Experiments with eddy currents: the eddy current brake

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Abstract
A moderate-cost experimental setup is presented to help students to understand some qualitative and quantitative aspects of eddy currents. The setup operates like an eddy current brake, a device commonly used in heavy vehicles to dissipate kinetic energy by generating eddy currents. A set of simple experiments is proposed to measure eddy current losses and to relate them to various relevant parameters. Typical results for each of the experiments are presented, and comparisons with theoretical predictions are included. The experiments, which are devoted to first-year undergraduate students, deal also with other pedagogically relevant topics in electricity and magnetism, such as basic laws, electrical measurement techniques, the sources of the magnetic field and others.

1. Introduction

Eddy currents are one of the most outstanding of electromagnetic induction phenomena. They appear in many technical problems and in a variety of everyday life situations. Sometimes they are undesirable because of their dissipative nature (e.g. transformer cores, metallic parts of generators and motors etc). In many other cases, however, eddy currents are valuable [1] (metal detectors, coin recognition systems in vending machines, electricity meters, induction ovens, etc).

However, little attention is paid to eddy currents in many of the textbooks commonly used in introductory physics courses [1–3]: they are often dealt with only from a phenomenological point of view, and they are considered in some cases only as a topic for optional reading [1, 3]. Furthermore, most of the commercially available experimental setups concerning eddy currents treat only their qualitative aspects.

This paper presents a set of laboratory experiments intended to help students better understand the phenomenon from a quantitative point of view. The experiments may be helpful to physics and electromagnetism students in first-year undergraduate courses.
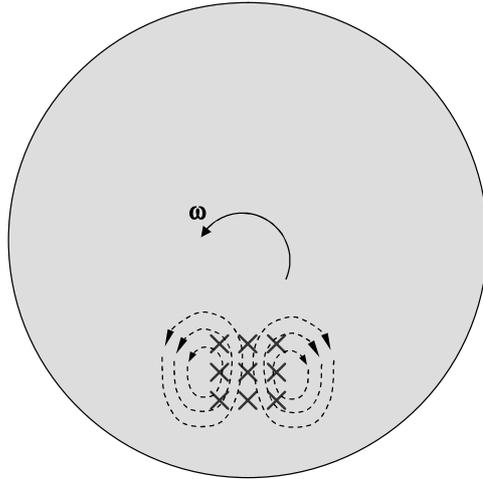
Figure 1. A sketch of the eddy currents in a rotating disc. The crosses represent a steady magnetic field perpendicular to the plane of the disc. According to Faraday's law, eddy currents appear in those points of the disc where the magnetic field increases or decreases.

2. Theoretical foundation

Induced currents appear when electrical conductors undergo conditions of variable magnetic flux. In particular, we talk about eddy currents when bulk conductor pieces instead of wires are involved. There are two basic procedures to achieve such conditions:

- exerting a time-varying magnetic field on a static piece;
- exerting a steady magnetic field on a moving one.

An example of the latter class will be investigated. It consists of a rotating metallic disc, which is subjected to the magnetic field present at the gap of an electromagnet. Eddy currents appear inside the disc and brake its rotation. This is the foundation of the electromagnetic braking systems used by heavy vehicles such as trains, buses or lorries [2].

Even in such a geometrically simple case, the pattern of eddy currents is complex. Figure 1 and [3] show simplified sketches of this pattern. It is easy, however, to obtain an approximate expression for the power dissipated by eddy currents. Since the magnetic field B is steady, the induced electric field in each point of the disc is given by $E = v \times B$, where v is the velocity of that point [4]. Instead of measuring B directly, we will relate it to the excitation current I_{ex} in the coil of the electromagnet, which is easily measurable. For the moment we will assume that B is proportional to I_{ex} (the validity of this hypothesis, which is not true for magnetic media, will be discussed later). Then the following proportionality law holds:

$$E \propto \omega I_{ex}$$

where ω is the angular speed of the disc. This means that for any loop of eddy current the induced electromotive force, being the line integral of the induced field, is also proportional to ωI_{ex}. Finally, the basic laws of electric current state that the power dissipated in that particular loop is proportional to the square of the electromotive force and to the inverse of the electrical resistivity of the disc. The same holds for the power dissipated in the whole disc:

