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EXPERIMENTAL STUDY OF THE DEPENDENCE OF MAGNETIC FIELD INDUCTION ON CURRENT STRENGTH AND DISTANCE

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Abstract

This article scientifically covers the physical nature of the magnetic field generated by an electric current, the main properties of magnetic induction, and its dependence on the current strength and the distance from the current-carrying conductor to the observation point. The study uses an analytical approach based on the Biot–Savart–Laplace law and Ampere's law to analyze the induction expressions for the fields of a straight conductor, a circular coil, and a solenoid. The methodological structure of the experimental study, the assessment of measurement errors, and the interpretation of the results are considered.

Keywords

magnetic induction, current strength, Biot–Savart–Laplace law, Ampere's law, magnetic permeability, straight conductor, solenoid, Hall sensor, superposition principle, measurement error.

Introduction. The connection between electricity and magnetism is one of the most important discoveries in the history of physics. In 1820, Hans Christian Oersted observed the deflection of a magnetic needle near a current-carrying conductor, and the idea that a magnetic field is created around moving charges gained scientific support. Later, research by Biot, Savard, Laplace, and Ampere allowed us to determine the quantitative relationship between current and magnetic field. Today, these relationships are widely used in such fields as electrical engineering, electronics, medical diagnostics, materials science, and energy.

The main force characteristic of a magnetic field is the magnetic induction vector, which describes the force effect of the field at each point in space. Experimental study of its dependence on current strength and distance is of great importance in terms of

confirming theoretical laws, forming physical thinking in pupils and students, and developing practical measurement skills. The problems of teaching and learning electric and magnetic fields at the university level were thoroughly analyzed by Saarelainen, and the study emphasizes the role of experiment and modeling in students' mastering the concepts of fields.

The purpose of the study is to analytically analyze the dependence of magnetic field induction on current strength and distance and to develop methodological foundations for its experimental verification. To achieve the goal, the following tasks were set: to clarify the physical essence of the concept of magnetic induction; to show the interrelation of the Biot–Savart–Laplace and Ampere laws; to analyze the induction expressions for conductors of different geometries; to justify the experimental scheme and measurement procedure; to discuss the expected results and sources of errors.

Theoretical foundations. Physical essence of magnetic induction. A magnetic field is created by moving electric charges and a changing electric field. The magnetic induction vector is introduced as a description of the strength of the field. Its magnitude can be determined by the ratio of the maximum force acting on a test charge or current element to the magnitude of the current element. In the International System of Units, the unit of magnetic induction is the tesla, and one tesla corresponds to the force exerted by a conductor one meter long carrying one ampere of current perpendicular to the induction lines by one newton.

Magnetic induction is a vector quantity, the direction of which is determined by the right-hand rule. If the forward motion of the armature corresponds to the direction of the current, the direction of rotation of its handle indicates the direction of the induction lines. Magnetic induction lines are closed loops , they do not have starting and ending points. This is due to the fact that individual magnetic charges (monopoles) are not observed in nature and is mathematically expressed in the form of the fact that the magnetic induction flux through any closed surface is zero.

Biot–Savart–Laplace law. In 1820, Jean-Baptiste Biot and Félix Savart measured the period of oscillation of a magnetic needle near a straight current-carrying conductor and found that the field strength is inversely proportional to the distance from the

conductor. Pierre-Simon Laplace generalized these results and proposed a differential law for the field produced by a current-carrying element. According to the law, the magnetic induction produced by a current-carrying element at any point in space is directly proportional to the current strength, the length of the element, and the sine of the angle between the element and the radius-vector, and inversely proportional to the square of the radius-vector. The proportionality coefficient is equal to the ratio of the magnetic constant in vacuum to four pi, which is approximately equal to four pi to the power of ten minus seven, that is, 1.2566 henrys divided by meters.

Ampere's law (law of total current). The circulation of the magnetic induction vector along an arbitrary closed contour is equal to the product of the algebraic sum of the currents enclosed by this contour times the magnetic constant. This law significantly simplifies the calculation of the field in systems with high symmetry, that is, in cases such as infinitely long conductors, coils, and solenoids. The law is true for stationary currents, and was generalized by Maxwell for alternating fields by introducing the displacement current. Ampere's law and the Biot–Savart–Laplace law lead to mutually equivalent results in the stationary case, but the former represents an integral approach, and the latter a differential approach.

