New method of researches of the magnetic fields force lines structure

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Abstract. A new method for constructing an optical image of the configuration of magnetic field lines using a ferrofluid cell with a magnetic fluid is considered. The carried out experimental researches have shown that the proposed method allows to determine the volumetric inhomogeneity of the field in the magnetic system. It is shown that the optical image can be used in real time to adjust the magnetic system to the minimum induction values ΔB in three planes.

1. Introduction.
One of relevant problems of fundamental physics is the research of structure of force lines of magnetic fields [1-5]. The greatest difficulties arise at the research of structure of force lines of the magnetic field in the interpolar space of magnetic systems of various designs [3-6]. When studying various media using the magnetic systems (spectrometers, tomographs, relaxometrs, etc.) it is desirable to know the picture of force lines of this magnetic system in three planes [6-13]. The use of Hall sensor in most cases allows to obtain information on value of induction B in a point of its placement location [6-11]. For definition of degree of inhomogeneity of magnetic field only in one plane it is necessary to move Hall sensor or place two, three and more sensors along one straight line between poles. It allows to estimate the change of heterogeneity of the magnetic field from the center of the magnetic system to its edges, but it is impossible to construct the picture of force lines of the magnetic field (the distance between force lines is considerably less than between sensors). When moving the Hall sensor an error of determination of the coordinates between poles is sufficiently high [6, 8-11]. The use of sensors on the basis of the phenomenon of the nuclear magnetic resonance (NMR) allows to determine heterogeneity by width of the line ΔB in the volume from which the nuclear magnetic resonance signal is registered [6, 8, 12]. But at its movement there appear the same problems, as with Hall sensor.

One of the possible solutions of this problem can be the method of investigation of force lines of the magnetic field developed by us with the using of a ferrofluid cell.

2. The experimental setup and measurement technique.
As a result of experiments [3, 7, 14] that were conducted by us earlier it was established that nanoparticles in magnetic liquid are located along force lines of a magnetic field. They form the transparent and opaque zones in the ferrofluid cell for a laser radiation with the definite period. This period depends on the inhomogeneity of a magnetic field (i.e. density and configuration of force lines).

Besides, the carried out experiments showed that as magnetic liquid better to use an aqueous solution of one-domain nanoparticles of hematite with a volume concentration 0.054 together with the superficial...
active material (SAM) oxyhydroxide a tetraethylammonium [3, 7, 14]. Now data on structure of force lines in pole space of magnetic systems with "neutral", which are used in spectrometers, flowmeters, magnetometers and etc., are most demanded [5-7, 12, 14]. Information on the degree of inhomogeneity of a magnetic field in three planes of magnetic system as well as the force lines density is necessary for carrying out researches and measurements in various media with use of these devices.

Considering features of magnetic systems with "neutral" (restriction on the directions of impact of a laser radiation on a ferrofluid cell and conditions of registration the scattered radiation passed through it) [5-8, 12, 14] for a research of structure of force lines of a magnetic field in three planes. We constructed two variants of the experimental setup. In one case the diffraction image from the laser radiation which passed through a ferrofluid cell was registered. In two others – the laser radiation reflected from a cell was registered. In the first case used the ferrofluid cell with two transparent sides and the semiconductor laser with \( \lambda = 613 \text{ nm} \). In two other cases a cell with one transparent face and a laser with \( \lambda = 515 \text{ nm} \) was used.

In Figure 1 the block diagram of experimental setup for registration of the diffraction pattern from the laser radiation which passed through a ferrofluid cell is represented. Thickness of a layer of magnetic liquid in it in the direction of action of a laser radiation is equal to \( d_k = 1 \text{ mm} \).

![Figure 1. Structural scheme of experimental setup](image)

As a result of the conducted researches we found peculiarities of measurement of a grating constant of \( d_r \) which corresponds to distance between force lines of a magnetic field. Unlike classical consideration of provision of the diffraction peaks and minima location in case of ferrofluid cell using it is necessary to consider at their definition thickness of \( d_1 \) of the transparent walls of a ferrofluid cell and thickness of a layer of magnetic liquid in it.

