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Experimental confirmation of Lenz's law

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Abstract

The paper presents a series of experiments that demonstrate the phenomenon of electromagnetic induction. These make it possible to determine the direction of the induced current and so confirm Lenz's Law. The simple experiments can be reproduced in a school laboratory and can be recommended for students' project activity.

1. Introduction

In our previous paper [1] we describe a simple Faraday electromagnetic generator and a series of experiments demonstrating the principles of electricity generation and the conservation of electricity to other forms of energy with practical application. But that paper did not discuss Lenz's law. Now we want to show that this law can be demonstrated and investigated using the Faraday generator.

In a well-known experiment, a cylindrical neodymium magnet falls freely inside a copper or aluminum tube. This experiment is often demonstrated when studying electromagnetic induction and Lenz's law. The result of this experiment impresses those who see it for the first time. Many authors advise using the braking of a magnet falling inside a conductive tube when teaching for the investigation of the phenomenon of electromagnetic induction theoretically, experimentally and numerically [2–8]. Hare and Jones study the phenomenon of electromagnetic induction qualitatively using a coil and a permanent magnet [9, 10]. Nicklin [11] tests Faraday's law in an educational laboratory quantitatively. He uses a cylindrical rod magnet falling through a coil. A voltage pulse appears, when the rod magnet moves along the axis of a circular coil at a constant speed. Manzanares, Bisquert, Garcia-Belmonte, Fernandez-Alonco [12], Nunn [13] and Najiya Maryam [14] investigate the voltage pulse theoretically and experimentally. Kingman, Rowland, Popescu [15], Bonanno, Bozzo, Camarca and Sapia [16] study the induced voltage with a computer oscilloscope and demonstrate a close agreement between the predicted results and the observed ones. Liu Tao, Wu Xiufang and Liu Yi [17] advise using LEDs to demonstrate Lenz's law. Kraftmakher describes a computer demonstration of Lenz's law [18].

The paper by Wood, Rottmann and Barrera [19] comes closest to our paper. The authors investigate the accelerated motion of a magnet through a coil. The position of the magnet and the induced electromotive force in the coil are measured as functions of time. When the coil is closed with a load resistor, an induced current appears. This current creates a magnetic field, and the field reduces the acceleration of the magnet. The experiment allows you to observe the effects that Lenz's law explains.

Lenz's law is formulated as follows: an induced current flows always in such a direction as to oppose the change which causes it. In this paper we describe a series of simple qualitative experiments which can be used in teaching to show the following ideas: (1) a current appears in a closed conducting circuit when the magnetic

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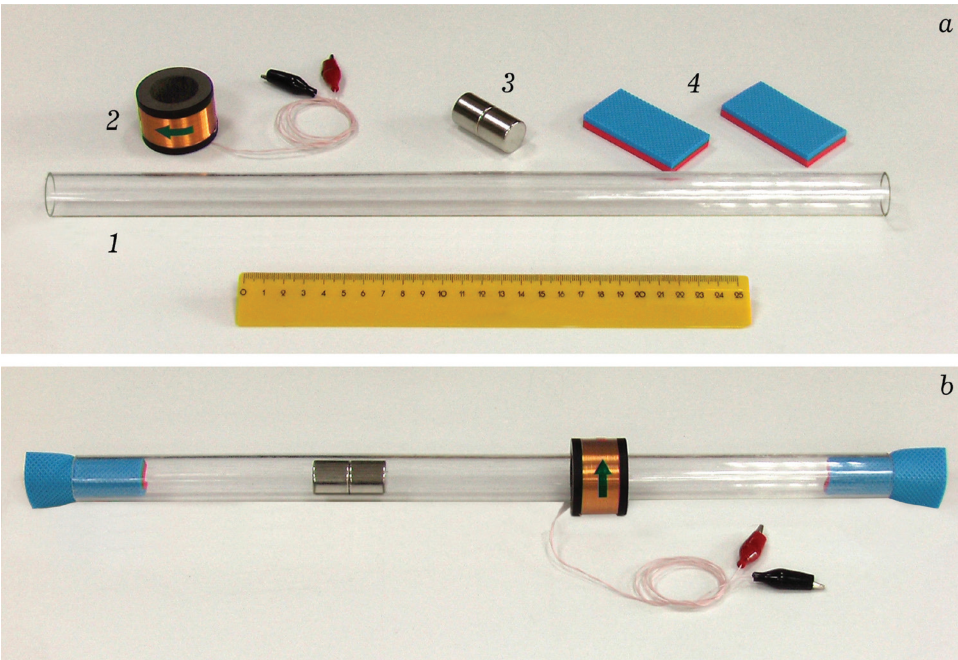

Figure 1. A big Faraday's electromagnetic generator: (a) details of the apparatus; (b) the assembled apparatus.

flux through the circuit is changing, this process is called electromagnetic induction; (2) the magnitude of the induced current depends on the rate of change of the magnetic flux through the circuit; (3) the magnetic field of the induced current opposes the change inducing that current.