Induction expressions for different geometries.

From a straight conductor of infinite length. As a result of integrating the Biot–Savart–Laplace law along an infinitely long straight conductor, it is determined that the magnetic induction modulus at a point at a distance r from the conductor is equal to the ratio of the product of the magnetic constant and the current strength to two pi and the product of the distance. Therefore, the induction is directly proportional to the current strength and inversely proportional to the distance. The induction lines consist of concentric circles lying in a plane perpendicular to the axis of the conductor. This result also follows directly from Ampere's law: the induction circulation along a circular contour with radius r is equal to the product of the induction modulus and the length of the circle, and it must be equated to the product of the current in the conductor and the magnetic constant. From a straight conductor of finite length. In a real experiment, the length of the conductor is finite. In this case, the induction depends on the difference of

the sines of the angles of view from the observation point of the ends of the conductor. Near the middle of the conductor and at small distances relative to its length, the result is close to the formula for an infinitely long conductor, and as the distance increases, compared with the length of the conductor, the field decreases faster than the inverse distance law. Therefore, in the experiment, it is recommended to place the observation point significantly closer to the length of the conductor.

Circular current (winding). On the axis of a circular winding with radius R, at a point at a distance z from the center, the magnetic induction constant is equal to the product of the current strength and the square of the radius divided by two, and is equal to the ratio of the sum of the squares of the radius and the distance to the third power. At the center of the winding, the induction is equal to the ratio of the magnetic constant and the product of the current strength to the second power of the radii. At large distances on the axis, the induction decreases inversely proportional to the third power of the distance, which is a characteristic of the magnetic dipole field. The dependence on the current strength in this case is also linear.

Solenoid. Inside a solenoid, the length of which is much greater than the diameter, the field is almost uniform, and the induction is equal to the product of the magnetic constant, the number of turns per unit length, and the current strength. Outside the solenoid, the field is very weak. If a ferromagnetic core is inserted inside, the induction increases in proportion to the relative magnetic permeability of the medium, but in this case the linear relationship with the current strength may be violated due to the phenomenon of saturation.

Experimental methodology.

The purpose of the experimental study is to verify two main relationships: the first, the dependence of induction on current strength when the distance is constant; the second, the dependence of induction on distance when the current strength is constant.

Equipment and supplies. The experiment requires a constant current source with adjustable voltage and current, an ammeter, a set of sufficiently long straight copper conductors or several parallel conductors, a circular coil or solenoid, a Hall effect sensor or teslameter for measuring magnetic induction, a millimeter scale and a displacement

device for accurate distance measurement, as well as connecting wires and a rheostat. The Hall sensor is based on measuring the transverse potential difference across the plate from a semiconductor placed perpendicular to the magnetic field, and this voltage is directly proportional to the induction.

First experiment: dependence on current strength. The sensor is fixed at a specified distance from the conductor. The current strength is increased in equal steps starting from zero, and the induction is measured at each value. The measurement is repeated at least three times at each point, the direction of the current is changed, the zero displacement of the sensor and the influence of the Earth's magnetic field are taken into account. According to the results, a graph of the dependence of the induction strength on the current strength is constructed and its deviation from a straight line is evaluated.

Second experiment: distance dependence. The current is kept constant, and the sensor is moved successively to different distances from the conductor. The results are plotted on a graph of the inverse of the distance or on a logarithmic scale of both quantities. In logarithmic coordinates, the coefficient of deviation of the curve for a straight conductor is expected to be approximately minus one, and at large distances along the axis of a circular coil it approaches minus three.

Methods for monitoring the magnetic field by external measurements are also used in practical diagnostics. For example, Bavab developed a method for non-invasively determining the internal current distribution in fuel elements by external magnetic field measurements; this approach is an example of how to use it to solve the inverse problem of the dependence of magnetic induction on distance and current distribution. The work of Kolell, Blumich, and Appelt, who studied nuclear magnetic resonance spectroscopy at low fields, shows the importance of stable and homogeneous generation and accurate measurement of small induction fields.