Taking into account the established feature the measuring technique of the diffraction peaks location was developed and the corresponding calculation were carried out executed for them. In Figure 2 the scheme of distribution of a laser radiation through a ferrofluid cell in a magnetic field of century is shown the refraction of laser radiation. On borders of media air-glass, glass - magnetic liquid, magnetic liquid-glass and glass-air is taking account refraction of a laser radiation. It is found that the intensity of twice reflected laser radiation from limits of sections of media (glass - magnetic liquid and glass-air) in passed radiation has not significant effect on formation of the diffraction image. Therefore, the derivation of the ratio for the diffraction maxima this part of radiation is not considered. In an experiment the photoreceiving device (screen 3) is placed at the distance \( L \) from a lateral face of a ferrofluid cell. In its plane the diffraction image is registered. The location of each maximum on the screen with respect
its center (a point 0) is defined by order of diffraction \( k \) and depends on the period of the formed diffraction grating \( d_r \).

\[ \frac{d_r^2 - \lambda^2 k_1^2}{k_1^2 \lambda^2} \Delta Y^2 + 2L \frac{k_1^2}{d_r^2 - k_1^2 \lambda^2} \Delta Y + 4L^2 \frac{k_1^2 \lambda^2}{(d_r^2 - k_1^2 \lambda^2)} \frac{d_r^2 - k_2^2 \lambda^2}{k_2^2} - L^2 = 0 \quad (1) \]

where \( L \) – distance between the ferrofluidic cell and camera; \( k_1 \) and \( k_2 \) - orders of diffraction maxima (\( k_2 > k_1 \)).

The recorded diffraction pattern measures \( \Delta Y \) (the distance between peaks) for the corresponding values of \( k_1 \) and \( k_2 \). From the measured value of \( \Delta Y \), using (1), the value of \( d_r \) is determined as the order of the diffraction grating (the distance between force field lines in investigation plane of the magnetic system space between poles).

In Figure 3 the block diagram of the experimental setup for registration of the diffraction pattern in the reflected laser radiation is represented. In the conducted researches the ferrofluid cell 4 with one transparent side is used. Thickness of a layer of magnetic liquid in a ferrofluidic cell is equal to \( d_k = 3 \) mm. It is enough that the reflected intensity from an opaque side of a ferrofluid cell did not influence formation of the diffraction pattern in the reflected radiation.

**Figure 2.** Scheme of propagation of laser radiation rays in a ferrofluidic cell when a diffraction pattern is recorded in transmitted light: 1 - walls of a ferrofluidic cell; 2 - magnetic fluid layer in the direction perpendicular to the magnetic field with the thickness equal to \( d_r \); 3 - the screen.

As a result of the made experiments by us it was determined that on distance \( L = 20 \) cm value of the additional padding shift along the axis of \( OY \) which is formed due to the refraction of radiation on borders of media is of infinitesimal size in comparison with the distance between two adjacent maxima long the \( \Delta Y \). This shift in calculating the position of the maxima in the radiation passing through the ferrofluidic cell, in contrast to the consideration of the case with the registration of the radiation reflected from it, is inadvisable. Therefore, to determine the distance \( \Delta Y \) between the peaks \( k_1 \) and \( k_2 \) in the diffraction pattern on screen 3 (Figure 2) we obtained the following relation:
Figure 3. Structural scheme of experimental setup 1 – semiconductor laser; 2 – diaphragm; 3 – lens; 4 – ferrofluid cell; 5 – magnetic system; 6 – polarizer; 7 – photosensitive element; 8 – processing device.

In Figure 4 the scheme of distribution of beams of a laser radiation in a ferrofluid cell is represented.