2. Devices for students' experiments on electromagnetic induction

Several simple devices are necessary to perform the experiments described below. The devices can be reproduced in an educational laboratory and can be recommended for students' project activity.

2.1. A Faraday's electromagnetic generator

A simple Faraday generator is described in our article [1]. This apparatus is made of a plastic tube with an inner diameter of 22 mm and 240 mm long. Let us call this generator as *small*. It is shown below in figure 7. The generator allows you to perform all experiments described in this paper.

But the possibilities of the experiment increase if we make the transparent tube of the generator longer. Details of a *big* generator are shown in figure 1(a). You will need: 1—a glass or plastic tube with an inner diameter of 22 mm, a wall thickness of 2 mm and 450 mm long; 2—a coil containing approximately 1000 turns of copper wire 0.35 mm in diameter in varnish insulation (an inner diameter of the coil is 27 mm, and a height is 20 mm); 3—two neodymium magnets each with a diameter of 20 mm and 20 mm long; 4—soft plates of polyethylene foam for making plugs. The resistance of the coil wire of the device is approximately 25 Ohm. The direction of winding is shown by an arrow marked on the coil. A conductor with a red alligator clip is connected to the beginning of the coil wire. A conductor with a black alligator clip is connected to the end of the coil wire. The north and south poles of the neodymium magnet are indicated by the red and blue marks. The assembled big Faraday's generator is shown in figure 1(b).

2.2. The indicator of the polarity of EMF of a source

The apparatus consists of green and red LEDs. The LEDs are fixed on a cardboard plate and are connected antiparallel. A resistance of 22 Ohm is connected to the LEDs in series. Figure 2 shows

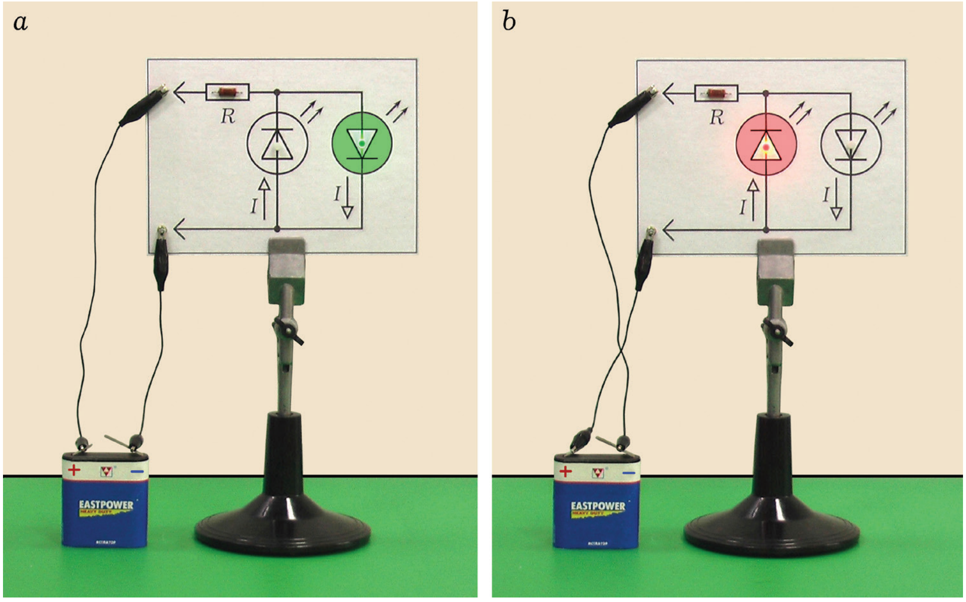

Figure 2. The indicator of polarity of EMF: (a) the green LED lights; (b) the polarity of the connection of the source to the LED indicator is changed, and the red LED lights.

how the indicator allows you to determine the polarity of an EMF source. A 4.5 V battery is used as the source.

2.3. The indicator of direction of an electric current

The direction of an electric current flowing through the coil of the Faraday's generator can be determined with the indicator of EMF described above. But a lighted LED has a big resistance and substantially limits a current flowing through the coil. Therefore to determine a direction of a current through the coil, it is better to make a special apparatus with a small input resistance. A schematic circuit of the current indicator is given in figure 3. The input resistance of the apparatus is determined by the resistor $R1$ and is not more than 2 Ohm. The resistor voltage is amplified by an operational amplifier $DA1$, and the green or red LED lights up. The choice of the LED depends on the direction of the current through the resistor $R1$. Resistances $R5$ and $R6$ are selected so that the brightness of the red LED and the brightness of the green LED are perceived to be equal. In figure 3 LED $HL1$ is marked by a colour. This LED lights if the current I flowing through resistor $R1$ has a direction marked by the arrow. If the current is directed oppositely, then the other LED lights.

