult for most students [1]. Unlike mechanics, where many situations involve familiar macroscopic objects, more abstract concepts such as field and flux [2] are often discouraging for students. Moreover several studies have emphasized students’ conceptual troubles in understanding the role of magnetic field flux and its time variation [3-6] in experimental configurations.

Both demonstrations [7] and experiments [8-10] about electromagnetic induction have been designed to help students overcome their learning problems while some recent studies analyzed both from a theoretical and experimental point of view the magnetic braking[11-14].

In this paper we propose an experimental approach to the study of magnetic induction which starts from the observation of the magnetic braking force acting on a moving conductor (a coil of wire or an aluminium plate) as it passes between the poles of a permanent magnet. The behaviour of this complex system is modelled by means of a sequence of experiments aimed at:

- studying from a quantitative point of view the characteristics of the force acting on a metallic sheet entering and exiting from a region where a magnetic field is present;
- analyzing the role of ohmic resistance in establishing the strength of magnetic braking on a conductor moving in a magnetic field. For this purpose a simple experimental set up is used where the ohmic resistance of the conductor can be easily varied.

An interpretation of the experimental results is given from the energy point of view by comparing the transfer of mechanical energy in thermal energy through electrical resistive dissipation with the work done by a viscous like friction force. This approach allows students to understand how the magnetic braking depends on the value of the resistance in the circuit and to correlate the theoretical model to the experimental results.
The experiments were carried out by employing on-line sensors (Microcomputer Based Laboratory) to acquire data and to create graphs in real time. The activities are designed to create an environment where students gain experience of electromagnetic phenomena. Students can recognize how the variation of the flux of B field is the quantity always involved in these phenomena and for this reason it is the quantity used to describe and to interpret them.

2. The “magnetic friction force”

When a non-ferromagnetic metallic plate passes between the poles of a magnet, eddy currents are induced in the conductor as the plate enters and exits from the field (Figure 1, left). The action of the magnetic field on the induced currents produces a braking force. The problem posed to the students is: what kind of forces act on the conductor?

To explore this phenomenon students are invited to use an equipment which allows to quantify the force acting on the metallic sheet and to study its properties: the aluminium plate, mass $m$, is now pulled through the magnetic field by a falling mass $M$ as in a kind of Atwood machine (Figure 1, right).

![Figure 1 - Experimental apparatus to measure the strength of the “magnetic friction force”](image)

(Right) A metallic sheet of mass $m$, is connected by a string over a pulley to a falling mass $M$ and is pulled through a magnetic field. (Middle) A motion sensor on the floor gives the position as a function of time of the sheet moving through the magnetic field. (Right) The different phases during the motion: an accelerated motion when the sheet is completely inside (I) or completely outside (III) the magnetic field region, and a motion governed by the competitive effects of the tension force and the magnetic braking force when the sheet is partially outside (II).

Thanks to the measurements made with a motion sensor [15], graphs of position versus time are obtained (Figure 2). Three different phases (Figure 1.Right) can be recognized in the movement of the metallic sheet: an accelerated motion when the conductor is completely inside the magnet, a uniform motion with a drift velocity $v_d$ when the plate is partially inside, an accelerated motion when the sheet is completely outside. Thus students observe the
presence of a “braking force” only when the sheet is exiting from the magnetic field. When the motion of the sheet is uniform this force has the same value as the tension force,

\[ F_T = ma_T = \frac{M - m}{M + m}mg. \]

By changing M it is possible to study the relation between \( F_T \) and the drift velocity \( v_d \) reached by the sheet and measured by the motion sensor. Experimental data, reported in Figure 2 Right, show the linear dependence of \( v_d \) on \( F_T \). We can argue that a linear relation exists also between the magnetic friction force and the drift velocity, so we can characterize the magnetic damping as due to a *viscous* friction force, that can be expressed as:

\[ \vec{F}_{\text{Viscous Friction}} = -b \vec{v} = -m\beta \dot{v} \]

(1)

![Image](image_url)

**Figure 2** - (Left) Position versus time plot obtained with a motion sensor. The presence of a “friction force” which causes a uniform motion is observable when the sheet is exiting from the magnetic field. (Right) Experimental values of the drift velocity of the conductor obtained for increasing values of the driving force \( F_T \). Data are fitted by a linear relation according the rule \( v_d = F_T / (\beta m) \)

3. **The role of the ohmic resistance**

To explore the energy transfer connected with the action of the magnetic braking force a different experimental apparatus is proposed. A metallic plate oscillates in the magnetic field produced by two permanent magnets. Students observe the strong damping of this *eddy current pendulum*, also known as *Waltenhofen’s Pendulum*, and are requested to explain why does the mechanical energy decrease.

