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The Process of Stacking a Conductor with Current Within the Interpolar Line of a Permanent Magnet

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ABSTRACT

The article provides a description and geometric definition of a new concept – the interpolar line of a permanent magnet. A method of observing the actual interpolar line of a permanent magnet by means of a magnetic film is presented – with an explanation of its principle. The results of a new physical experiment on the phenomenon of winding of a conductor with current on a permanent magnet within its interpolar line are presented, which confirm the existence of such a line in any permanent magnet having two magnetic poles. An example of the course of the experiment for a selected permanent magnet and a conductor with current is given. A description of the reaction of forces acting on a conductor with current lying near the interpolar line of the permanent magnet is presented, which explains the principle of this phenomenon. Four cases of forces acting on a conductor with current near the interpolar line of a permanent magnet are compiled, which are the basis for further work using the interpolar line. The possibilities of using the results of the conducted physical experiment to build a group of novel of technical devices is indicated.

Keywords: *LMB* interpolar line, permanent magnet, *LMB* phenomenon, magnetic film, magnetic force, magnetic pole.

INTRODUCTION

The physical interaction of permanent magnets in the form of attraction of dissimilar poles and repulsion of one-name poles is well known [1-3]. In [1], the modeling and energy recovery of a system with two pseudo levitating magnets that repel each other is presented, in [2], an analysis of levitation forces generated by high-temperature superconductors located within the magnetic field of a UAV catapult system, in [3], a miniature ball contact sensor for completion of singular points of an energizing magnetic field is presented. Similarly, the electrodynamic force acting on a conductor with current in a homogeneous magnetic field – can be calculated from the Lorentz formula used in [4-6] and the direction of the force vector can be determined from Fleming's left-hand rule used in [7, 8]. What is new, however, is the interaction of a conductor with current in the inhomogeneous field of a permanent magnet near the interpolar line of that magnet. Such interaction can be observed in the experiment conducted by the author and the process of stacking a conductor with current within the interpolar line of a permanent magnet – can be used to build a new type of *LMB* (in Polish: linia między-biegunowa) technical devices. Nowadays, permanent magnets are used extensively in the construction of modern electric motors of the PMSM [9, 10] and BLDC [11-13] types, which are the basis of drives in electric vehicles.

The magnetic field lines of force a permanent magnet can be easily observed by placing the permanent magnet under a thin pane of glass, on which iron filings are gently sprinkled. Under the influence of the permanent magnet's magnetic field, they line up along the magnetic field lines of force to form visual lines between the magnet's *N* and *S* poles (Figure 1).

From Figure 1, it can be seen that the force magnetic field lines of the permanent magnet between the *N* and *S* poles of this magnet are lines having the shape of arcs, forming on both sides of the magnet (top and bottom) figures similar to concentric circles. If one were to schematically depict only the top side of the magnet (Figure 2) in the same plane as in Figure 1 and place within the magnetic field a number of sample current conductors, then according to Fleming's left-hand rule (Figure 3), one could mark the magnetic induction vectors *B* along with their corresponding forces vectors *F*. The current vectors *I* have directions directed away from the observer toward the plane under consideration.

It can be seen that all the lines that are extensions of the *F* force vectors intersect at a single point - the *LMB* line, which - located perpendicular to the plane under consideration in Figure 2 – is represented as a point. If one were to look at it from the perspective, any point of the conductor with current located near the *LMB* line of the permanent magnet (in the configuration discussed above) will be subjected to *F* forces (of different values), directed toward the *LMB* line.