If assembled correctly, then the apparatus does not need any additional adjustment. To power the apparatus it is convenient to use two 9 V batteries. The amplifier plays a secondary role in the indicator. Therefore it is better to fasten the LEDs $HL1$, $HL2$ on the front face of the apparatus and to draw two arrows corresponding to the directions of the current I (figure 7). The panel can be made of cardboard. The amplifier together with the power supply is fixed on the back side of the panel.

3. Demonstration experiments

It is necessary to teach students to identify the conditions of each experiment clearly, observe the phenomena attentively and explain these phenomena using electrodynamics laws correctly.

3.1. Experiment 1. An induced current

The coil is fixed in the middle of the glass tube with the help of a rubber strip. A soft damper is inserted into the lower end of the tube. The upper end of the Faraday electromagnetic generator is fixed with the help of a support so that the generator is in a leaning position. The coil terminals are connected to an incandescent lamp (2.5 or 3.5 V). A neodymium magnet is introduced into the open

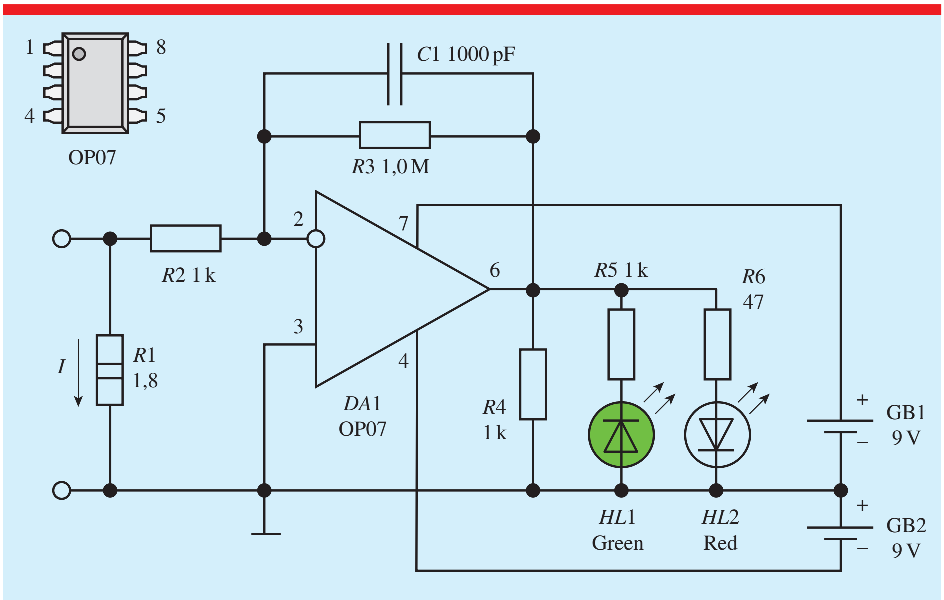

Figure 3. The indicator of direction of an electric current.

hole of the tube and released. When the magnet goes through the coil, the lamp lights (figure 4). When a magnetic flux changes, a vortex electric field arises. The field induces an electromotive force in the coil. The electromotive force produces an induced current in the closed circuit.

3.2. Experiment 2. The polarity of the induced EMF

The generator coil is fixed near the lower end of the tube and the coil terminals are connected to the *indicator of induced EMF* (figure 5(a)). The magnet is inserted into the tube with its south pole and released. When the magnet reaches the coil, its magnetic induction is directed upwards and the magnetic induction increases inside the coil. At the same time, the indicator shows that the potential of the winding start is higher than the potential of the end. Consequently, the induced current flows through the coil from the end of the winding to its start. This corresponds to the Faraday's law of electromagnetic induction:

$$\mathcal{E} = -\frac{\mathrm{d}\Phi}{\mathrm{d}t}.$$

The minus is determined by Lenz's law. Next, the tube is turned so that the magnet slides back to the open end of the tube. The direction of the induced current is reversed.

In the second part of the experiment, the coil is fixed in the middle of the tube. Now the students see that one LED lights up when the magnet gets into the coil (figure 5(b)), and the other LED lights up when the magnet comes out the coil (figure 5(c)). If the tube is rotated so that the magnet moves through it in the opposite direction, the sequence of flashes remains the same. However, if the tube and coil are in their original positions but the poles of the moving magnet are reversed, then the LED sequence is reversed.