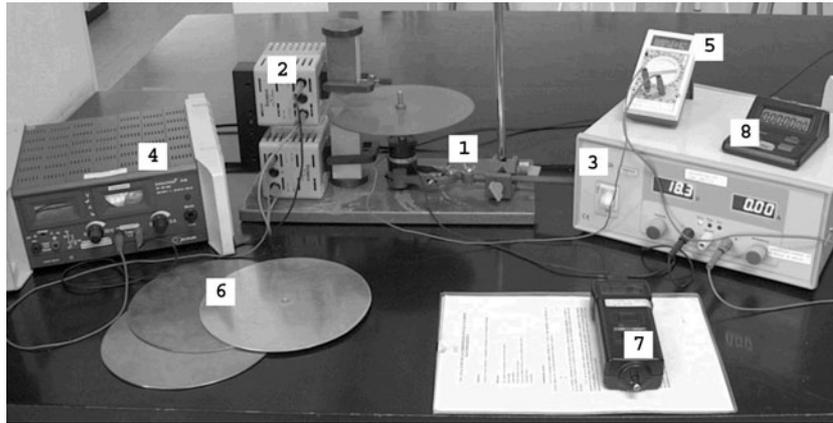$$P_e = K \frac{\omega^2 I_{ex}^2}{\rho} \tag{1}$$

Figure 2. The whole experimental setup. 1: dc motor with one of the discs attached to it. 2: Electromagnet. 3: dc power source for the motor with built-in voltmeter. 4: dc power source for the coil with built-in ammeter. 5: Ammeter for the motor. 6: Discs of other materials. 7: Optical tachometer. 8: Stopwatch (photograph courtesy F Herrera).

where 'e' stands for 'eddy'. The proportionality constant K depends mainly on geometric parameters of the disc and cannot be obtained by analytical procedures. Nevertheless, the functional dependence of P_e on ω, I_{ex} and ρ shown in (1) is itself important, and will be tested in this work.

3. The experimental setup

Figure 2 is a photograph of the proposed setup. A list of all necessary elements follows:

- a 24 V, 3 W dc motor. Its angular speed is 230 rpm at 24 V when unloaded;
- electromagnet with iron core and a coil with 500 turns. The width of its gap can be adjusted;
- a variable 0–24 V dc power source for the motor;
- a variable 0–5 A dc power source for the coil;
- ammeters and voltmeters;
- four geometrically identical (200 mm diameter and 2 mm thick) discs made of copper, steel, brass and aluminium to be attached to the motor axis;
- optical tachometer to accurately measure the angular speed of the motor;
- electronic stopwatch.

Many changes in this list are possible. For instance, any of the dc variable power sources can be replaced by a fixed source combined with a rheostat, the angular speed can be measured by stroboscopic techniques, etc.

4. Experimental procedure. Results and discussion

This section describes several kinds of measurements that can be carried out with the proposed experimental setup. In all cases typical results are included.

4.1. Braking time of the disc

First of all, the time necessary for the disc to completely stop from a fixed initial angular speed when the motor is turned off can be measured as a function of the excitation intensity. We
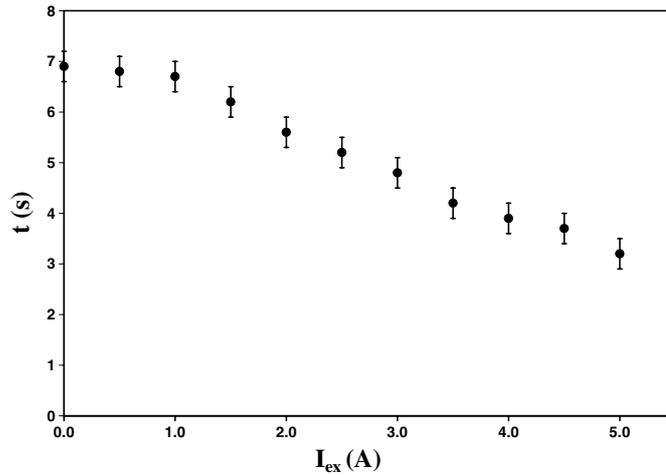
Figure 3. Braking time for the copper disc versus excitation intensity. The initial speed of the disc was set to 200 rpm.

must keep in mind that the larger the excitation intensity is selected, the larger the voltage applied to the motor must be to achieve that initial speed.

