Laboratory experiment

Measurement of the force acting on a current-carrying conductor

1.1 Tasks

Explore the relationship between the current flowing through a conductor placed in a magnetic field and the force acting on a current-carrying conductor.

1.2 Magnetic field force effects

The electromagnetic field as such (and the magnetic field is part of it) is described by Maxwell's equations. The four so-called main Maxwell's equations summarize the interrelations between the quantities describing the field and, when supplemented with material relations, the field can be calculated from them. However, if the electromagnetic field did not exert a force on the electric charges, it would be more of an intellectual exercise, since it would not be possible to convince oneself of the existence of the field by measurement. However, the electromagnetic field does have force effects: the relevant relations for the force are called after H. A. Lorentz (1853-1928).

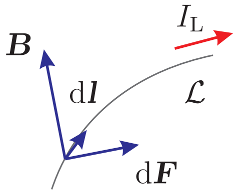
1.2.1 Lorentz force

The Lorentz force is described by formula

$$\boldsymbol{F} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}),$$

where q is the charge, $\boldsymbol{E}$ is the electric field vector, $\boldsymbol{v}$ is the velocity vector of the charge, and $\boldsymbol{B}$ is the magnetic field vector.

This is the force acting on an electric charge; it is assumed that the charge is "a point charge-particle", i.e., it is located at a single point. In most cases, however, we think not of individual moving charged particles, but of the electric current as a continuous quantity.



1.2.2 Force acting on a current-carrying conductor

Especially for the force exerted by magnetostatic field on a conductor carrying electric current I_L: **a)** it is not necessary to account for the interaction of electric fields of charges (the whole is so-called charge neutral; the second term in the relation for the Lorentz force is sufficient), **b)** the following formula can be easily derived

$$\mathrm{d}\boldsymbol{F} = I_{\mathrm{L}} \mathrm{d}\boldsymbol{l} \times \boldsymbol{B}, \tag{1.1}$$

where $\mathrm{d}\boldsymbol{F}$ is the force acting on an element of the current-carrying conductor, which is considered infinitesimally thin, namely, its width can be neglected compared to other relevant dimensions; $\mathrm{d}\boldsymbol{l}$ is the oriented direction of the electric current. The relation (1.1) is sometimes called the Ampère force. The magnetic field $\boldsymbol{B}$ can change point-to-point, as well as its mutual orientation with respect to the vector $\mathrm{d}\boldsymbol{l}$. It is why the relation (1.1) is expressed "only" in the differential form.

To determine the total force acting on the current-carrying conductor, the individual contributions must be summed – integrated as

$$\boldsymbol{F} = I_{\mathrm{L}} \int_{\mathcal{L}} \mathrm{d}\boldsymbol{l} \times \boldsymbol{B}. \tag{1.2}$$

Let's assume a straight current-carrying conductor with length l, oriented by an unit vector $\boldsymbol{i}_0$, flown with electric current I_{L} (in the direction of $\boldsymbol{i}_0$) placed in an uniform magnetic field $\boldsymbol{B} = B\boldsymbol{j}_0$, where $\boldsymbol{j}_0$ is an unit vector. The force acting on this conductor can be, substituting into (1.2), calculated as

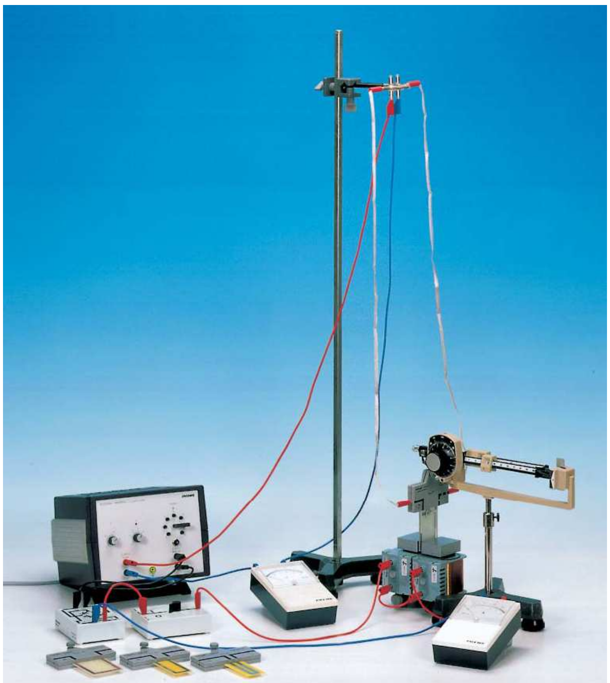
$$\boldsymbol{F} = BI_{\mathrm{L}}l(\boldsymbol{i}_0 \times \boldsymbol{j}_0)$$