The glow of the incandescent lamp and LEDs shows that an induced current caused by the movement of a magnet through a coil has energy. According to the law of conservation of energy, when an induced current arises, the energy of the mechanical motion of the magnet must decrease. That is possible if the magnetic field of the arising induced current counteracts a cause of this current. Thus, it is necessary to verify the following hypothesis: the induced current counteracts the motion of the magnet through the coil.

3.3. Experiment 3. An induced current counteracts a cause of this current

In the conditions of the previous experiment, the terminals of the Faraday generator coil are open. A neodymium magnet is introduced into the upper hole of the generator tube and released.

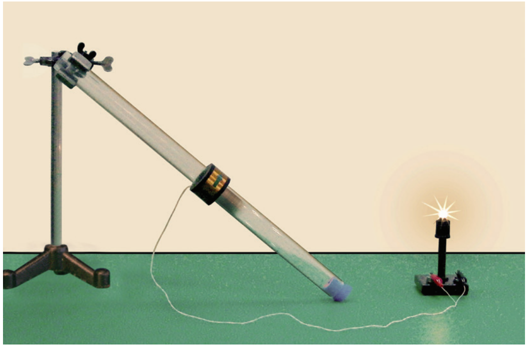

Figure 4. A demonstration of an induced current with the help of a lamp.

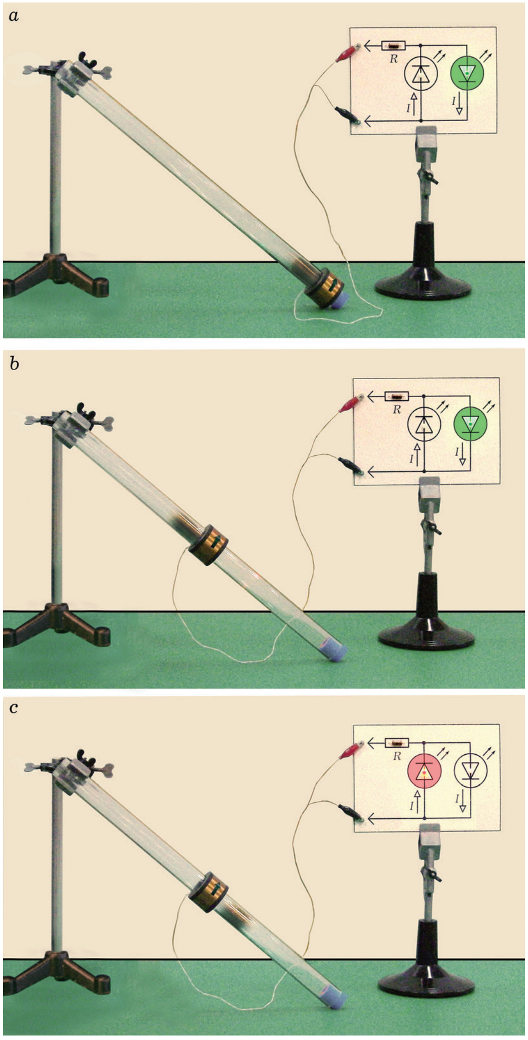

Figure 5. An investigation of EMF of induction: (a) a magnet comes into the coil; ((b), (c)) the magnet passes through the coil.

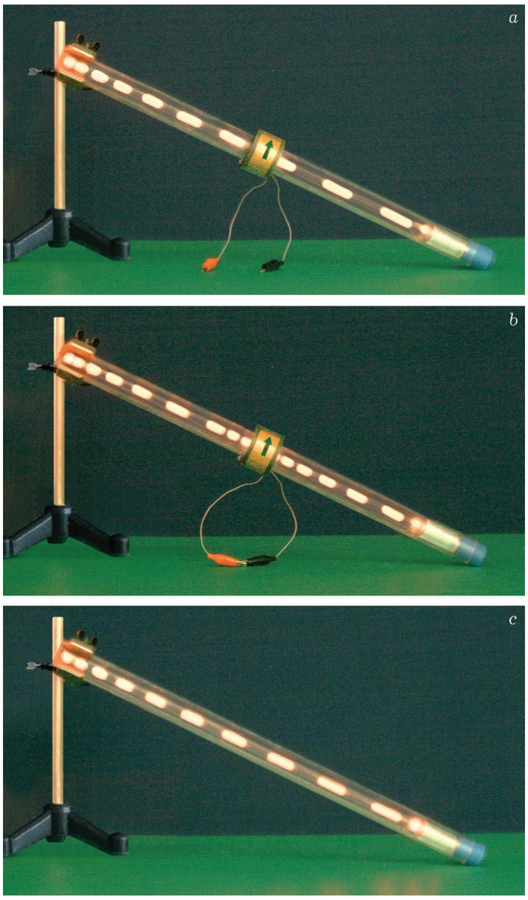

Figure 6. Stroboscopic photographs of the moving magnet: (a) the coil terminals are open; (b) the coil terminals are closed; (c) the coil is removed.