Figure 3 shows how larger excitation intensities make the braking time shorter as a result of more powerful eddy currents. Error bars have been set to 0.3 s, a typical uncertainty when using stopwatches.

Equation (1) implies that the eddy current braking torque is proportional to the instantaneous angular speed. However, the results plotted in figure 3 are not suitable for verifying this fact, due to the lack of a known model for the internal braking torque acting on the motor. Therefore, the result of this first experiment cannot be numerically tested.

4.2. Eddy current losses versus angular velocity

To test the proportionality between P_e and ω^2 shown by equation (1) a fixed excitation intensity I_{ex} must be chosen. Then the voltage supplied by the power source of the motor must be varied in order to select various angular speeds. For any chosen speed ω of the disc the power consumption of the motor $P_m(I_{ex}, \omega)$ can be calculated as the product of its voltage and intensity. The power consumption $P_m(0, \omega)$ when the electromagnet is turned off must be computed in the same way. Then the power dissipated only by eddy currents is simply:

$$P_e(\omega) = P_m(I_{ex}, \omega) - P_m(0, \omega) \qquad (I_{ex} \text{ fixed}). \qquad (2)$$

Results are plotted in figure 4. Standard error analysis techniques have been used to calculate error bars, assuming uncertainties of 0.2 V for voltages, and 1 mA for intensities. As we can see, the constancy of $P_e(\omega)/\omega^2$ within our experimental uncertainties is consistent with equation (1).

4.3. Eddy current losses versus excitation intensity

Equation (1) states that P_e is proportional to the square of the excitation intensity in the coil. To verify this result a fixed angular speed ω must be chosen. Then the power consumption of the motor for various excitation intensities as well as for $I_{ex} = 0$ must be measured. The eddy current losses are calculated in the same way as given by (2)

$$P_e(I_{ex}) = P_m(I_{ex}, \omega) - P_m(0, \omega) \qquad (\omega \text{ fixed}). \qquad (3)$$
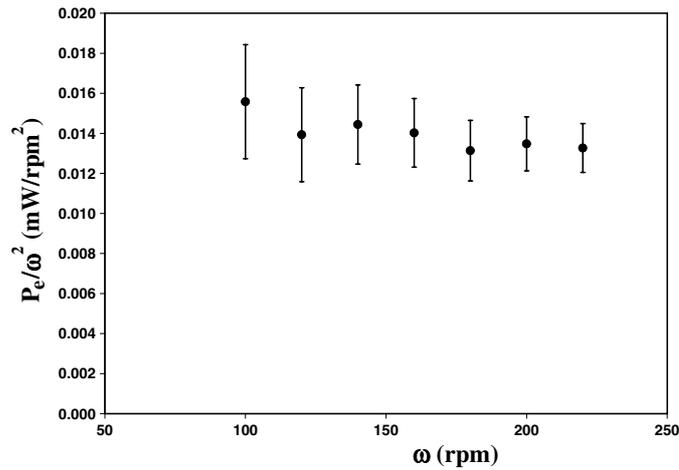
Figure 4. An example to test the proportionality between P_e in the copper disc and ω^2. The excitation intensity was fixed to 3.0 A.
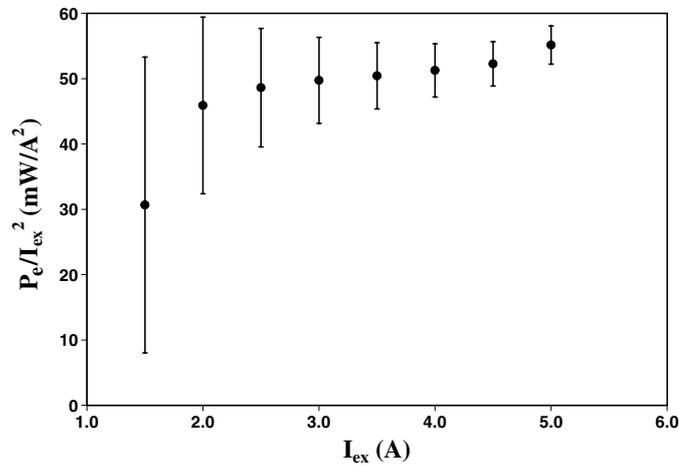

Figure 5. An example to test the proportionality between P_e in the copper disc and I_{ex}^2. The angular speed was fixed to 200 rpm.

