More ideas from Malá Hraštice: magnets' repulsion

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Abstract

This paper presents a handful of experiments using simple tools for measuring the force between small magnets. The force is measured using cheap digital scales, torsion balance or using a simple balance. The measurement implementing torsion balance serves well as an analogy to the Cavendish experiment or to Coulomb's measurements of the force between electric charges; a historical analogy to measurements using rocker arm exists as well. Described measurements are not intended as a large, demonstrational experiments, but rather as an example how handmade devices can be used to measure even small forces (in the order of tens of μN) to which regular digital scales do not respond.

Introduction

The idea for the measurements described below arose at the spring camp for future physics teachers (see [1] or [2] and other references therein). This years' professional program's main topic was „Mutual interaction". Magnets' repulsion is a neat problem that called for experimentation. Among other reasons because we had experimented with a levitating pencil at this years' Elixir to Schools conference workshop. That experiment is based precisely on magnets' repulsion – see fig. 1 and paper [3].

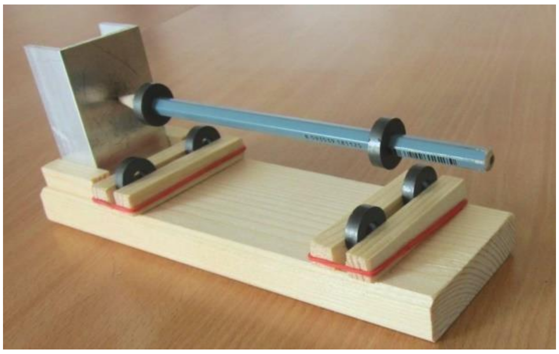

Fig. 1 – Magnets' repulsion used to make a pencil levitate (adapted from [3]).

Magnets' repulsion can be obviously noticed even in simpler experiments, for example when magnets are placed on top of the table with the same poles facing upward, see fig. 2.

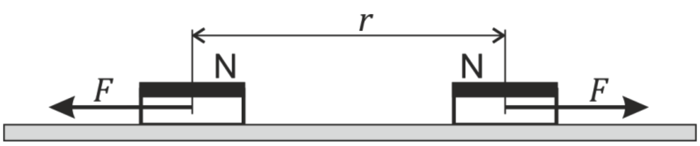

Fig. 2 – Magnets arranged in this way, e.g. placed on the table, repulse each other.

Experience dictates that when the magnets are closer together the repulsion is stronger. But how much stronger? In other words, **how does the repulsion of magnets depend on distance?**

The force on magnets can be theoretically derived, supposing that the magnets are so small, that they can be thought of as elementary dipoles. In this case the force decreases with fourth power of the distance:

$$F \sim 1/r^4\ . \qquad (1)$$

The theoretical derivation can be found in university textbooks, mostly for the case of electric dipoles, see e.g. [4], it will not be further discussed here. Instead, we will try to verify the relation (1), and how large the forces between magnets really are, using simple experiments.

Measurement with small digital scales

Small digital scale can be bought cheap nowadays (for hundreds of Czech crowns) and are usually already implemented in physics experiments, see e.g. [2]. The more sensitive ones have accuracy to 0.01 g, which corresponds to the force of 0.01 mN. An example how they can be used to measure the force between magnets and measured results are shown in fig. 3.

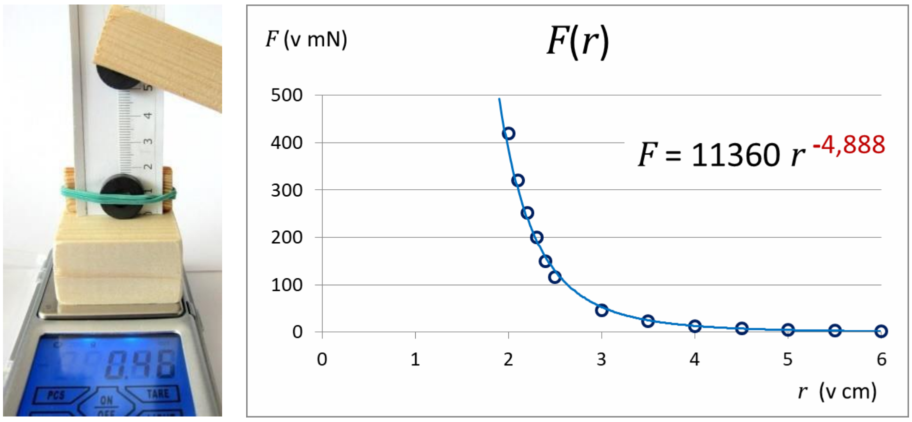

Fig. 3 – An example of experimental arrangement for measurement of the force by digital scales and measured results.