In the case under consideration, any conductor with current located in close proximity the

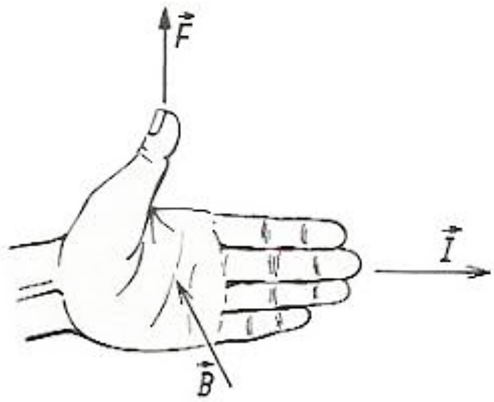

Figure 3. Mutual arrangement of the vectors: magnetic induction *B*, current *I* and force *F* according to Fleming's left-hand rule [15]

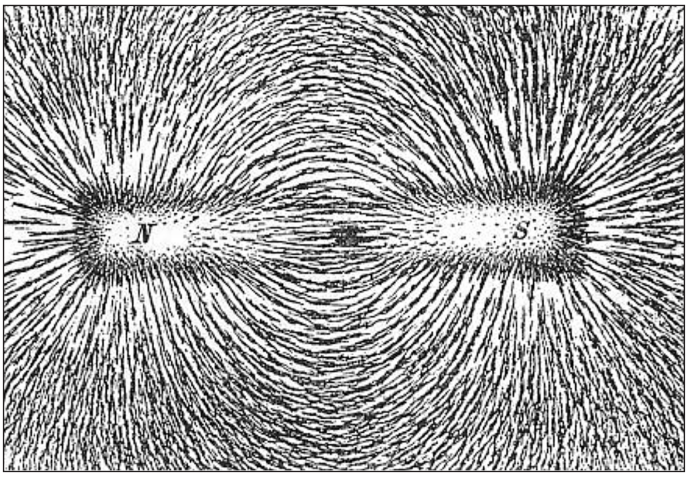

Figure 1. An actual permanent magnet with iron filings arranged along the magnetic field lines [14]

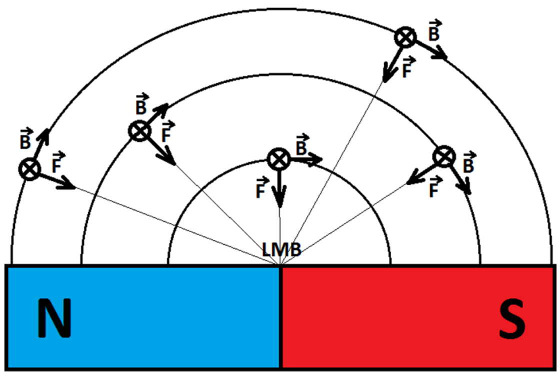

Figure 2. Schematic representation of the directions of the *F* force vectors acting on conductors with current

magnetic field of a permanent magnet will be attracted to the *LMB* line of that magnet. The opposite direction of the current in the conductor will result in its repulsion from the *LMB* line of the magnet. If one were to analyze the lower part of the magnet in Figure 2 - to the *LMB* line conductors with current will be attracted , the directions of which will be opposite to the directions of the currents from the upper part, thus flowing from the plane towards the observer.

In the inhomogeneous magnetic field of the permanent magnet, the force of attraction F of the conductor with current to the *LMB* line increases as it approaches the *LMB* line. According to relation Lorentz (1), when the conductor is positioned perpendicular to the magnetic field line, the electrodynamic force F is proportional to the flowing current I, the magnetic induction B of the permanent magnet and the length of the conductor l located nearby the *LMB* line this magnet [4-6].

$$F = B \cdot I \cdot l \quad (1)$$

where: B – magnetic induction, I – current flowing in the conductor, l – the active length of the conductor.

The magnetic field force lines of the permanent magnet encompassing the conductor with current also interact with the magnetic field lines formed around the conductor with current and having the form of concentric circles. If one were to assume that a section of current conductor I with a length equal to the length of the permanent magnet was placed in parallel over the *LMB* line (Figure 4), then on a plane perpendicular to the conductor, intersecting the permanent magnet at, for instance, half its length the magnetic field lines for both the permanent magnet and the current conductor I could be marked. Above the conductor, the magnetic field force lines of the permanent magnet and the conductor with current I point to one side – they add up, and below the conductor – the magnetic field force lines of these elements are opposite to each other – they subtract. So the value of magnetic induction B over the conductor is greater than under the conductor. In such a configuration, direction of the force F is directed to the *LMB* line of the permanent magnet.