Figure 4. Scheme of propagation of laser radiation rays in a ferrofluid cell when a diffraction pattern is recorded in reflected light: 1,3 - walls of the ferrofluidic cell; 2 – the layer of the magnetic fluid with the thickness equal to $d_r$ in the direction perpendicular to the magnetic field; 4 - the screen.

For the recorded diffraction pattern in a reflected light positions of the diffraction peaks along the axis OY were determined as well as the value of their shift $\Delta Y_k$, arising because of refraction of a laser radiation on borders of four media: air – glass, glass – magnetic liquid, magnetic liquid – glass, glass –
air. The screen 7 (a photosensitive element) when carrying out calculations was placed at the distance \( L \) from a ferrofluid cell. The laser radiation illuminated the ferrofluid cell in point A at an angle \( \alpha_1 = 45^\circ \). Then radiation after refraction on cell wall once again feel on the diffraction grating formed by nanoparticles with the period equal to \( d \). The structure of the diffraction grating from which the "reflection" takes place at the distance \( d_1 \) from the internal wall of the ferrofluid cell. In this case for calculation the value \( \Delta Y \) we derived the following ratio:

\[
\Delta Y = \frac{d_c}{d_t} \left[ \frac{t_1}{1 - \frac{t_1^2}{d_t^2}} - \frac{t_2}{1 - \frac{t_2^2}{d_t^2}} \right] + d_1 \cdot n_m \cdot \sqrt{\frac{1 - \frac{t_1^2}{d_t^2}}{n^2 - n_m^2 \left( 1 - \frac{t_1^2}{d_t^2} \right)}} - \sqrt{\frac{1 - \frac{t_2^2}{d_t^2}}{n^2 - n_m^2 \left( 1 - \frac{t_2^2}{d_t^2} \right)}} + \\
+ L \cdot \frac{\sqrt{\frac{n^2 - n_m^2 \left( 1 - \frac{t_1^2}{d_t^2} \right)}{1 - n_m^2 \left( 1 - \frac{t_1^2}{d_t^2} \right)}} - \sqrt{\frac{n^2 - n_m^2 \left( 1 - \frac{t_2^2}{d_t^2} \right)}{1 - n_m^2 \left( 1 - \frac{t_2^2}{d_t^2} \right)}}}{1 - n_m^2 \left( 1 - \frac{t_2^2}{d_t^2} \right)}
\]  

(2)

(3)

where \( n_m \) – the refractive index of a magnetic fluid, \( n_c \) – refractive index of the transparent glass wall of the cuvette, \( d_1 \) – distance from the cell wall to the first layer of nanoparticles in a magnetic fluid that forms a diffraction grating, \( k_1 > k_2 \) – orders of diffraction maxima.

Our calculations showed that the difference \((\alpha_1 - \alpha_2)\) between the angles of the laser radiation leaving the ferrofluidic cell at point B (after all 4 refractions) from the direction of the beam at point C (the classical diffraction case in reflected radiation) is less than \( 0^\circ 30' \), the value of \( \Delta Y_k \) - less than \( 10^{-3} \) mm. Therefore when determining the position of the diffraction peaks this shift on an axis of OY was taken into account in (2) unlike the case of the diffraction pattern in registration in the radiation passed through a ferrofluid cell.

Measuring distance between maxima of the diffraction pictures \( \Delta Y \) which is registered by means of photosensitive element 7 (Figure 3), it is possible to calculate by means of (2) of the diffraction grating \( d_c \) in a zone of its placement in pole space of magnetic system. And it is also possible define structure of force lines of magnetic field in this plane.

The experiments carried out showed that it is much more difficult to take into account to shift value \( \Delta Y_k \) in the reaction (2) when in a case angle of incidences of a laser radiation are considerably differing from \( 45^\circ \). Therefore, at a research of magnetic systems of the complex configuration there can be difficulties when determining size \( \Delta Y \) in various points of pole space. It is the single possible restriction in application of this method.