and, if it holds $\boldsymbol{i}_0 \perp \boldsymbol{j}_0$, we get the well known formula for the magnitude of this force

$$F = BI_{\mathrm{L}}l. \tag{1.3}$$

1.3 Experimental set-up

To demonstrate and measure the effect of the magnetic field on a current-carrying conductor, it is advisable to construct an experimental apparatus with as simple a geometry as possible: so that the magnetic field vector is **a)** constant and uniform, i.e., everywhere the same magnitude and in the same direction, **b)** perpendicular to the current-carrying conductor, then the vector product is replaced by the product of the vector magnitudes, see the relation (1.3), and **c)** the effect of the sections through which the current is flown into the magnetic field must be eliminated.The exerted force can be measured by a device very similar to an ordinary balance; hence the name.



1.3.1 An electromagnet and its field

The source of the uniform magnetic field is an electromagnet powered by DC current. The electromagnet is already assembled (do not disassemble it after the measurement). It consists of two coils, a U-shaped iron core, and pole-pieces. The width of the air gap between the pole-pieces is 1 cm (by turning them, it can be increased to about 4 cm, but don't do that – the field is not uniform enough then). The magnetic field in the space between the pole-pieces can be considered uniform within 2–3 mm. Instead of measuring the magnitude of the magnetic field vector at the point of measurement, measure and vary the magnitude of the current I_m flowing through the coils of the electromagnet, to which the magnitude of the magnetic field is proportional.

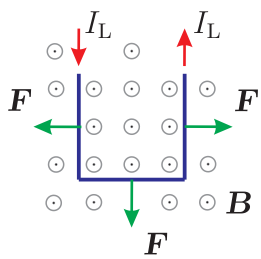
When converting current to magnetic field, consider that its magnitude is proportional to the magnetizing current I_m and for $I_m = 870\,mA$ it applies $B = 168\,mT$.

1.3.2 Current balance

It is a standard balance scale. On the left balance is suspended a jig with a conductor in the form of a rectangular loop, which is balanced on the right side by 10 g and 100 g weight and fine balancing. It is balanced so that the line on the right-hand balance coincides with the line "0" on the balance frame. The fine balancing you are about to use is done with a rotary knob with a pointer calibrated in the range 0–10 g (lines numbered 1–10), tenths of g are read between the numbered lines, hundredths of g are read on the auxiliary vernier scale. The decisive line on the vernier scale is on the right side, marked with a zero. **Caution, the balance must be handled gently!**

1.3.3 Geometry of the measured segment, elimination of the influence of inlets

The force that the magnetic field exerts in the central (horizontal) part of the loop suspended in the space between the pole-pieces attached to the electromagnet is measured. Of course, the forces also act on the vertical parts of the loop, but they cancel each other out. The inlets to the loop to be measured are made of thin textile strips interwoven with fine copper fibres, which can be considered perfectly flexible–therefore almost no force is exerted on the suspension.



1.4 Procedure

1.4.1 Getting acquainted with the experimental set-up

Start by taking a close look at the entire experimental set-up. See where the magnetizing current flows and where the actual current circuit is to determine the Lorentz (Ampère) force. On the left-hand scale beam, perhaps from the previous measurement, is a fixture with a current-carrying conductor; on it is written the length of the loop section to be measured (in German – Leiterschleife, $l = 12.5, 25,$ or 50 mm) and the number of turns ($n = 1$ or 2). Test how the scales are balanced.