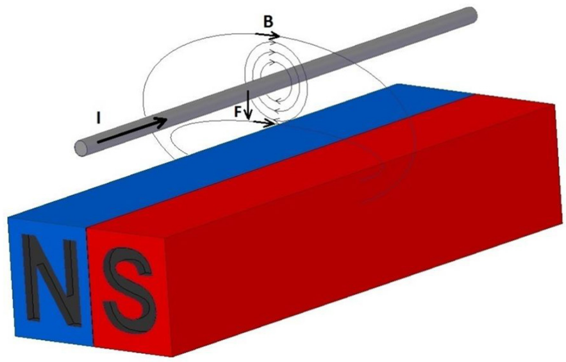

Figure 4. Interaction of magnetic field lines of a permanent magnet and a conductor with current

The more the conductor with current under the force F approaches the surface of the magnet (*LMB* line), this the difference in the value of magnetic induction B above the conductor is greater than under the conductor, so the value of the force F also increases. This is also related to the fact that the greater the distance from the magnet – this the intensity of the magnetic field decreases.

A magnetic film is also used to observe the magnetic field of permanent magnets by bringing it close to the surface of the permanent magnet. The magnetic film contains microcapsules with nickel flakes inside, filled with mineral oil. Under the influence of the magnetic field, the nickel

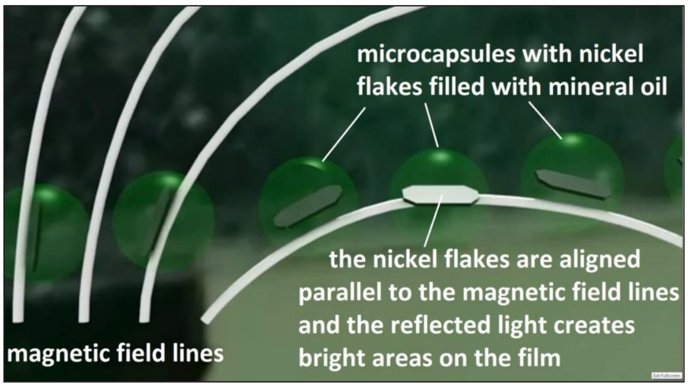

Figure 5. The principle of magnetic film [16]

flakes arrange themselves parallel to the magnetic field lines and, reflecting the incident light, form bright areas on the film [16, 17] (Figure 5). The purpose of the author's research was to experimentally confirm the *LMB* phenomenon involving the attraction (or repulsion) of a conductor with current (placed near a permanent magnet) to the *LMB* interpolar line of that magnet – depending on the direction of the flowing current. The occurrence of the *LMB* phenomenon allows its creative use in the construction of innovative devices based on the *LMB* principle.

OBJECT OF RESEARCH

The object of research is the *LMB* interpolar line occurring in a permanent magnet and its interaction with a conductor with current placed in its vicinity. The term "*LMB* interpolar line" of a permanent magnet (in Polish: Linia MiędzyBiegunowa – *LMB*, in English: InterPolar Line – *IPL*) has not been used so far, probably because of the lack of technical significance and practical use of such a line. The introduction of this term simplifies further considerations and enables easier understanding and analysis of the interactions associated with the *LMB* line, and descriptions of the use of this line in technical devices, based on the phenomenon of interaction of current flowing in a conductor with the *LMB* line of a permanent magnet.

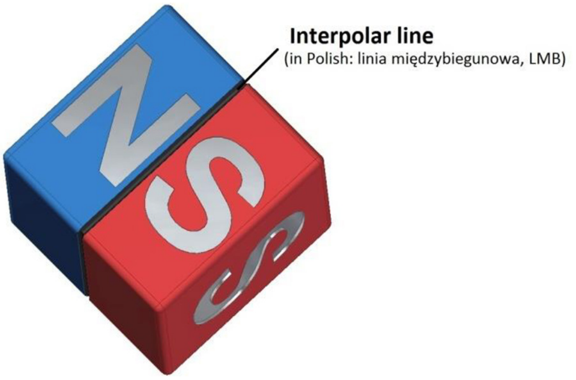

Figure 6. Representation of the location of the *LMB* line on the surface of a permanent magnet

The simplest geometric definition of the LMB interpolar line (Figure 1) is as follows:

> for a permanent magnet, the *LMB* interpolar line is the contractual boundary line between the *N* and *S* poles, lying on the surface of that this magnet.