The role played by the intensity of the induced current in determining the damping of the pendulum is studied by substituting the aluminium plate with a coil oscillating in the magnetic field and connected to an external circuit whose resistance can be varied (see Figure 3, Middle). Motion and current/voltage sensors allow measure the amplitudes of the oscillations, the velocity of the *coil pendulum*, the electromotive force and the current induced in the coil. Graphs of position vs time are obtained in real time (Figure 3, Right).
Figure 3 - Experimental set up (Left) and its schematic representation (Middle). (Right) Graphs of position versus time for different values of the shunt resistance.

The role played by the resistance of the circuit (and then by the intensity of the induced current) in determining the damping of the oscillations of the coil pendulum, due to the magnetic friction force, is stressed. Students observe how the damping of the oscillations increases when the circuit resistance decreases. This is for most of the students an unexpected result.

If the students have already studied the motion of a harmonic oscillator damped by viscous friction forces it is possible to extend the analysis and find a relation between the viscous friction coefficient $\beta$ and the shunt resistance $R$.

According to the theory, the angular position versus time of a pendulum, damped by a viscous friction force, is described by the equation

$$\vartheta(t) = \vartheta_0 \exp\left[-\frac{\beta t}{\omega_0^2}ight] \cos(\omega t)$$

where

$$\omega = \sqrt{\omega_0^2 - \frac{\gamma^2}{4}}$$

and $\omega_0$ is the frequency of the un-damped oscillator. It follows that, in the hypotheses of small oscillation amplitude and friction force proportional to the velocity, the relation between the amplitude and the number $n$, of the accomplished oscillations is

$$\vartheta_n = \vartheta_0 \exp\left[-\lambda n\right] \quad \text{where} \quad \lambda = \frac{\beta}{\omega} \pi = \frac{\beta}{2} T.$$

By using the graphs reported in Figure 3 students can find, for each value of the resistance, the amplitude of the oscillations at different time values and plot $\vartheta_n$ versus $n$, (Figure 4, Left).

The data are fitted by exponential curves and the damping factor $\lambda$ is obtained for the three value of the resistance, $R=1 \ \Omega$, $R=2 \ \Omega$, $R=\infty$ (open circuit).
The amplitudes of the oscillations of the magnet are reported as function of the number $n$ of the accomplished oscillations for different values of the resistance $R$ of the circuit (Left). Experimental values of the viscous friction coefficient are reported for different values of the resistance $R$. The data fit with the relation in eq.(2) (Right).

The plot in Fig. 4.Right shows how the experimental values fit with a relation

$$\beta = \beta_0 + \frac{\kappa_0}{R},$$

(2)

where $\kappa_0$ is a constant while $\beta_0$ includes the contribution to the damping of air resistance, sliding friction at the pivot etc. In this way students verify that the damping of the oscillations and the coefficient $\beta$ increase when the circuit resistance decreases.

4. The energy point of view

The energy point of view can be used not only to give a qualitative interpretation of the experimental results (the loss of the mechanical energy of the conductor can be explained with the increase of the internal energy of the circuit, where a resistive thermal conversion takes place), but also to derive a quantitative explanation. In particular, the theoretical relation between the resistance $R$ and the magnetic friction coefficient $\beta$ can be obtained and compared with the experimental results. At this aim we consider a simple system constituted by a wire loop which enters with velocity $v$ into a region where a uniform magnetic field is present (Figure 5).
Figure 5 - Schematic plot of a wire loop which enters in a uniform magnetic field with starting speed $v$. When the coil moves fully outside or fully inside the region where the magnetic field is present no current flows in the wire. When the coil is just partially inside the region with magnetic field, the magnetic flux changes and the induced emf produces a current flowing in the wire.