3. Results and its discussion.

In Figure 5 is represented as an example the diffraction pattern (after computer processing) from the laser radiation which passed through a cell in the direction perpendicular to an induction B of a magnetic field. Transparent faces of the cell are located perpendicular to the laser radiation incident on them and the side faces of the "neutral" of the magnetic system. In addition, the transparent faces of the cell are parallel to the bases of the "neutral" magnetic system. For the magnetic field lines that are located in the interpolate space of the magnetic system the direction must be perpendicular to the pole tips for both the electromagnets and the permanent magnets. At present use cylindrical tips in magnetic systems. The side surfaces of cylindrical tips must be strictly parallel to each other and the lateral faces of the "neutral". This ensures the maximum value of B and the minimum value of \( \Delta B \) in the interpolate space.
The angle between the surfaces of the side faces and the base should be 90°. Numerous experiments have shown the inexpediency of using magnetic systems in which the pole tips are parallel to one another, but located at different angles to the side faces and the base of the “neutral”.

![Figure 5 (a, b).](image)

**Figure 5 (a, b).** The diffraction pattern of the laser radiation in the case of the magnetic fluid placing: (a) in a uniform magnetic field; (b) in an inhomogeneous magnetic field.

In Figure 6 the dependence of distribution of intensity of the recorded laser radiation on the vertical section of a ferrofluid cell at the choice of a line on the center of the image (Figure 5) recorded by a photoreceiving device is presented as an example.

![Figure 6 (a, b).](image)

**Figure 6 (a, b).** The graph of dependence of intensity as function of force lines of a magnetic field (a) in a uniform magnetic field (b) in an inhomogeneous magnetic field.

The analysis of the received results allows on distribution of intensity on the section of a ferrofluid cell to make a conclusion on degree of uniformity of a magnetic field and about the distribution of its force lines in this zone of pole space. In case of the homogeneous magnetic field the intensity of the recorded peaks and distance between them with respect to the central maximum are equal. Small deviations in the form of peaks (Figure 6a) can be explained by the irregularity of magnetite particles distribution over the ferrofluid cell volume for various reasons. In case of the inhomogeneity field (Figure 6b) the symmetrical distribution between peaks is absent. The pronounced maximum of intensity in Figure 6b is also absent. It is means that the pole tips of the magnetic system, for example, of the electromagnet, are not parallel to one another or their centers are not located on a straight line that is perpendicular to the side face of the “neutral”.

The experiments carried out that it is more convenient to use the dependences presented in Figure 6 for tuning of magnetic system at the minimum of inhomogeneity of a magnetic field in real time for substance placement in the subsequent in this zone the samples of with investigated medium etc. [5, 7, 12, 14].
During the experiments, additional problems arise in the case of placing transparent faces of the ferrofluid cell not parallel to the lateral bases of the "neutral". Selecting the position of the photoreceiver behind the ferrofluid cell, decoding and subsequent spatial interpretation of the recorded diffraction images into force lines and etc. For example, to obtain information about magnetic field lines in the z-plane, the cell will need to be moved (its coordinates in the x and y plane). On the z axis, it is more efficient to move the laser and the photodetector. The conducted studies are shown inadvisability to have transparent faces of the ferrofluidic cell at angles to the lateral faces and the base of the "neutral", which are not equal to 90° and 180°. During the experiments it was established that the study of the structure of magnetic fields using ferrofluid cells to obtain results with an error of not more than 1% should be carried out in the temperature range T from 283 to 313 K. The temperature of the ferromagnetic liquid in the ferrofluid cell in the interpolar space of the magnetic system was controlled by an infrared remote temperature meter Testo 845 (Testo AG-Germany) along the end of the ferrofluid cell. The sensitivity to the temperature change of this device is 0.1 K. The temperature of the poles of the magnetic system was controlled by Testo 845. In experiments we used an electromagnet to create a magnetic field. That made it possible to create a magnetic field with induction B from 0.0005 to 0.86T. The value of B was controlled by a magnetic induction meter SH1-1 (NMR sensor - magnetic field is measured at the resonance frequency of protons) and measure AC and DC magnetic field DX-160 (Hall sensor). The inhomogeneity of the magnetic field was measured by SH1-1 along the line width Δf_res of the NMR signal at the resonance frequency. In modern stationary NMR spectrometers and relaxometers (for example, ER-100M or Minispec - Bruker), an electromagnet is used in vibrating sample magnetometer (for example, VSM model 7410 - Lake Shore Cryotronics Inc.) to generate magnetic fields with induction up to 2.6 T [14 -16]. In desktop NMR spectrometers (for example, Pulsar - from Oxford Instruments) to create magnetic fields B up to 2 T the permanent magnets are used. In portable (small-size) NMR spectrometers and relaxometers, systems with the permanent magnets are used too [12, 16, 17]. At present, in all the devices considered for the study of condensed matter in the temperature range T from 283 to 313 K the magnetic systems are stabilized.