The *LMB* line lying on the surface of a permanent magnet girdles it and splits the two poles of that magnet: the north *N* (usually marked in blue) and the south *S* (usually marked in red) [18, 19]. This is a contractual line, lying halfway along the length of the permanent magnet on the *N-S* direction. It can be observed thanks to magnetic film (Figure 7), which shows directed parallel to it – the magnetic field lines.

With the use of magnetic film, it is easy to observe one of the basic principles of connecting permanent magnets, according to which – when two identical magnets are connected by dissimilar poles, one magnet with *N* and *S* poles will be formed (Figure 8). A common *LMB* interpolar line will be formed between the merged magnets, which will be formed from the offset of the two *LMB* interpolar lines of the two permanent magnets being merged.

An interesting phenomenon is the formation of a mutual *LMB* interpolar line between the

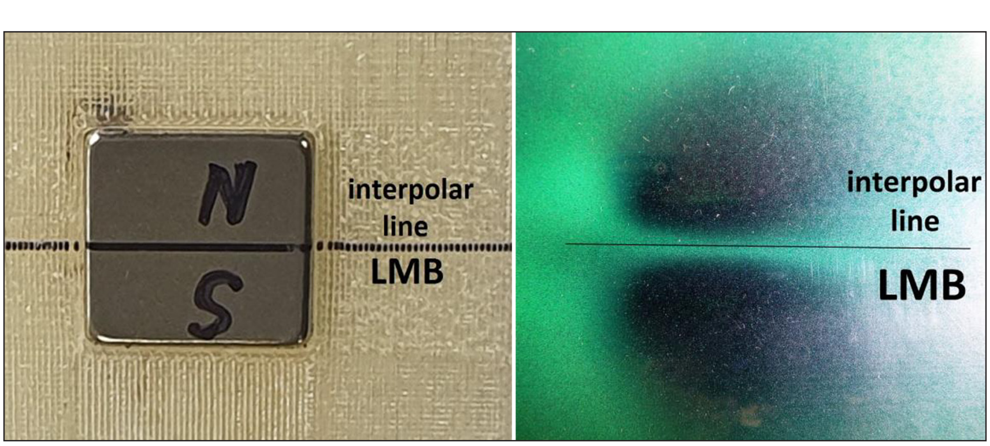

Figure 7. *LMB* line marked on the surface of an MPL 15x15x15/N38 permanent magnet and observed with magnetic film

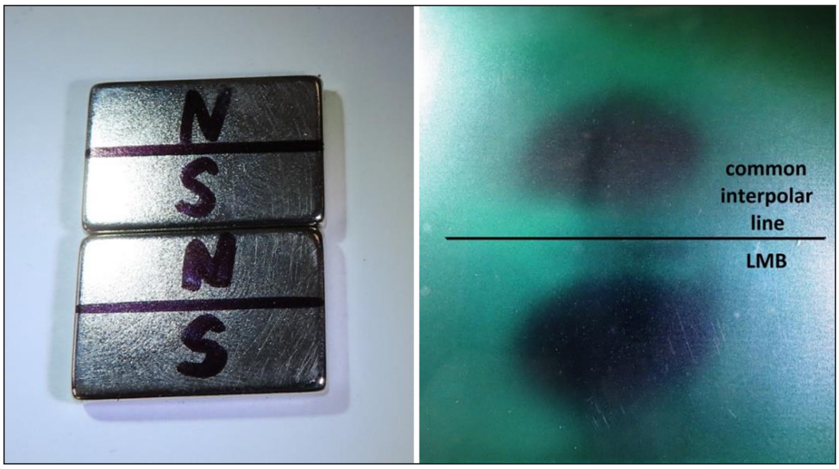

Figure 8. A mutual *LMB* line at the junction of two equal, connected permanent magnets observed with magnetic film

