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Demonstration of magnetic force in the process of studying physics

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Abstract

A conductor with current flowing through it and placed in a magnetic field is acted upon by a force. It is called magnetic force. This paper describes two simple small-sized devices to demonstrate this force.

Keywords: Physics; Demo; Device; Magnetic; Force

1. Introduction

The force $\mathbf{f}$ that acts on a charged particle moving in a magnetic field is called the Lorentz force. It can be calculated using the following formula [1]:

$$\mathbf{f} = q\mathbf{v} \times \mathbf{B},$$

where q is the charge of the particle, **v** is its speed and **B** is the magnetic field induction (vector physical characteristics are indicated in bold).

If an electric current of magnitude I flows through a conductor, then all free carriers in it move with a directed speed **v**. During the time Δt, the carriers pass of conductor of length Δl. The magnitude of the current I is then equal to:

$$I = \Delta Q/\Delta t,$$

where ΔQ is total charge flowing during time Δt through the cross section of the conductor.

All particles move with speed $\mathbf{v} = \Delta\mathbf{l}/\Delta t$ and the Lorentz force acting on each particle is equal to:

$$\mathbf{f} = q\,(\Delta\mathbf{l}/\Delta t) \times \mathbf{B}$$

In this formula, a conductor of small length Δl written in vector form. The direction of this vector concides with the direction of movement of positively charged particles.

The total force **ΔF** acting on all particles in this section of the conductor is ΔN times greater, where ΔN is the number of particles:

$$\Delta\mathbf{F} = \Delta N q(\Delta\mathbf{l}/\Delta)t \times \mathbf{B} = (\Delta Q/\Delta t)\,(\Delta\mathbf{l}) \times \mathbf{B} = I\Delta\mathbf{l} \times \mathbf{B},$$

Where ΔQ is the total charge of all particles moving directionally with speed $\Delta\mathbf{l}/\Delta t$ in a piece of conductor of length **Δl.**

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If we are given a straight conductor of not small length $\mathbf{L}$, then all forces $\Delta\mathbf{F}$ acting on the small sections $\Delta\mathbf{l}$ that make up the conductor are directed in the same direction. In this case, the total Lorentz force acting on all charged particles in this conductor (and as a result on the entire conductor as a whole) is equal to:

$$\mathbf{F} = I (\mathbf{L} \times \mathbf{B}) \qquad (1)$$

This force $\mathbf{F}$ is called magnetic force (it is sometimes also called the Lorentz or Ampere force). This force is quite small. As can be seen from the last formula, its value is proportional to the current flowing trough the conductor. Therefore, in the classic versioon, when demonstrating this in a large classroom, a current of tens amperes is used, passed through a copper foil tape. The tape is easily deflected under the influence of small force, and its area provides good cooling when a high current flows.

At the same time, in such a demonstration experiment it is poissible to use a conductor deflected in a magnetic field in the form of a small section of a conventional stranded installation wire. Since in this case the dimensions of the conductor, as well as its deflection, are small, when demonstrating the experience to a large classroom, you need to use a document projector with a screen. The device itself for conducting the experiment can be very small in size.

2. Device structures

When designing a mini-device to demonstrate magnetic force, it was decided to use one AA alkaline battery as a current source. This choice ensures the low cost of the device, its simplicity, as well as its autonomy during the experiment. The electronic circuit of such a simple device is shown in Figure 1.