1.4.2 Setting the magnetic field and current I_L through the loop

The electromagnet is powered from the right side of the power supply unit (2 – 15 V AC). The AC voltage is converted to DC via a bridge rectifier. The two coils of the electromagnet are connected in series. The magnetizing current is set in steps by a carousel switch on the right side of the power supply unit, measured (before rectification) using an ammeter; the current must not exceed 1.3 A.

The current I_L passing through the loop being measured is supplied from the left side of the power supply unit and measured with an ammeter; the current must not exceed 5 A.

1.4.3 The state of things

There are four variables in the problem: the magnetizing current I_m passing through the coils of the electromagnet, the current I_L passing through the conductor segment in the magnetic field, its length l (in the case of a two-threaded conductor it is double) and finally the force $\boldsymbol{F}$ acting on the current-carrying conductor. Which of these variables are independent and which depend on the others?

The results of the measurements will be both in the form of tables (non-demonstrative), and – and this will be your main task – in the form of graphs; these are the best way to see how linear the dependencies are, i.e., how directly proportional the measured quantities are to each other.

In a (two-dimensional) graph, the dependence of one variable on the other is plotted; the influence of the third variable can be shown in the form of a parameter: there will be several curves of measured values in the graph, each curve for a different value of the third variable. But how to display the relationships between the four variables? In this case it is convenient that the length of the conductor is determined by the measuring fixture (12.5, 25, and 50, respectively 100 mm), therefore the length of the conductor can also be taken only as a parameter; the measurement results will then be on several graphs.

1.4.4 Actual measurement

Vary the magnetizing current I_m through the electromagnet coils from 0 to 1 A. Vary the current I_L flowing through the conductor from 0 to 5 A.

Always first balance the scales in a state where no current passes through the electromagnet coils and the current-carrying conductor in the fixture ($I_m = 0\,A$, $I_L = 0\,A$) – for this purpose, the corresponding cords are equipped with switches. The scale must be balanced after each change of the fixture with measured conductor.

The magnitude of the force acting on the current-carrying conductor in this experiment depends on the magnitude of the magnetic field (which is proportional to the current I_m), the current I_L, and the length of the conductor segment l. You can measure this dependence with minimal effort, for example, as it is explained below.

For one fixture ($l = const.$) and five different currents I_m, measure the dependencies $F = F(I_L)$, plot at least three of these dependencies in one graph, where the current I_m is the parameter of each dependency. Use the same measured values[1] for the second graph where you plot at least three dependencies $F = F(I_m)$, where the parameter of the individual courses is the current I_L.

In the next step, for a fixed current I_L and I_m, measure the dependence of the force on the length of the current-carrying conductor segment, the measurements will be made for each of the fixtures, i.e., for $l = 12.5, 25, 50$, and 100 mm. In the third graph, plot the dependence $F = F(l)$.

You can create the graphs using, for example, the Universal tool for plotting graphs, available at

http://planck.fel.cvut.cz/praktikum/

where you approximate the measured data by the first-degree polynomials (straight lines).

[1] For example, set these values of I_L: 1 A, 2 A, 3 A, 4 A, 5 A using the current limiter on the power supply unit, the current I_m is set using five chosen positions of the carousel switch. This way you get 25 values of the force magnitude F.

1.4.5 Measurement results and conclusions

The physical theory, see relation (1.3), states that the magnitude of the force acting on a current-carrying conductor is directly proportional to the length of the conductor l, the current I_{L} passing through it and the magnitude of the (uniform) magnetic field B at the conductor location. Examine the graphs obtained and indicate how well this agrees with your measurements. The measured values will never correspond exactly to direct proportionality. Therefore, try to explain (and this is the focus of your work) the reasons for the observed deviations.

1.5 References

Whatever university textbook on the theory of electromagnetic field.

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