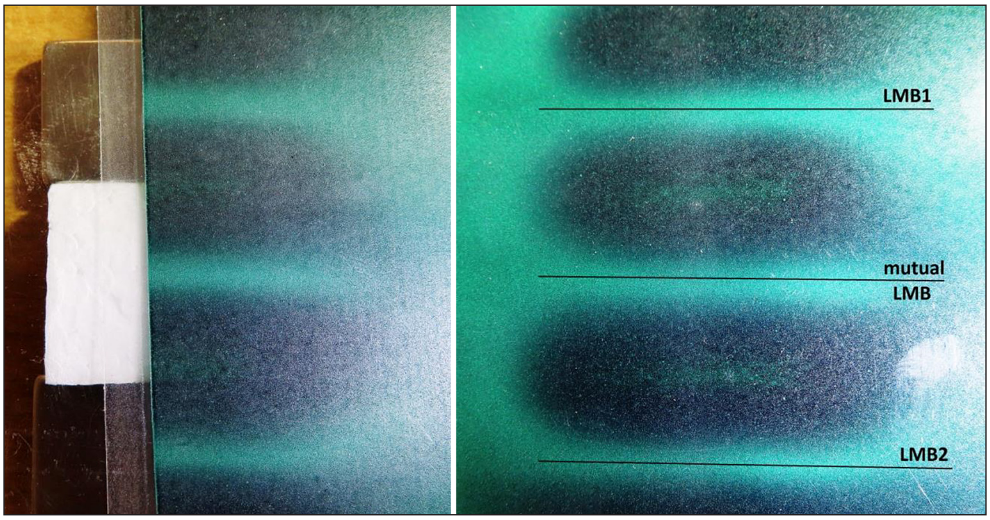

Figure 9. Two attracting permanent magnets separated by a piece of Styrofoam with their own interpolar lines (*LMB1*, *LMB2*) and one mutual line visible

dissimilar poles of two permanent magnets, unconnected but distant from each other (Figure 9).

MEASUREMENT METHOD

An experimental test method was used to study the effect of the *LMB* interpolar line of a permanent magnet on a conductor with current, which made it possible to observe the stacking process of a conductor with current within the *LMB* interpolar line of a permanent magnet – depending on the direction of current flow in the conductor and the value of current flowing through the conductor.

In order to physically observe the interaction of the conductor with the current within the *LMB* interpolar line of the permanent magnet, a simple experiment was performed using a MW70x20 cylindrical neodymium permanent magnet, a loop of copper winding wire DNE ø 0.2 mm with a length of 1200 mm and a power source – a 12 V battery. In series in the measuring circuit were included two resistors R1 and R2 1Ω/8W, which limited the maximum current flowing in the loop of copper winding wire DNE ø 0.2 mm – to a value of $I = U/R = 12V/2\Omega = 6$ A. The research out were recorded with a high-speed Sony FDR-AX700 digital camera at 1000 fps with parameters:

- Multi-layer image sensor: CMOS Exmor RS type 1.0 (13.2×8.8 mm);
- Recording: 4K HDR (HLG);
- Resolution: 14.2 megapixels (16:9);

- Lens: wide-angle (29.0 mm) ZEISS Vario-Sonnar T;
- Zoom: optical 12×, digital zoom 192×;
- Image processor: BIONZ X;
- Focus: Fast Hybrid AF with phase detection up to 273,000 points;
- Screen: widescreen (16:9) Xtra Fine LCD™ 8.8 cm (3.5”), 1555K dots;
- Color OLED 1.0 cm (3.5”) viewfinder, equivalent resolution of 2359K in color, 296K dots;
- Shutter opening: up to 960 (NTSC)/1000 (PAL) fps in ultra slow motion mode;
- Playback: fast approximately 5× / 10× / 30× / 60×; slow – forward: 1/5 speed, reverse: 1/2 speed.

The circuit diagram is shown in Figure 10.