It is observed that in this case the magnet moves inside the tube from its upper end to the lower end without deceleration (figure 6(a)). The coil terminals are short-circuited and the experiment is repeated. In this case, the magnet moves substantially slowly when it approaches the coil and leaves the coil (figure 6(b)). If we have removed the coil altogether (figure 6(c)), then the magnet moves as it does in the conditions of the open coil terminals (figure 6(a)). To photograph the movements described, we fix a small LED on a pole of the neodymium magnet. The LED is connected to a generator of rectangular pulses with a frequency of 20 Hz with thin flexible wires.

This and previous experiments allow us to suppose that (1) an induced current arises in the coil when the magnetic flux through the coil changes, and (2) the magnetic field of the induced current

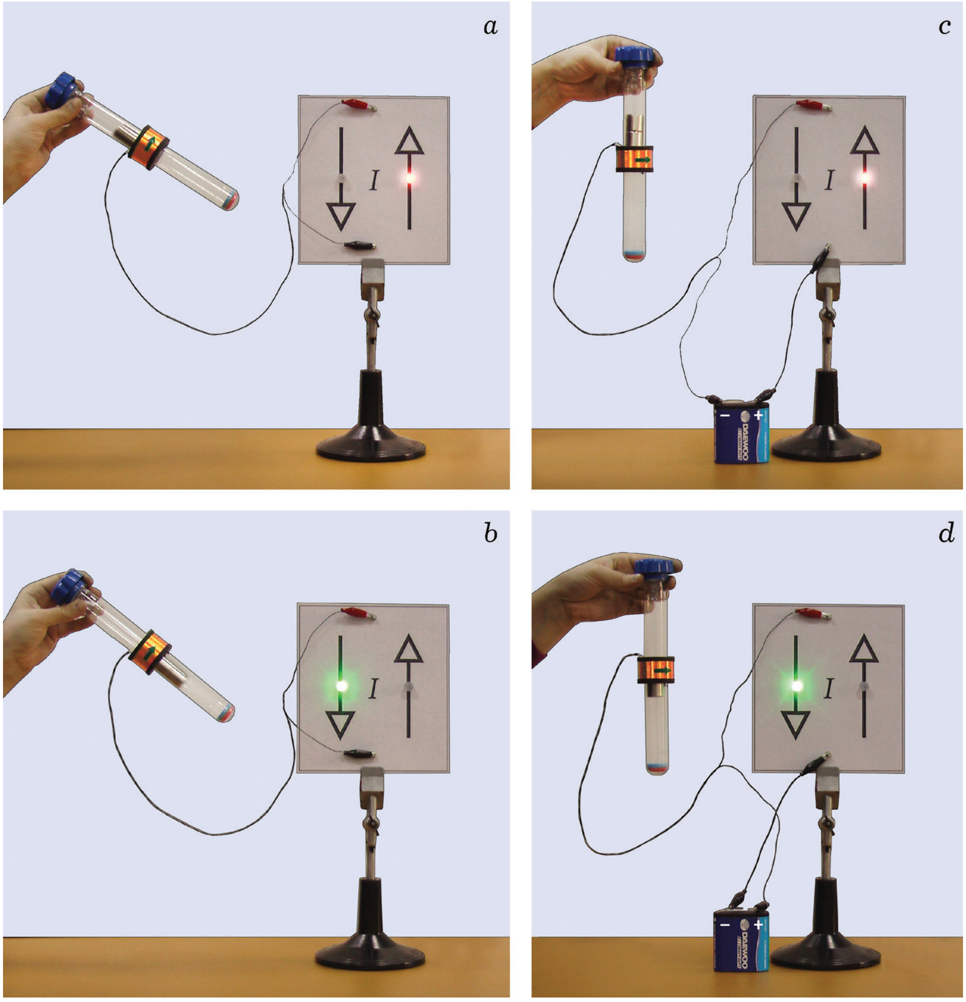

Figure 7. A demonstration of Lenz's law: (a) as the magnet enters the coil, the induced current lights the right LED; (b) as the magnet leaves the coil, the induced current lights the left LED; (c) if a current, flowing from an external source, lights the right LED, then the current repels the magnet; (d) if a current, flowing from an external source, lights the left LED, then the current attracts the magnet.

opposes the movement of the magnet. These suppositions need experimental verification.

