Visualizer of magnetic fields

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Abstract. The method of constructing of the optical image of the magnetic field intensity spatial structure distribution with the help of the ferrofluid cell is considered. The experimental research results showed, that the suggested method allows to determine in real time besides the intensity lines structure also the irregularity of the magnetic field and its direction. The possibility of the magnetic system tuning with the help of intensity field lines optical image was examined having in view the realization of necessary field parameters in the course of the experiment. The experimental research results of the magnetic system constructing and tuning quality at different temperatures are represented.

1. Introduction

In order to solve many problems of applied and theoretical physics, as well as to improve the operation efficiency of different devices and instruments (for instance, thermomagnetic engines, spectrometers, magnetic sorting systems, etc.) one must create between the magnetic system pole tips the fields with the assigned values of magnetic induction and its irregularity, as well as with the intensity field lines structure [1, 2]. In order to measure the magnetic field induction B and it is irregularity ∆B were developed and successfully applied methods based on the Hall’s sensor and nuclear magnetic resonance [3]. But difficulties appeared while investigating the intensity field lines spatial structure between the poles in of the system. The measured values of B and ∆B in the different points of the gap between the magnetic tips don’t allow the construct the adequate pictures of the intensity field lines.

The traditional methods of intensity field lines image construction with the help of magnetic particles or needles either can’t be applied or give the image of lines only in one plane. One can use a vessel filled with the liquid having magnetic particles and immerse the magnetic system into it to get the spatial image of lines but it is not rationally, because the size and weight of magnetic systems differ greatly. Besides that, the tuning of the magnetic system placed in liquid is impossible.

Besides that, in magnetic system where "shimaes" [4] are used in order to improve the uniformity of the magnetic field in the gap between the magnetic poles tips, the magnetic particles form the united structure, because the force lines are located too close. In case the width of the gap between the poles is smaller than 10 cm it is rather difficult to observe the spatial structure of the force lines, because the most of particles are attracted towards the magnetic poles and distort the field distribution with the increase of B (magnetic induction) between the poles the number of attracted particles increases, and the spatial structure of the force lines is destroyed. And the application of this lines method becomes non-effective.

The application of the methods on the basis of the Hall probe line can be effective only in case, if the distance between the measuring elements matches the distance between the force lines. This correspondence it rather difficult to realize in the fields with the high homogeneity of the magnetic intensity. That is why the development of the new methods of the magnetic field force lines spatial images construction represents an actual problem.
2. The method and experimental technique

One of the possible solutions of this problem is the use (the application) of the colloidal solution of the ferromagnetic nanoparticles placed in the glass vacuum-sealed volume of the rectangular form (ferrofluid cell) having different size. This ferrofluid cell can be placed either between the magnetic system poles, or near the magnetic system of different geometry. Under the action of the magnetic field ferrofluid ferromagnetic nanoparticles (in the colloidal solutions the magnetite particles with the size from 30 to 120 mm are used) are magnetized and oriented along the field force lines. The smaller the ferromagnetic particles size, the more precise is the reproduction of the magnetic field force lines structure. Besides that, in case of the extremely high force lines density, the application of such a small particles allows to avoid the effect of the particles fusion with the formation of big clumps in comparison with the case when the iron filings are used. The magnetic field induction $B$ it's the gap between the poles in connected with the magnetic flux $\Phi$ by the formula

$$B = \Phi/S$$  \hspace{1cm} (1)

where $S$ - is the area of one of the poles tip. But this relation is not always suitable, that is why the induction is expressed in terms of the function the force lines density by distribution $j_B$ over the cross section of the magnet between the poles tips. In this case the induction $B$ can be represented in the following way

$$B = \int j_B(S)dS$$  \hspace{1cm} (2)

In this case due to the fact that $j_B(S) \sim N$ (proportional to the number of force lines over the area element), appears the necessity to estimate the quantity $N$ in different points of the space, as well as the distance between the force lines.

If the cell, placed in the magnetic field, is illuminated by the laser light, ferromagnetic particles, located at the force lines, will form a kind of the grating with the spacing equal to $d_p$. The rating spacing is equal to $d_p = a + c$, where $a$ is the thickness of the force lines, on which the ferromagnetic nanoparticles are located and $c$ - is the distance between lines. The constancy of the grating period, for instance, along the length of the magnetic system will depend upon the irregularity of the magnetic field. For the solution of different problems, the direction of the magnetic field irregularity investigation is chosen depending upon the configuration of the magnetic system or magnet. For example, while investigating the inter polar space of the magnetic system; in which the magnetic induction $B$ is orientated along the axis $z$, the density of the force lines distribution must be checked (controlled) both along the $x$ and $y$ directions.

In the figure 1 the experimental set-up for the investigation of the magnetic field uniformity represented. The laser radiation is focused by the lens 3 onto the assigned space region of the ferrofluid cell 4, placed in the magnetic system 5. The ferrofluid cell is installed on the special non-magnetic construction so that it can be moved over the magnetic field area, where one must know the field force lines distribution for carrying out different experiments [1,2,5-7]. While performing experiments the ferrofluid cells with different thickness of the colloidal solution layer $d_k$ in the direction of the laser radiation propagation are used, that is why for the regulation of the dissipated laser radiation (diffraction picture), received by the camera, the polarizer 6 is used. The diffraction pictures images are processed with far help of special programs.
Figure 1. The arrangement of the experimental installation. 1 – semiconductor laser; 2 – diaphragm; 3 – lens; 4 – ferrofluid cell; 5 – magnetic system; 6 – polarizer; 7 – camera; 8 – computer.