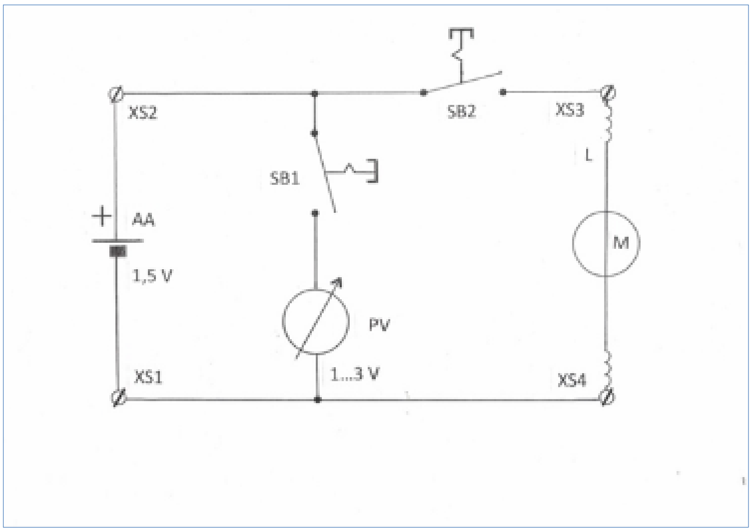

Figure 1 Electronic circuit of the first version of the device

An insulated stranded wire was used as a conductor L deflecting in the magnetic field. Its cross-section was 0.2 mm^2 and the total length was 26 cm. The conductor was installed between two clamp terminals XS3 and XS4. To achieve greater elasticity and mobility when magnetic force acts, the ends of the conductor where twisted into a spring. The measured conductor L resistance was 20 milliohms.

A small permanent magnet M (see **Fig.1**) was plased under the middle of the conductor. Using a push-button switch SB2, an electric current passed through the conductor for a short time (0.2...1.0 s). The source of the magnetic field was a neodymium flat magnet. Table 1 shows the values of measured average magnetic induction near the surface of flat some neodymium magnets at the author's disposal.

As we see, the magnetic induction, depending on the size of the magnet, is 40...160 mT. As can be seen from Figure 1, the current through conductor L is practikally a short circuit current, which primarily depends on the internal resistance of the battery. Table 2 shows the average internal resistance values of fresh AA batteries of four types (brands). Internal battery resistance were measured at the load of 2.7 ohms. The electromotive force of all batteries was in the range of 1.56 ... 1.62 volts. There were five copies of each brand.

Table 1 Magnetic induction near the surface of flat magnets

No	Magnet dimensions , mm	Magnetic induction, mT
1	29 x 9 x 1	40
2	29 x 9 x 3.5	130
3	38 x 18 x 9	160
4	Ø19 x 4	90
5	Ø24 x 3	50
6	Ø20 x 5	110

Table 2 Average internal resistance of AA batteries

No	AA battery brand	Average internal resistance, mΩ
1	Energizer (max)	205
2	Duracell	190
3	Varta (longlife)	225
4	Panasonic (Pro Power)	260

The data presente in Table 2 shows only the internal resistance of the batteries at the author's disposal (they cannot be considered as statistical data of the power sources of the listed brands).

Thus, from the point of view of the internal resistance of AA batteries, the current through the conductor cannot exceed approximately 8 amperes. In reality it will be even less. Contributing to the total resistance of the circuit during a short circuit are the conductor L resistance equal to 20 milliohms, the contact resistance XS1 … XS4, as well as the contact resistance of the high-current switch SB2. Measurements show that the resistance of this switch can reach several tens of milliohms. Thus, the maximum current will already be 5 … 6 amperes. In addition, due to oxidation of contacts, it may turn out to be unstable.

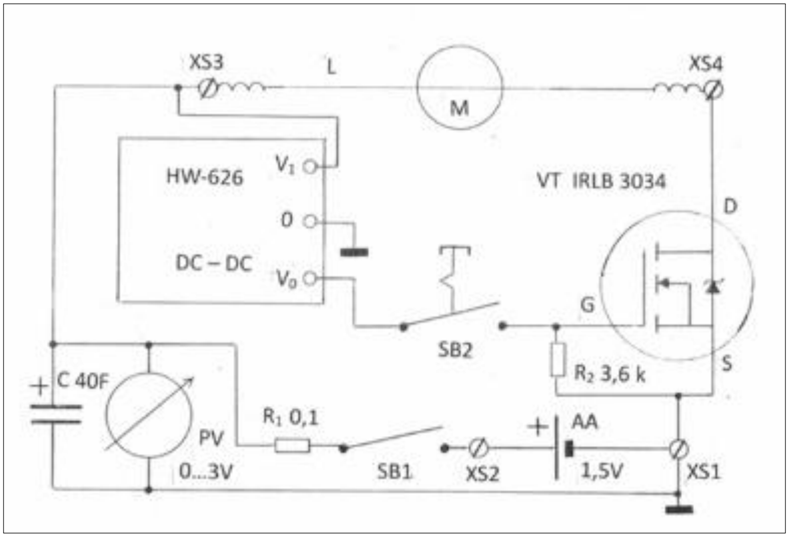

Figure 2 Electronic circuit of an improved version of the device

Push-button switch SB1 is used to measure battery voltage with a voltmeter PV.