In our case the measured force was between ring-shaped ferrite magnets with outer diameter of 17 mm, inside diameter of 7.5 mm and 5 mm in height; the magnets are the same as in the case of the “levitating pencil”. As can be seen in the picture, for the distance between magnets’ axes equal to 5 cm the scales display 0.46 g, hence the force is approximately 4.6 mN. (This is in good agreement with theoretical value that stems from magnets’ properties. Corresponding calculation for elementary dipoles yields about 4.8 mN.)

Alas, practical experiment shows that using these cheap digital scales is not a viable option for force measurements at greater distances – for small forces corresponding to weight below about 0.1 to 0.2 g, the scales often seem to “jam” and its accuracy is pour. In reality using said magnets allowed for measurements with distances up to 6 cm.

A second problem can be seen in fig. 3. When a power function was fitted to the data in Excel, the force appears to decrease rather with the fifth power of the distance, instead of the fourth power as the theory predicts.

This seemingly strange behaviour can be understood. Dependence (1) applies to elementary dipoles, in practise when the magnets' size is negligible compared to their distance. This is not fulfilled in measurements in fig. 3, when the distance between the magnets was as close as two centimetres. Therefore, it would be interesting to explore greater distances, although the cheap digital scales are not accurate enough for such measurements. Thus arose the necessity of a more precise device, capable of measuring much smaller forces.

Measurements with a torsion balance (of our own design)

We can be inspired by historical experiments: the Cavendish's measurement of the attraction of lead balls and Coulomb's measurement of the force between electric charges. Both of these measurements used torsion balances. In these, the arm of the balance is suspended on a thin fibre. A very small moment of force, i.e. a very small force at the end of the arm, is sufficient to twist the fibre and hence to cause an observable displacement of the arm.

Torsion balance can be made on your own. Fig. 4 shows one of the viable designs.

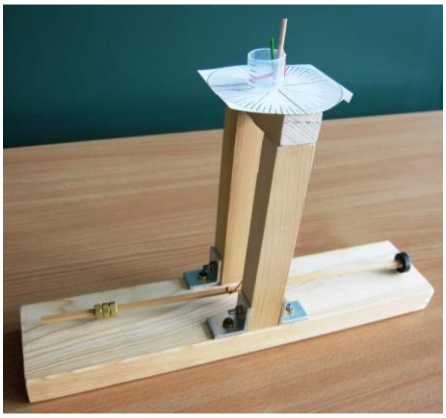
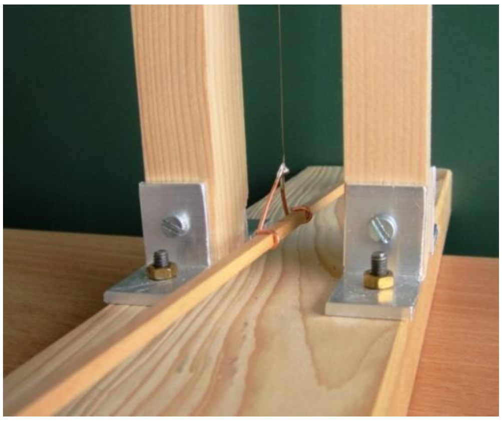

Fig. 4 – Simple torsion balance of our own design.

A copper wire from a thin copper cord is used as a fibre. The wire's diameter is 0.15 mm, and its length is a little bit over 10 cm. (This design is intended for transportation, so it is made quite sturdy. The same experiments can be conducted using significantly less complex designs of the torsion balance.) Results of the measurement are shown in fig. 5.
At first glance, it seems that the dependence of force on distance has been verified with fantastic accuracy. However, in this case, the fact that the exponent of the fitted function differs only slightly from -4 is merely a coincidence. (Realistically, values ranging from 3.8 to about 4.2 may pop out.)