Course of the experiment

A MW 70x20 neodymium permanent cylindrical magnet was placed with its N pole upwards on a flat, level and hard surface in such a way that the plane in which the *LMB* interpolar line is contained is parallel to this surface. Then a loop of thin insulated winding wire, 1200 mm long and 0.2 mm in diameter, was placed externally around the magnet (at some distance) in a free position. Both ends of the wire were connected via a series limiting resistor R = 2 Ω to a 12 V DC current source – a 12 V / 5 Ah gel battery (Figure 11a). The current flow was switched on by pressing the astable momentary switch and the moment of switching on was indicated by the lighting of the incorporated in parallel in a circuit - blue LED, which was included in the circuit (Figure 11b). After the circuit was switched on, the dynamic movement of the conductor with current in the strong magnetic field of the permanent magnet was recorded with a high-speed digital camera at 1000 fps.

The resistance of the section of wire used in the experiment – 1200 mm long and 0.2 mm in diameter – was 0.64 Ω. The current flowing through the wire loop was 4.54 A. During the experiment, the permanent magnet was arranged in two positions (changing the mutual position of the poles) with different directions of the current flowing in the winding wire. These tests were also performed for another neodymium permanent magnet, a MW 38×12 cylindrical magnet and a DNE winding wire ø 0.3 mm. For both magnets, 10 series of experiments were carried out each at a voltage of equal value. Tests were also performed for several different values of current in the wire.

RESULTS AND DISCUSSION

The course of the experiment is illustrated in Figures 11. With the use of a high-speed camera, the time of the research performed was also recorded. The recorded end result (Figures 11c and 12) was the winding of 3 scrolls of the winding wire with the current around the circuit of the neodymium cylindrical permanent magnet at the height of the *LMB* interpolar line. When the current was disconnected, the wire, by means of elastic forces, partially unwound and the retained coils did not adhere tightly to the *LMB* of the permanent magnet.

The research carried out confirmed the thesis that a conductor with current placed in the vicinity of a permanent magnet arranges itself around the *LMB* interpolar line of that magnet while maintaining the proper direction of the flowing current. In the example shown, the winding time for the first scroll of wire around the permanent magnet’s *LMB* was 95 ms, the second scroll was 274 ms and the third scroll was 220 ms. The total

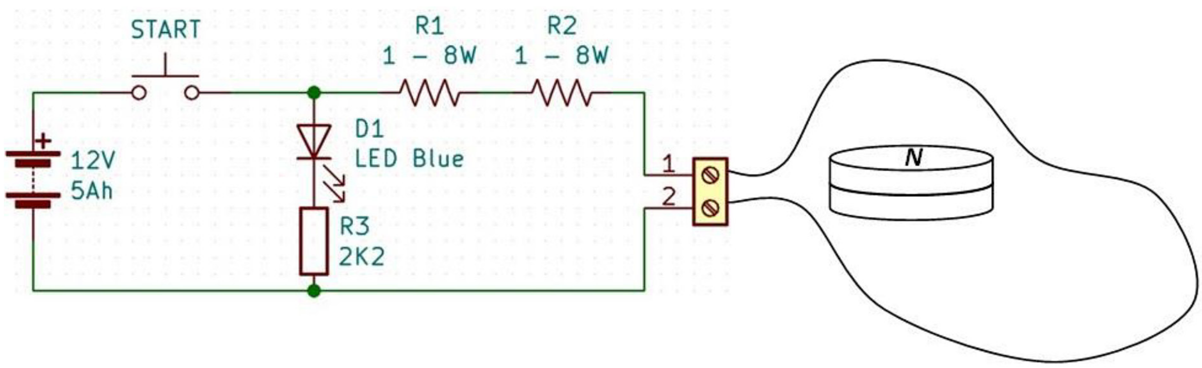

Figure 10. Electronic circuit diagram of experiment

a)

b)

c)