Figure 5 shows a set of typical results. It appears that the proportionality between P_e and I_{ex}^2 does not hold, especially at low intensities. Nevertheless, we must recall that the core of the electromagnet is made of iron, i.e. a nonlinear medium, while equation (1) was obtained under the assumption of proportionality between B and I_{ex}. In fact, it would be interesting to use a coil alone as a truly linear source of magnetic field. Unfortunately, the absence of a ferromagnetic core results in low magnetic fields and therefore P_e becomes too low to be measured with conventional ammeters and voltmeters.

4.4. The influence of disc resistivity

Finally the inverse proportionality between P_e and ρ expressed by equation (1) can be tested. To carry out such a test, both rotation speed and excitation intensity must be fixed, and the power consumed by the motor with each of the discs attached to it must be calculated. P_e is

Table 1. A test of the inverse proportionality between P_e and disc resistivity ρ. The angular speed and the excitation intensity were fixed to 200 rpm and 3.0 A, respectively.

Disc	ρ ($\mu\Omega$ cm)	P (mW)	P_e (mW)	ρP_e
(no disc)	–	170	–	–
Aluminium	3.4	530	360	1200
Copper	1.7	770	600	1000
Brass	6.4	390	220	1400
Steel	72	280	110	7900

estimated by subtracting from this power the power consumption of the motor alone turning at the same angular speed (better, a non-conducting disc equal in size to the conducting ones should have been used, but the difference is negligible). Table 1 shows the results.

The constancy of the products ρP_e must be cautiously analysed. Tabulated resistivities were extracted from a general reference [5], and exact coincidence with those of the sample discs cannot be guaranteed, especially in the case of alloys. As we can see, results for aluminium, copper and brass show a reasonable agreement with equation (1). The case of steel, however, is clearly anomalous because of its ferromagnetic behaviour. The time variation of the magnetic field applied on every point of the disc results in hysteresis loops creating an additional braking effect superimposed to eddy current torque (see, for example, [6]). This is probably the main reason for the high total losses observed in steel.

5. Conclusions

As we have seen, our experimental setup allows students to investigate one of the most outstanding aspects of eddy currents, namely their dissipated power. Simple tests to measure P_e and to study its functional dependence on the velocity, the sources of the magnetic field and the sample resistivities have been carried out. The results show a reasonable but not indisputable agreement with theoretical predictions. Nevertheless the author believes that the experiments deal with concepts, instruments and measurement techniques with high didactic value for the students, regardless of whether the agreement between theory and experiments is good or poor.

Acknowledgments

References

[1] Serway R and Beichner R 2000 *Physics for Scientists and Engineers with Modern Pysics* 5th edn (Fort Worth: Saunders) pp 997–9
[2] Tipler P 1999 *Physics for Scientists and Engineers* 4th edn (New York: Freeman) pp 938–9
[3] Sears F W, Zemansky M W, Young H D and Freedman R A 1999 *Física Universitaria, Novena Edición* vol 2 (México: Addison-Wesley) pp 957–8
[4] Marshall S V and Skitek G G 1990 *Electromagnetic Concepts and Applications* 3rd edn (Englewood Cliffs, NJ: Prentice-Hall) pp 298–9
[5] Lide D R (ed) 2000 *CRC Handbook of Chemistry and Physics on CD-ROM* 80th edn (London/Boca Raton, FL: Chapman and Hall/CRC press)
[6] El-Hawary M E 2000 *Electrical Energy Systems* (Boca Raton, FL: CRC Press) pp 36–40