Error estimation. The main sources of error are: instrumental error of the ammeter and sensor; uncertainty in distance measurement, especially at small distances; finite size of the sensitive surface of the sensor and its incorrect orientation relative to the axis of the conductor; influence of the Earth's magnetic field and surrounding ferromagnetic objects; change in resistance due to the finite length of the conductor and its heating.

The rule of square addition for relative error is used to estimate the total contribution of the errors in measuring current, distance, and induction.

Results and discussion

Based on the generalization of analytical analysis and experimental methodology, the following results were formed.

First, in all the considered geometries, the magnetic induction is directly proportional to the current strength. This conclusion follows from the participation of the current strength in the first degree in the Biot–Savart–Laplace law and the validity of the superposition principle in the case of a linear medium. The experimental graph is expected to be in the form of a straight line passing through the origin; the difference of the initial ordinate from zero is usually explained by the external background field or the displacement of the sensor. In the presence of ferromagnetic materials, linearity is violated due to hysteresis and t- play, therefore it is advisable to use systems with pure air or non-magnetic cores.

Secondly, the distance dependence is strictly dependent on the geometry of the field source. For an infinitely long straight conductor, the induction is inversely proportional to the distance, that is, when the distance is doubled, the induction decreases by half. At large distances from the coil on the axis of a circular coil, the induction decreases inversely proportional to the cube of the distance, since the coil acts as a magnetic dipole. Inside the solenoid, the field is practically independent of the distance from the axis, and outside it decays rapidly. These differences indicate that the spatial structure of the field is determined by the geometry of the source.

Thirdly, when interpreting the experimental results, it is necessary to distinguish between the concepts of near and far zones. At very close distances from the conductor, the finite size of its cross-section and the distribution of the current density must be taken into account: inside the conductor, the induction increases directly proportionally to the distance from the center, reaches a maximum at the surface, and then begins to decrease inversely proportionally outside. The sensor dimensions and its minimum distance from the conductor must therefore be chosen carefully. The work of Bommier, devoted to the coordination of vertical and horizontal gradients of the sunspot field, also shows the

importance of taking into account the structure of the field source and the divergence-free condition for the correct interpretation of the field gradients, although it concerns an object of a different scale.

Fourth, the fundamental aspects of the theoretical models should be discussed. The Ampere, Biot–Savart–Laplace, and Weber approaches give the same measurable results for closed current loops, so it is difficult to distinguish them experimentally. However, when the current elements are considered separately, they give different force expressions, and this issue remains controversial in theoretical physics. The concept of field-free electrodynamics proposed by Moerkamp, however, has raised questions about the physical reality of the magnetic field by showing that electromagnetic effects can be described without the concept of a field, through direct relations between charges. Nevertheless, the classical field approach is the most reliable and practically convenient model for master's level learning experience.

Fifth, the practical applications of the experiment are wide. In electric power engineering, the assessment of the field around overhead lines, the creation of a homogeneous field for magnetic resonance devices in medicine, the non-invasive observation of current distribution in fuel cells and batteries, as well as spectroscopic measurements in small areas rely on these laws. Therefore, a precise study of the dependence of current and distance is not only educationally important, but also from an engineering point of view.

Sixth, recommendations were developed to improve the quality of the experiment: conducting measurements away from ferromagnetic objects; taking the average value by reversing the current direction; setting the sensor to zero before each measurement; amplifying the signal using several parallel conductors or a multi-turn coil; connecting the current for a short time to limit the heating of the conductor; processing the results using the least squares method. These measures reduce systematic and random errors and improve the agreement with theoretical predictions.

Conclusion.

According to the results of the study, the magnetic field induction is directly proportional to the current strength, and its dependence on the distance is determined by

the source geometry: for a straight conductor, it is inversely first-order, for a long zone of a circular coil it is inversely third-order, and inside a long solenoid it is practically unchanged. While the Biot–Savart–Laplace law is a general calculation tool, Ampere's law provides an effective solution for systems with high symmetry. The experimental methodology is based on quantitative verification of the two main dependencies using a Hall sensor, error estimation, and logarithmic analysis of the results. The conclusions obtained can be used both in the educational process and in practical measurement problems.

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