3.4. Experiment 4. The direction of the magnetic field of an induced current

The current direction indicator (figure 3) is connected to the coil of the small Faraday generator (figure 7). The apparatus is inclined so that the magnet slides slowly inside the tube. Students confidently observe that when the magnet approaches the coil, the magnet is decelerated, and, for example, the red LED lights up (figure 7(a)). When the magnet emerges from the coil, the magnet is again decelerated, and the green LED lights up (figure 7(b)). Consequently, braking of the moving magnet that caused the induced current is related with the direction of the induced current in the coil. We know the direction of the induced current thank to LEDs, and we know the winding direction of the coil. It allows us to find a direction of the magnetic field of the coil and make sure that this field is directed opposite to the change in the field of the moving magnet that caused this current.

3.5. Experiment 5. Interaction of a permanent magnet and a coil with a current

It is possible to eliminate all doubts about the correctness of the theory of electromagnetic induction if we show that the current flowing in the coil from an external source acts on the magnet exactly as an induced current. For example, when the magnet approaches the coil and decelerates, a red LED lights up (figure 7(a), in this figure, photos of a small Faraday generator are shown for convenience). Then we connect the external source so that the current flows through the coil in the same direction. Such current is also indicated by the red LED. In this case, the current with the same direction as the induced current really repels the magnet from the coil (figure 7(c))! Now we change the current direction (figure 7(d)). Such current does not release the magnet from the coil. It is clear that an induced current cannot stop the magnet, opposing to the experiment with an external source, since a magnet does not excite any induced current if it is fixed relative to the coil.

3.6. Experiment 6. The principle of relativity in electrodynamics

The magnet is fixed in the middle of the tube of the help of two strips of foamed polyethylene. The coil is released so that it can slide freely on the tube. Experiment 3 is repeated, but now the coil is moving relative to the magnet that is stationary in the laboratory reference frame. In this case the moving coil is retarded by the magnet if the coil terminals are closed. We conclude that the relative motion of a magnet and a coil is important in the phenomenon of electromagnetic induction.

To obtain the photographs of this experiment, we attach a LED to the coil. The LED is connected to a generator of short-duration pulses with frequency of 20 Hz with the help of thin flexible wires. In addition, we lengthen the magnet: we insert a cylinder 16 mm in diameter and 30 mm in length of mild steel between the neodymium magnets. The photographs clearly show that when the coil terminals are open, the coil slides along the tube without braking as if the magnet is absent (figure 8(a)). When the coil terminals are shorted, the coil is retarded approaching the magnet and moving away from it (figure 8(b)). If the magnet is removed, the coil slides along the tube without braking, when its terminals are closed or open (figure 8(c)).

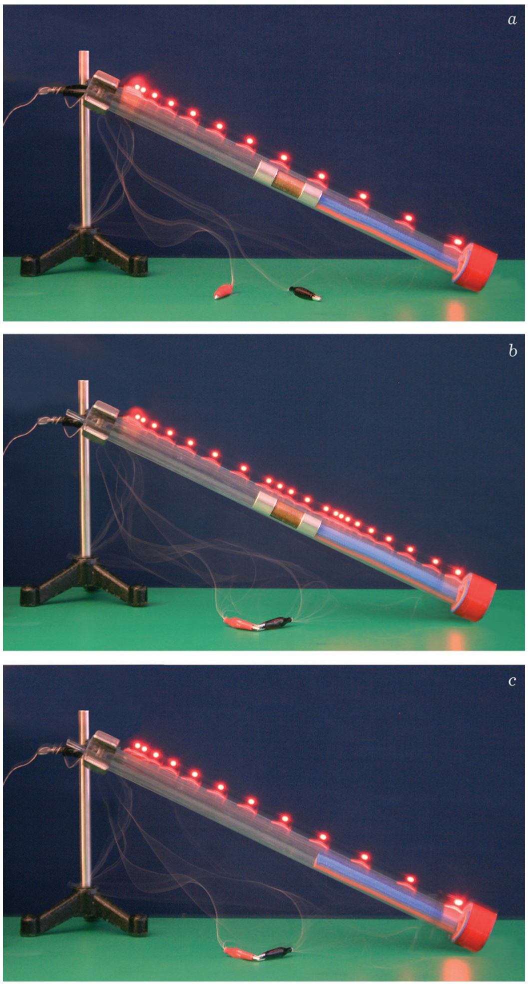

Figure 8. Stroboscopic photographs of the motion of the coil, if the magnet is stationary relative to the laboratory: (a) the coil terminals are open; (b) the coil terminals are closed; (c) the magnet is removed.

3.7. Experiment 7. Dependence of the electromotive force $\mathcal{E}$, the induced current I and the coordinate s of the magnet at time t

A more detailed study of the motion of the magnet through the coil can be carried out with the help of a computer and a camera. The experimental set-up consists of a Faraday generator fixed with the help of a tripod and the computer monitor located next to the generator. A resistor of 3.6 Ohm is connected to the generator coil.