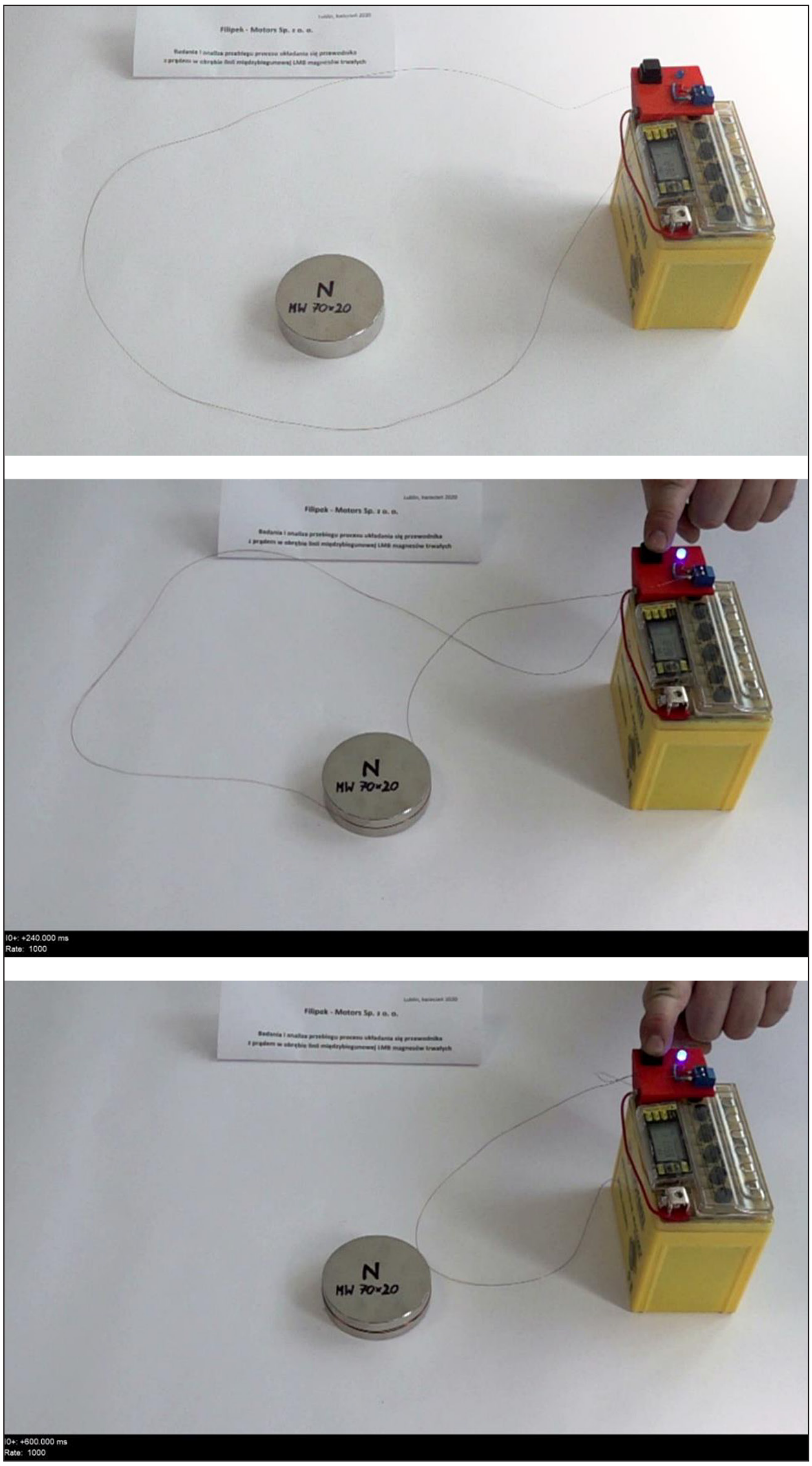

Figure 11. Experiment – initial state (a), experiment – 0.24 s after power on (b), experiment – 0.60 s after power on – termination (c)

winding time for all 3 scrolls was 589 ms, with the first scroll winding unobstructed, the second scroll bouncing off the battery wall and the third scroll wrapping behind the battery - introducing additional delays. The varying state of wire tension throughout the winding phase should also be taken into account. In addition, the third scroll in the final phase instead of winding up - overlapped, which significantly reduced the winding time. The average winding time per one scroll in 10 series was estimated to be about 150 ms. The theoretical basis for the process of laying a

Figure 12. Magnification of the final alignment of the current carrying conductor within the *LMB* of the permanent magnet (3 scrolls)

conductor with current along the interpolar line of the *LMB* of a permanent magnet, and a description of the physical phenomena occurring within the *LMB* and the forces acting on the conductor with current – is included in the introduction. Therefore, in the experiment carried out, an elastic conductor with current (Figure 11) lying inertially near the permanent magnet was attracted to the *LMB* line of the permanent magnet under *F* forces in such a way that it adhered towards her and wrapped around it tightly and uniformly.