The torsion balance allows force measurements up to a distance of about 25 to 30 cm, although it is not possible to measure at small distances where the forces are too great. At a magnet distance of 10 cm, the fibre was twisted by more than 270 degrees and when the magnet was moved away it remained twisted a little, apparently due to plastic deformation of the copper from which the fibre is made. It can be seen that with our equipment we have not yet "covered" the force measurements at distances between about 6 and 11 cm.

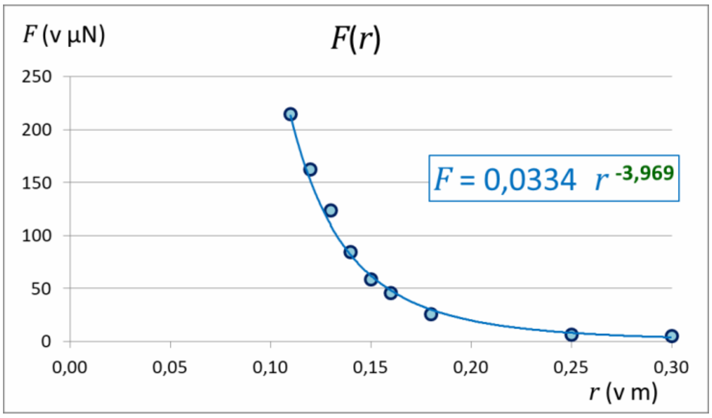

Fig. 5 – Results of the measurement using torsion balance.

Measurements using a simple balance

A fairly ordinary balance can be a useful measuring device. It too has been used in history - John Robison used it to measure the force between electric charges, in 1769, even before Coulomb measured it.

Fig. 6 shows the design that has proven itself in the measurements and the measurements with the balance.

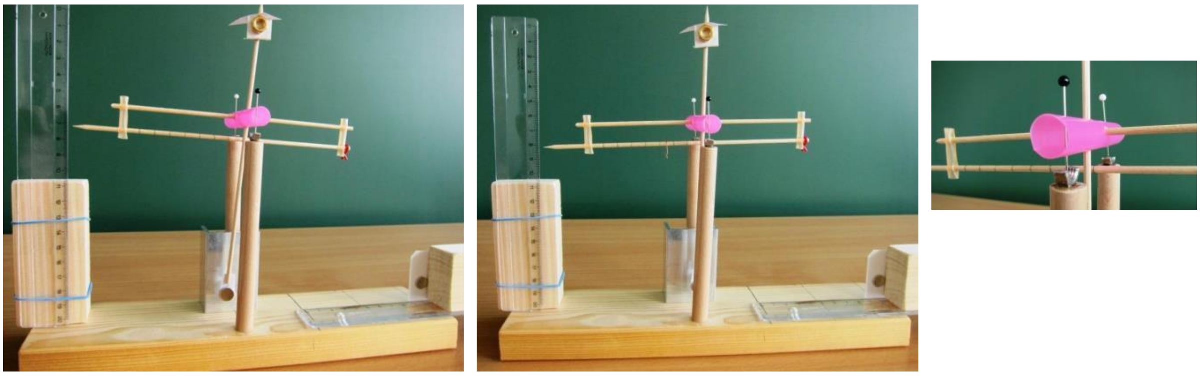

Fig. 6 – The balance for measuring the force between magnets.

The balance consists of skewers, which are used to pierce a piece of thick straw. At the end of the vertical skewer is a magnet. (In this case, both the magnet on the pendulum and the magnet being approached were small neodymium magnets. The force between them is comparable to that between larger ferrite magnets, but in fact it is about 0.42 times smaller.) To minimize friction, the balance is supported by the tips of the pins on metal "bases", which are the halves of a slit nut, see the detail on the right in fig. 6. Small weights, made of thin copper wire, are placed on the bottom horizontal pin of the balance, which is at the same height as the pin tips. (Weigh a metre or two of wire on a digital scales, then take a suitable length from it.) The weights are trying to turn the balance in the direction opposite to the rotation caused by the magnets' repulsion, see the middle photo in fig. 6; the balance is balanced by moving the weights along the skewer. The nut on the vertical skewer above the axis is used to bring the centre of gravity of the balance as close as possible to the axis given by the junction of the pin tips, this is how we control the sensitivity of our device. And one more detail: the pendulum oscillation is dampened by a piece of aluminium profile; the movement of the magnet is dampened by eddy currents.