As experiments show, for this version of the device the deflection of the central part of the conductor is insignificant and, as a rule, does not exceed several millimeters. Thus, in turn, may affect students' perceptions of magnetic force.

The following device, the electronic circuit of which is shown in Figure 2, helps to eliminate the influence of the internal resistance of the battery, battery socket terminal resistance, and the contact resistance of the switch SB2.

The device uses an energy storage in the form of a supercapacitor and electronic switch based on a MOSFET transistor. The capacity of the supercapacitor is 40 farads with a maximum permissible voltage not exceeding 2.7 volts. Its internal resistance does not exceed 30 milliohms [2]. A MOSFET transistor IRLB 3034 is used as a electronic switch, the drain-source resistance of which at a gate voltage of 5 volts does not exceed 2 milliohms [3]. To increase the voltage from 1.5 volts to 5 volts, a DC – DC modul is used, which, at an input voltage of 0.9 … 5 volts provides an output voltage of 5 volts. Note that in this circuit the switch SB2 may be low-current.

When the SB1 is turned on, the supercapacitor begins to charge. The voltage on it is controlled using a voltmeter PV. It takest time to fully charge supercapacitor, no more than one minute. Then, with a flat magnet located under the middle of the conductor L, press the push-button SB2 for 0.2 … 1.0 sec. Depending on the elongation (elasticity) of the conductor, the deflection of this middle should be from several millimeters to two centimeters.

The dependence of the current in the conductor on time (when the switch SB2 is pressed for 0.4 sec) is shown in Figure 3. The capacitor was in this case charged to a voltage of 1.5 volts.

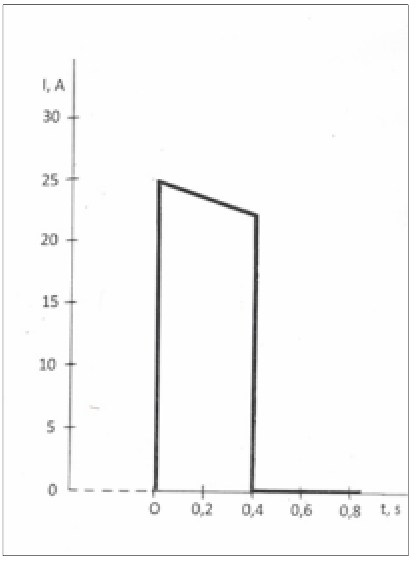

Figure 3 Dependence of current strength in a conductor on time

In this case, the initial current reaches a value of 25 amperes, which is approximately five times more than in initial simplest versioon of the device. Thus the total resistance of the discharge circuit is approximately 60 milliohms. On this value, 20 milliohms will be applied to the resistance of conductor L, approximately 30 milliohms – to the internal resistance of the supercapacitor, the rest – to the resistance of the transistor, the resistance of XS3 and XS4 terminals and remaining wires of the circuit.

It should be noted here that the presence of magnetic force can be demonstrated without waiting for the supercapacitor to charge to the full battery voltage. You can conduct an experiment with the voltage of a charged capacitor, starting from 0.8 … 0.9 volt. Naturally, the deflection of the conductor will decrease somewhat. The appearance of the second (improved) version of the device is shown in Figure 4.

If you want to increase the current in the conductor, you need to increase the capacitance of the supercapacitor. In this case, the internal resistance of the supercapacitor decreases and, consequently, the total resistance of the discharge circuit also decreases. For example, when the capacitance of the supercapacitor was increased by parallel connection of an additional capacitor from 40 farads to 90 farads (all supercapacitors were of the JGNE brand), the initial current in the discharge pulse increased from 25 amperes to 33 amperes (of cource, this would also roughly double the charge time of the supercapacitor).

Figure 4 Appearance of the second version of the device

3. Conclusion

In conclusion, we can say that the described device was repeatedly used in physics classes in gymnasiums and high schools to demonstrante the action of magnetic force. Knowing the direction of the current in the conductor and the direction of the magnetic field induction vector, we can use formula (1) to predict the direction of the magnetic force acting on the conductor and confirm this experimentally. The device has a simple design, small weight and size and does not require external power. It is also characterized by great reliability. One AA battery is trough for a large number of demonstrations.

Compliance with ethical standards

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