The diffraction picture of the laser radiation passed through the ferrofluid cell, that is registrated by the camera, represents a number of alternating maxima and minima. If the period \( d_p \) is constant in the area of the laser radiation influence on the ferrofluid cell (i.e. the field homogeneity is high), the then diffraction picture is symmetric with respect to the central maximum. In this case for maxima and minima for following relations are valid

\[
d_p \sin \varphi_k = k\lambda, \quad d_p \sin \theta_k = (2k + 1) \lambda/2
\]

where \( \varphi_k \) and \( \theta_k \) - are angles at which the number “k” maxima and minima are registrated.

But before the registration device the radiation passes interfaces of different mediums with different reflection indices, that is why an additional displacement of the diffraction maxima and minima by angles \( \Delta \varphi_k \) and \( \Delta \theta_k \), takes place, that can be calculated for each maximum and minimum. By measuring the angle \( \varphi_1' \) between the zero and first maxima, that is equal:

\[
\varphi_1' = \varphi_1 + \Delta \varphi_1
\]

It is possible to calculation the value of a + c with the help of the relation (3). The similar measurements and calculations can be carried out for the angle \( \theta \) between the zero maximum and zero minimum. As a result, we get two equations with two unknowns, that allow to determine the values of a and c. The received data give a possibility to estimate the distance between the magnetic field force lines (the density of magnetic field force lines). Displacing by the fixed distance the ferrofluid cell over the gap of the magnetic field in the xy plain we investigation the force lines structure in the magnetic system "operational sector" [6-8].

In case the period \( d_p \) in the ferrofluid cell changes due to the non-homogeneity of the magnetic field in the region of the laser radiation influence on the cell, the structure and position of diffraction maxima and minima along the x and y axes will change. Comparing received diffraction pictures it is possible to estimate the change of the irregularity of the magnetic field along the ferrofluid cell displacement direction.

It is necessary to mention also, that during these experiments the medium optical density (the spectral transparent coefficient) value appeared to be a very important characteristics. That is why before the magnetic field irregularity investigation the dependence of the spectral transparent coefficient of colloidal solution upon the different parameters (volume concentrations, nanoparticles size and so on) is determined. At permits selecting the colloidal solution parameters and \( d_k \), exclude the polarizer 6 from the experimental installation. This simplifies the calculation of \( \Delta \varphi_k \) and \( \Delta \theta_k \) values and allows to decrease the errors in calculating a and c.
3. Results and discussion

As an example in the figure 2 (a, b) the curves of the dependence of the colloid solutions transmission coefficient (the intensity relation of the transmitted $I_p$ and falling $I_0$ laser radiation). Upon the light wave length are represented. As the colloid solution the water solution of unidomain magnetite nanoparticles (the volume concentration of 0.027) with kerosene as the surface active substance is used. Before the colloid solution investigation, the cell where this solution is placed must be tested the curve 1 in figure 2a, 2b.

\[ \text{Figure 2 (a, b).} \text{ The spectral transmittance of the colloidal solution of (a) -- graphs 2, 3, 4 correspond to the volume concentration of 0.008; 0.027; 0.054, (b) -- graphs 2, 3 corresponds to a particle size in mm: 60; 80. The thickness } d_k = 1 \text{ mm, } T = 293.1 \text{ K.} \]

The received results analyses shows that during the magnetic field irregularity investigation by colloid solution application one must use the laser radiation of the visible range with $\lambda$ from 500 to 600 nm. It was determined that besides the absorption process in the colloid solution the intensity of the transmitted radiation depends also upon the dissipation process on the ferromagnetic particles (figure 2b).

In the figure 3 (as an example) are represented the registred by the camera images of the laser radiation, transmitted through the ferrofluid cell, placed in the field of the laboratory and in the disk magnet field. The environment temperature was equal to $T = 291.4 \text{ K.}$

\[ \text{Figure 3 (a, b, c).} \text{ The diffraction pattern of the laser radiation: (a) - magnetic field in the laboratory, (b) and (c) - for different directions in of the external magnetic field acting on the cell.} \]

The received results show, that the magnetic field, where the ferrofluid cell was located is non-uniform both in the laboratory and in the area of the disc magnet action. After the transformation of the received images into the pseudo-colors MRI with the help of them it is possible to calculate the integral static-moments, to determine the spot area, the mass center position and orientation of the magnetic field in the area of the radiation influence area for a) – 33.095°, b) – 22.094°, c) – 26.056°.
As a result of the carried out investigation of it was started that for the determination of the magnetic field force lines structure between the poles and the degree of their irregularity the most effective way is to use the ferrofluid cell with thickness $d_k$ equal from 1.5 to 2 mm and with the volume concentration of particles not less than 0.02. For dissipated magnet fields structure investigation, the value of $d_k$ must be not less than 3 mm, and the particle volume concentration must not exceed 0.03. The ferromagnetic cells constructed to day allow to determine the magnetic field direction change of 1 degree with the accuracy of 1 percent.

The experimental results analysis shows the possibility of the magnetic field intensity lines investigation with the help of the suggested method, as well as the field parameters determination by the registered image. Besides that, it is possible to tune more precisely the magnetic system using the image of the scattered laser radiation in order to solve different problems. On the other hand, the experiments carried out, showed that the necessity of the ferrofluidic cell construction improvement, as well as the development of the new colloidal solutions. It is especially actual in case of the visualizer application for the investigation of the geomagnetic field intensity lines in the magnetosphere during the influence of the solar wind upon it. Processes taking place as a result of that influence are the reason of the Earth magnetic storm, northern lights, etc.

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