The experiment showed that with the given design it was possible to measure distances ranging from about 4.5 to 15 cm. The measured results are shown in fig. 7. In the right part of the figure, the distance dependence of the product $F{\cdot}r^4$ is plotted, which should be constant for the force between the elementary dipoles. It can be seen that at the given distances, the force between the magnets is pretty close to the theoretical dependence (1). (The values of $F{\cdot}r^4$ usually do not differ by more than twenty percent, while the force ratio at distances of 4.5 and 15 cm is more than one hundred.)

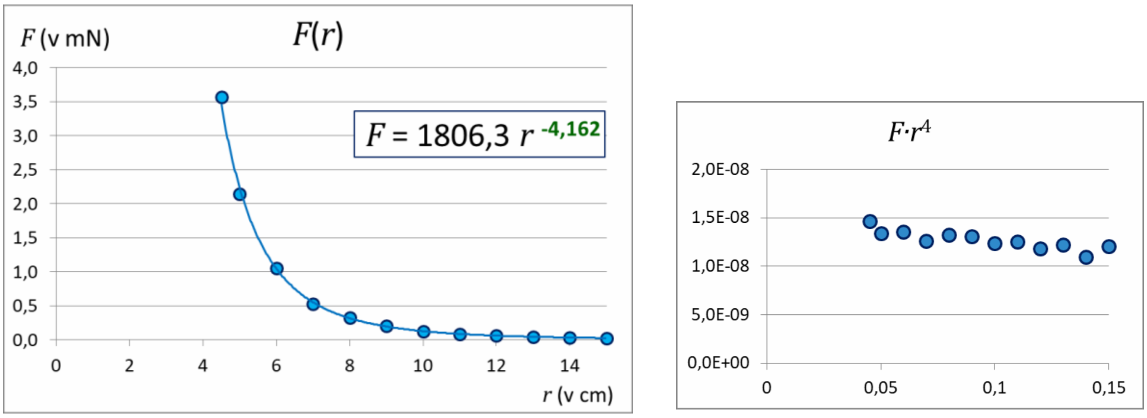

Fig. 7 – Results of the force measurements with a simple balance.

A simpler design can be used for the pendulum experiments. On the other hand, it is a challenging task to try to make the pendulum as sensitive as possible. But of course a very sensitive pendulum will also be sensitive to all sorts of external influences, airflow, etc.

Conclusion

With the designs described above, really small forces can be measured. In the case of the simple balance, the smallest force measured was about 25 μN, in the case of the torsion balance only about 5 μN. This corresponds to a weight of half a milligram.

Torsion balances are, however, very sensitive to the air flow in the room, their balance oscillates with a long period (more than one minute) and is difficult to stabilise; furthermore, in order to determine the moment of force by which the fibre twists the balance arm, it is necessary to measure the period of oscillation with weights at different positions on the arm – so this method is more suitable for those with serious interest in physics.

Measurement with a balance is much simpler in terms of physical analysis, the oscillations of the balance can be more easily dampened, and the design of the balance could probably be enlarged so that it could be used for demonstrations as well Thus, further development of simple balance devices for small force measurements is quite an attractive challenge. Besides, there is still a lot to measure: the force when the magnets are in different positions, the force when they are attracted, ... Next time perhaps.

References

[1] Kácovský P., Koupilová Z. a kol.: *Malá Hraštice. Jarní soustředění pro budoucí učitele fyziky a spřízněné duše*. Available online: https://kdf.mff.cuni.cz/hrastice/main.php

[2] Dvořák L., Kácovský P.: *Další nápady z Malé Hraštice (jednoduché pokusy se slavnými jmény v pozadí)*. In.: Veletrh nápadů učitelů fyziky 23. Sborník z mezinárodní konference. Ed. M. Šerý, Jihočeská univerzita v Českých Budějovicích, 2018, s. 64-73.

[3] Dvořák L.: *Magneticky levitující tužka – jak ji udělat co nejlepší*. In: Sborník konference Elixíru do škol 2019. Will be published and available online.

[4] Sedlák B., Štoll, I.: *Elektřina a magnetismus*. Academia, Praha, 1993.