4. Conclusion
The received results of experimental investigations showed that on the measured values of a grating constant in three planes of pole space of magnetic system with use of two types the ferrofluid of cells it is possible to construct a volume picture of force lines of a magnetic field. Such image of a configuration of force lines cannot be received when carrying out even approximate calculations of fields of magnetic systems.

As a result of researches we also found that in the ferrofluid cells for a research of structure of force lines of magnetic fields it is desirable to make its transparent sides of a quartz glass. It considerably reduces influence of various re-reflected radiation on intensity and position of maxima in the recorded diffraction image.

5. References
[1] Suharnikov K V, Rychkov M M 2015 Radiophysics and Quantum Electronics 58 132-138
[2] Cherepov C V, Moroz O H, Derecha D A 2011 Radiophysics and Quantum Electronics 54 137-145
[3] Logunov S E, Koskin A Yu, Davydov V V, Petrov A A 2016 Journal of Physics: Conference Series 741(1) 012092
[4] Zaitsev N I, Ilyakov E V, Kulagin I S, Shevchenko A S 2006 Radiophysics and Quantum Electronics 49 120-127
[5] Karseev A Yu, Vologdin V A, Davydov V V 2015 Journal of Physics: Conference Series 643(1) 012108
[6] Davydov V V, Dudkin V I, Karseev A Yu 2015 Technical Physics 60 456-460
[7] Davydov V V, Dudkin V I 2016 Technical Physics 61 1115-1119
[8] Davydov V V, Dudkin V I, Karseev A Yu 2015 Instruments and Experimental Techniques 58 787-793
[9] Kudasov Yu B, Makarov I V, Maslov D A, Platonov V V, Popov E Ya, Surdin O M, Voronov S L, Malyshev A Yu, Korotkov S V, Vodovozov V M 2015 *Instruments and Experimental Techniques* **58** 781-787

[10] Stolypko A L 2013 *Instruments and Experimental Techniques* **56** 649-654

[11] Cherepov S V, Moroz O Kh, Derecha D A, Hesse O P 2011 *Instruments and Experimental Techniques* **54** 273-279

[12] Davydov V V, Myazin N S 2017 *Measurement Techniques* **60** 183-189

[13] Petrov A A, Davydov V V 2017 *Journal of Communications Technology and Electronics* **62** 289 – 293

[14] Davydov V V, Myazin N S 2017 *Measurement Techniques* **60** 491-496

[15] Davydov V V, Cheremiskina A V, Velichko E N, Karseev A Yu 2014 *Journal of Physics: Conference Series* **541**(1) 012006

[16] Davydov V V, Velichko E N, Dudkin V I, Karseev A Yu 2015 *Instruments and Experimental Techniques* **58** 234-238

[17] Davydov V V, Dudkin V I, Karseev A Yu 2015 *Russian Physics Journal* **58** 146 – 152.