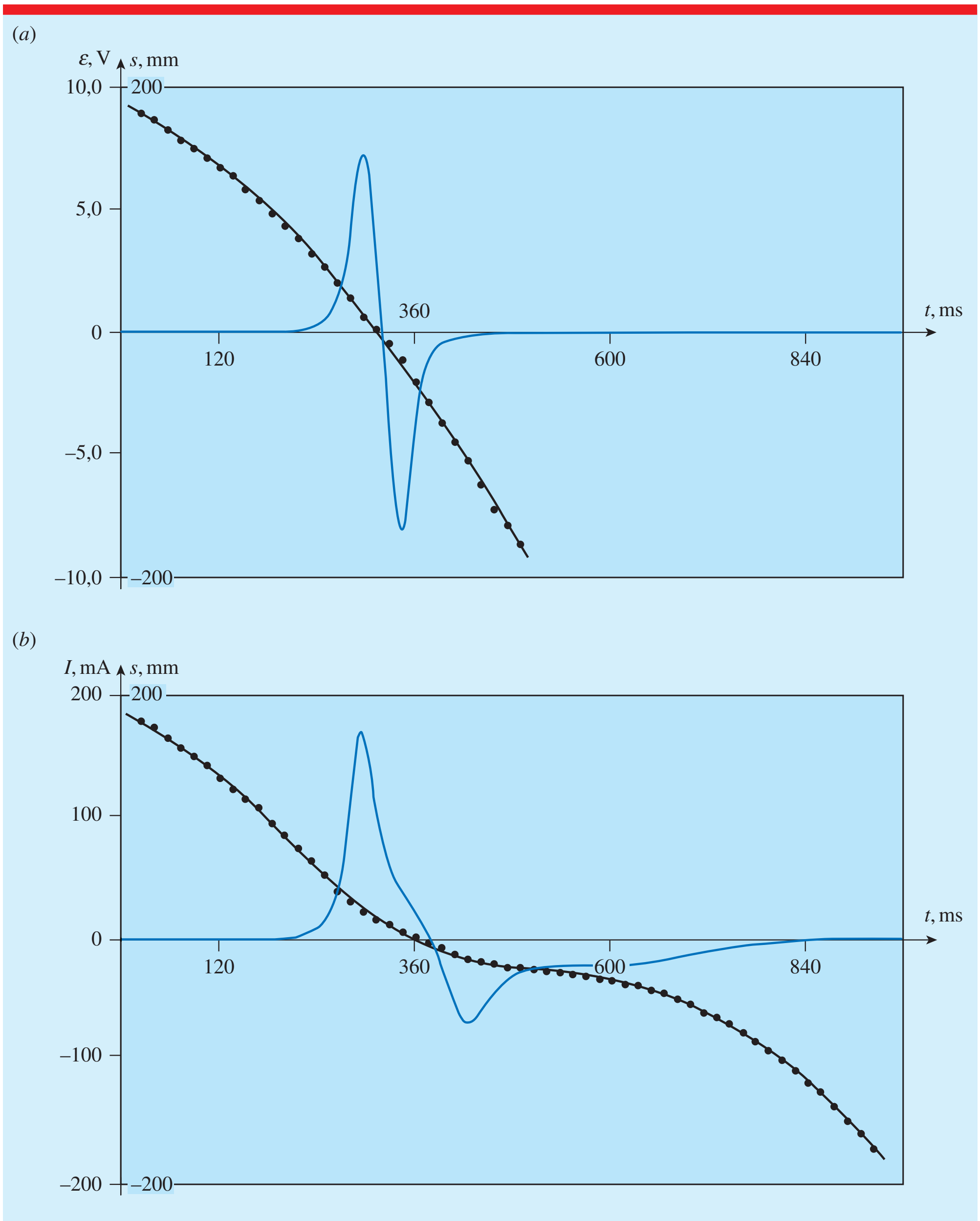

Figure 9. Investigation of EMF of the electromagnetic induction, the induced current and the motion of the magnet through the coil: (a) the oscillogram of EMF of induction and the graph of the motion of the magnet; (b) the oscillogram of the induced current and the graph of the motion of the magnet.

The resistor voltage is measured by a computer oscilloscope. The camera 'Casio' is located so that you can simultaneously take photos of the generator and the monitor. The neodymium magnet is lowered into the generator tube. We photograph the motion of the magnet at a rate of 60 shots per second. A series of photographs is obtained. The photos show the successive stages of the motion of the magnet and the corresponding sections of the oscillogram of the induced current. Next we repeat the experiment with the open coil terminals and photograph the motion of the magnet and the oscillogram of the electromotive force.

