Optical method for studying the magnetic field structure

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Abstract. The article discusses the photometric method for recording the variation of the magnetic field. The features of registration and processing of the signal of dispersion of a magnetic wave from a moving object are established. The basic parameters of an optical sensor for detecting a magnetic wave are determined. The results of experimental studies are presented.

1. Introduction

Currently, one of the actual tasks is to control the variations of the magnetic field to solve various problems [1-6]. The variations of the magnetic field (magnetic waves), which arise for various reasons, must be divided into global and local [1, 7-11]. Global storms include flares on the sun, meteor rain, etc. To local - earthquakes, explosions, the appearance in the area of measurement of moving magnetic objects and much more [7, 12-18]. To register these two types of magnetic field variations (magnetic waves), various types of magnetometers and optical devices based on different physical principles of operation have been developed [1, 3, 5, 7, 8, 18-29]. One of the most difficult tasks is to register variations from a moving object. The magnetic wave attenuates as it moves away from the measurement site. Especially many difficulties arise when solving problems of determining the position of moving magnetic objects in the marine area, especially at deep water [1, 3, 5, 7, 14, 30]. As shown by our studies, the solution of these problems is possible only by either quantum magnetometers, fiber-optic antennas and autonomous quantum sensors [3, 14, 15, 30, 31]. In the case of finding a moving magnetic object in the zone of sensitivity of the measuring device, this problem is successfully solved.

In some cases, especially to determine the position of marine moving objects, it is necessary to establish the probability of its being in a given zone of the marine area before measuring the variations of the magnetic field. The studies conducted by us and other scientists have shown that when a magnetic object moves under water, the magnetic waves form a magnetic track (magnetic track from a moving object) due to dispersion. This path gradually decreases in volume, the variations of the magnetic field in it attenuate. The configuration of variations of magnetic field lines in a magnetic track should reflect the direction of movement of a moving object. From the attenuation of the amplitude of the variations of the force lines, one can estimate the period of time in which they were formed.

Therefore, the task of detecting magnetic tracks in the marine area and the measurement of their characteristics is an actual and relevant task. One of the possible solutions to this problem is presented in our work.
2. The optical sensor and the method of recording the dispersion of magnetic waves.

Our previous studies [14, 15, 30-32] made it possible to establish that when a ferrofluid cell with a ferromagnetic fluid is located in a constant magnetic field. Nanoparticles, for example, hematite, line up in the direction of the magnetic induction vector. This is due to the fact that the energy of the magnetic field acting on the particle is greater than the energy of its thermal motion. Since thermal motion distributes the nanoparticles fairly evenly throughout the ferromagnetic fluid. Therefore, when a ferrofluid cell is placed in a magnetic field, they will shift to its nearest field lines and will be equally distributed as in the absence of a magnetic field.

With this arrangement, the nanoparticles in the ferrofluid cell in the space between the poles of the magnetic system form lines with different degrees of transparency for laser radiation. In the case of a high magnetic field uniformity, these bands are similar to a diffraction grating with a period corresponding to the distance between the magnetic field lines. To register the diffraction pattern from the laser radiation transmitted through the ferrofluidic cell, we developed a compact sensor. This sensor can be used to study magnetic fields (visualization of magnetic field lines), which is currently very important [33, 34]. Its structural diagram is presented in figure 1.

![Figure 1](image_url)

**Figure 1.** Block diagram of the experimental setup: 1 - semiconductor laser; 2 - laser power supply; 3 - electromagnet; 4 - stabilized current source; 5 - ferrofluidic cell; 6 - a specialized camera; 7 - scheme of image processing; 8 - data transmission control scheme; 9 - power supply; 10 - multifunctional voltage source; 11 – fiber-optic communication system.

To create a constant magnetic field in the ferrofluid cell, a specialized solenoid 3 is used. By varying the voltage on the power source 10, the induction of the $B_0$ field can be controlled from 0 to 2.4 mT. This allows, when the solenoid is switched on, to fix the nanoparticles on the magnetic field lines and form a diffraction grating. Further, the induction of the magnetic field decreases to $B_0 = 0.106$ mT (value close to the Earth's field). With this induction value, the field heterogeneity is $10^{-5}$ cm$^{-1}$. The diffraction pattern from the laser radiation transmitted through it, recorded by a specialized camera relative to the central maximum, is symmetrical. Signal processing is carried out by special algorithms and programs [14, 15, 32, 35].