The wire has a mechanical energy proportional to $v^2$. When the magnetic flux through the surface bounded by the wire loop changes an electromotive force (emf) is produced along the closed path of the wire. Since the emf is proportional to the rate of change of the magnetic flux, according to the laws of the electromagnetic induction,

$$\text{emf} = -\frac{d\Phi(B,t)}{dt} = -BL \frac{dy}{dt} = BLv,$$

where $L$ is the length of the wire side perpendicular to $v$. In the closed circuit with resistance $R$ a current flows and an increase of the internal energy of the wire loop takes place at rate $P_j = I^2R = \frac{\text{emf}^2}{R}$, corresponding to the power dissipated by the circuit. As a consequence the mechanical energy is reduced at the same rate:

$$P_j = \frac{\text{emf}^2}{R} = \frac{1}{R} \left( \frac{d\Phi(B)}{dt} \right)^2 = \frac{1}{R} \left( BL \frac{dy}{dt} \right)^2 = \frac{B^2L^2}{R} v^2.$$

This corresponds to the work performed during a second by a force $\vec{F}_{\text{emf}} = -M \beta \vec{v}$ with

$$\beta = \frac{B^2L^2}{MR}.$$

In this way the phenomenological law expressed by equation (1) is obtained, together with the theoretical dependence of the viscous friction coefficient on the resistance. The experimental
results reported in Figure 4 and eq.(2), agree with the theoretical prediction given by equation (5).

5. **Using the experiments with students**

The experiments have been tested with high school students and with student teachers in a postgraduate course for physics teacher education. The students carried out the experimental activities in groups of four and the activity sequence was developed according to the phases reported in Fig.6. Asking questions and stimulating a discussion before and after each experiment encouraged the students to think critically and to maintain a high level of interest.

**Figure 6** - The students carried out the experimental activities in groups of four and completed the experimental work in a session of three-four hours. One or two assistants (generally master students) worked as facilitators. The organization of the activities: students spent a large portion of their laboratory time observing, interpreting and discussing the experimental results with their peers.

Data collected during students’ activity show a progression of students’ ideas during the development of the sequence:

- The design of the experiment on the Atwood machine gave the students the possibility of easily distinguishing the three phases of the motion and perceiving when the magnetic force was active.
- Students recognized that the magnetic force has the same dependence on the velocity as a viscous friction force.
- The evidence of braking forces in the experiments revealed to be a strong motivation for students to investigate carefully and in a quantitative way the effects of electromagnetic induction.

By discussing students’ interpretations during and after the activity sequence we found that:

- The majority of the students evoked generically Lenz’s law by referring only to the magnetic field (without considering the induced currents). This way of using Lenz’s law might cause a misleading interpretation of the magnetic force. Students who think that field lines are real lines which can interact with each other often consider the force
as produced by the interaction between two magnetic fields, the induced one and the one generated by the permanent magnets.[16]

- Some students identified the induced emf with the braking force, by interpreting the electromotive force as a real force.
- Other students (a minority) tried to give a description of the braking magnetic force only by using Lorentz’ force. They attributed to the Lorentz’ force the character of damping force, thus arriving to the paradoxical consequence of attributing to this force the possibility of doing work, neglecting the role of the electrical resistance.[17,18]
- Based on the well known relation $W = \vec{F} \cdot \vec{R}$, many students were initially convinced that the damping of the oscillations would increase with the resistance. They spontaneously did not recognize that the variation of the resistance produced a variation of the current and that this variation strongly affected the resistive dissipation. Discussion after the experiment allowed the majority of the students to reflect on this point and on the meaning of the relation $W = \vec{F} \cdot \vec{R}$.

We interviewed many of the students who participated in the laboratory activities asking them an evaluation of their experience. They especially emphasized as positive the opportunity of setting up by themselves the experimental apparatuses, doing the measurements and proposing alternative experiments. Students appreciated that the study of the magnetic force was based on the investigation of physical phenomena rather than on the manipulation of abstract formulas in a textbook. Some of them also remarked “These physical phenomena are quite impressive in fact we were always surprised about what really happened”.

Some students observed how a good experimental analysis requires many concepts usually learned in different moments of the scholar instruction. One student wrote “the experiment is quite simple to be realized, because we used very common materials (magnets, coils, metallic sheets,…) but it is very hard to be understood. It was the most complex experience of our physics course”. One other noted “The explanation of the physical phenomena was quite difficult and we discussed several different proposals to explain what happened”.

References

[1] DarrenWong, Paul Lee and See Kit Foong A datalogger demonstration of electromagnetic induction with a falling, oscillating and swinging magnet PHYSICS EDUCATION 45, 394 2010