The photographs obtained are processed as follows. Firstly we take the middle of the coil as the origin and determine the coordinates $x = x(t)$ of the magnet sliding on the tube. These values are used to draw the dependence $s = s(t)$. This graph is superimposed on the oscillogram of the electromotive force of induction $\mathcal{E} = \mathcal{E}(t)$ (figure 9(a)). Then graphs of the dependence of the coordinate $s = s(t)$ and induced current $I = I(t)$ on the time are drawn (figure 9(b)). A comparison of the graphs shows that when the coil is open, the magnet moves through the coil with a uniformly acceleration. Only gravity and sliding friction act on the magnet. If the generator coil is closed with the help of a resistor, then a braking force acts on the magnet too, when it is near the coil. The force is caused by the induced current. As a result, the accelerated motion of the magnet is reduced to almost uniform motion near and inside the coil. When the magnet has moved sufficiently away from the coil, its acceleration resumes.

4. Conclusion

A famous book 'Experimental researches in electricity' [20] by Faraday begins with a series of experiments which discover electromagnetic induction and show the essence of the phenomenon. This first series convincingly reveals Faraday's method of investigation of physics phenomena: each of his experiments proves the existence of a phenomenon, confirms the validity or refutes a theoretical model proposed to explain the phenomenon or becomes the basis for new hypotheses. The Faraday method consists in a series of interrelated *experimental proofs*, and this method is effective in physics education whenever it does take not much time or involve burdensome material costs. The paper shows that a series of training experiments with Faraday's electromagnetic generator allows students to understand the physics essence of the phenomenon of electromagnetic induction at a qualitative level thoroughly. Students can later study electromagnetic induction quantitatively, based on on a physics model grounded in evidentiary experiments.

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References

[1] Mayer V V and Varaksina E I 2017 Electromagnetic Faraday generator and its application *Phys. Educ.* **52** 045018
[2] MacLatchy C S, Backman P and Bogan L 1993 A quantitative magnetic braking experiment *Am. J. Phys.* **61** 1096
[3] Sawicki C A 1997 A dynamic demonstration of Lenz's law *Phys. Teach.* **35** 47
[4] Ladera C L, Donoso G and Martin P 2012 One or two magnets falling in a conductive pipe: on-axis and off-axis fall and the role of the pipe wall thickness *Lat. Am. J. Phys. Educ.* **6** 216
[5] Irvine B, Kemnetz M, Gangopadhyaya A and Ruubel T 2014 Magnet traveling through a conducting pipe: a variation on the analytical approach *Am. J. Phys.* **82** 273
[6] Roy M K, Harbola M K and Verma H C 2007 Demonstration of Lenz's law: analysis of a magnet falling through a conducting tube *Am. J. Phys.* **75** 728
[7] Onorato P and De Ambrosis A 2012 Magnetic damping: integrating experimental and theoretical analysis *Am. J. Phys.* **80** 27
[8] Fodor P S and Peppard T 2012 Lenz's law demonstration using an ultrasound position sensor *Phys. Teach.* **50**
[9] Hare J 2002 Physics on a shoestring: the Shake-a-gen *Phys. Educ.* **37** 436
[10] Jones C 2003 Understanding and using the minus sign in Faraday's law *Phys. Educ.* **38** 526
[11] Nicklin R C 1986 Faraday's law—quantitative experiment *Am. J. Phys.* **54** 422
[12] Manzanares J A, Bisquert J, Garcia-Belmonte G and Fernandez-Alonco M 1994 An experiment on magnetic induction pulses *Am. J. Phys.* **62** 702
[13] Nunn J 2014 Educational inductive gravimeter *Phys. Educ.* **49** 41

[14] Maryam K M N 2014 EM induction experiment to determine the moment of a magnet *Phys. Educ.* **49** 319

[15] Kingman R, Rowland S C and Popescu S 2002 An experimental observation of Faraday's law of induction *Am. J. Phys.* **70** 595

[16] Bonanno A, Bozzo G, Camarca M and Sapia P 2011 Using a PC and external media to quantitatively investigate electromagnetic induction *Phys. Educ.* **46** 385

[17] Tao L, Xiufang W and Yi L 1992 Using LEDs to demonstrate induced current *Phys. Educ.* **27** 36

[18] Kraftmakher Y 2005 Demonstration of Lenz's law with an induction motor *Phys. Educ.* **40** 281

[19] Wood L T, Rottmann R M and Barrera R 2004 Faraday's law, Lenz's law, and conservation of energy *Am. J. Phys.* **72** 376

[20] Faraday M 1839 *Experimental Researches in Electricity* vol I (London: Richard and John Edward Taylor) pp 7–16

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