The *LMB* line can be easily determined visually using an experiment with a permanent magnet and a flexible conductor with current (Figure 12), or using magnetic film (Figure 7).

Conducting an experiment with a conductor with current placed near the *LMB* interpolar line of a permanent magnet and analyzing this phenomenon made it possible to establish four cases depending on the configuration of the permanent magnet's poles and the direction of the current flowing in the conductor. Depending on the alignment of the *N* and *S* poles of the permanent magnet (the direction of the magnetic field strength) with respect to the direction of the flowing current *I* in a conductor arranged parallel to the *LMB* line of the permanent magnet – four cases of force *F* can be presented. The conductor with current *I* is either attracted to the *LMB* line or repelled from it (Figure 13).

CONCLUSIONS

With the help of the experiment, the occurrence of the effect of winding the wire with current on the *LMB* interpolar line of the permanent magnet was confirmed. The observed movements of the conductor with current in the magnetic field of the cylindrical permanent magnet allow us to conclude that:

1) A conductor with current placed in the vicinity of a permanent magnet arranges (winds up) on the *LMB* interpolar line of that magnet while maintaining the corresponding direction of the flowing current.
2) Changing the direction of the current in the same arrangement of the permanent magnet causes the conductor with current to be repelled from the *LMB* interpolar line of that magnet. The loose conductor revers around and starts winding on the *LMB* line in the opposite direction.

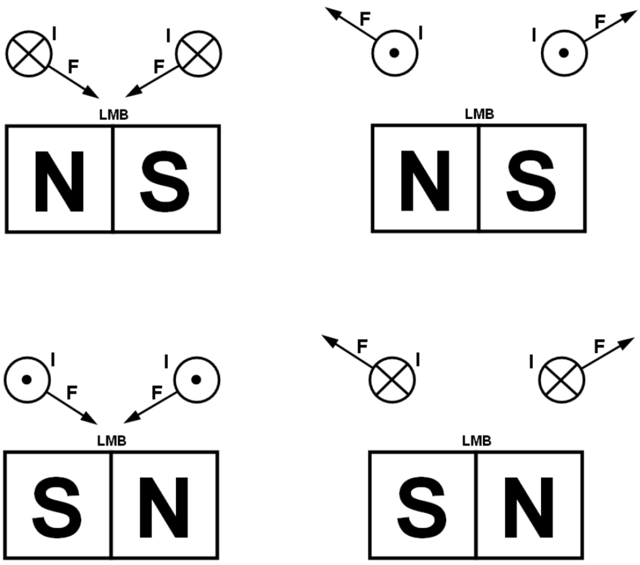

Figure 13. Four cases of force *F* acting on a conductor with current *I* near the *LMB* of a permanent magnet

3) The greater the value of the current in the conductor, the more forcefully and rapidly it wraps around the interpolar line *LMB* of the permanent magnet.
4) The larger the permanent magnet is in terms of dimensions, the more forcefully and rapidly the conductor with current winds around the interpolar line *LMB* of this magnet.
5) After the current in the conductor that has wound around the *LMB* interpolar line of the permanent magnet disappears, its inertial free motion associated with the elastic forces and stresses of its attached ends follows.

The introduction of the definition of the *LMB* interpolar line of a permanent magnet is helpful in the development and construction of technical devices using the *LMB* phenomenon. This definition simplifies the description of the operation of the device, according to which – the winding with current is attracted – or repelled from the *LMB*.

On the basis of the experiment carried out related to the action of force on a conductor with current located nearby the interpolar line of the *LMB* of a permanent magnet and the cases shown in Figure 13, various devices can be built using this phenomenon. These can include various types of solenoid valves, electromagnets, vibrators, sound transducers, speed rotation sensors, linear and rotary motors, generators, and many others.

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