If the solenoid hits the volume of the magnetic track, the position of the diffraction maxima relative to their initial location will change. The nature of these changes will depend on the amplitude of variations of the magnetic field in the magnetic track. If you register changes in the position of these maxima in the diffraction pattern and process the received signal, you can determine the presence of
this track in the marine area, as well as the nature of the attenuation of the amplitude of the magnetic field variations in the track. This will allow us to determine the data we need about the movement of a moving magnetic object that created this magnetic track.

To calculate the position of the diffraction maxima from the laser radiation transmitted through the ferrofluidic cell. In figure 2 shows a diagram of the propagation of laser radiation through a ferrofluid cell in a magnetic field B₀.

![Diagram of laser radiation propagation](image)

**Figure 2.** The scheme of propagation of laser radiation in a ferrofluid cell during the registration of the diffraction pattern from the transmitted radiation: 1 - walls of the ferrofluid cell; 2 - thickness of the magnetic fluid layer in the direction perpendicular to the magnetic field; 3 - screen.

At the boundaries of the mediums, air-glass, glass-magnetic fluid, magnetic fluid-glass, and glass-air take into account the refraction of laser radiation. It has been established that the intensity of doubly reflected laser radiation from the interfaces of media (glass-magnetic fluid and glass-air) does not have a significant effect on the formation of a diffraction image in the transmitted radiation. Therefore, when determining the position of the diffraction maxima, this part of the radiation should not be taken into account. In a quantum sensor, a specialized camera is placed on the spot screen 3 (figure 2) at a distance L from the side face of the ferrofluid cell. A diffraction image is recorded in a plane parallel to the magnetic field lines. The position of each maximum on the screen relative to its center (point 0) will be determined by the diffraction order k and depends on the period of the resulting diffraction grating dr.

For this case, we derived a formula for calculating the position of diffraction maxima on the screen:

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

(1)

where L is the distance between the ferrofluid cell and the chamber; k₁ and k₂ are the orders of the diffraction maxima (k₂ > k₁).

According to the recorded diffraction pattern after its computerized special processing, ΔY (the distance between the peaks of the peaks) is measured for the corresponding values of k₁ and k₂. From the measured ΔY value, using (1), the dᵢ value is determined - the order of the diffraction grating (the distance between the field lines in this interpolar plane of the magnetic system). Having performed the graduation of ΔY from the amplitude of the variation of the magnetic field in different planes of the optical image registration according to the results of studies of magnetic tracks, you can obtain the necessary data.
3. Research results and discussion
Experimental studies were conducted in a specialized pool of the institute. A permanent magnet with an average field induction of $B_m = 0.2 \, \text{T}$ was used as a moving marine object, which in a cylindrical case moved at different speeds at a depth of 2 m. The magnitude of the induction compensated for the size of the magnetic object and the speed, which differed from the real ones. During the research the following results were obtained. So on figure 3 shows a view of a diffraction pattern recorded by a camera placed in the zone where screen 4 was located (figure 2).

![Figure 3](image)

**Figure 3.** The diffraction pattern of the laser radiation in the case of the magnetic liquid placing: (a) in a uniform magnetic field; (b) in an inhomogeneous magnetic field.

Figure 3(a) corresponds to the picture obtained in a uniform field. You can see that the lines of the formed nanoparticles, which correspond to the force lines of a uniform magnetic field, are parallel to each other. This indicates a high value of homogeneity. Figure 3(b) - corresponds to the placement of the optical sensor in the zone with the dispersion of magnetic waves. Diffraction patterns in figure 3 are presented after computer processing.

The result obtained in figure 3.b indicates that the optical sensor is in a magnetic track from a moving object. The greater the distortion in the structure of the diffraction pattern, the closer the center of the magnetic track. Further studies have shown that the magnetic track under the action of relaxation processes decreases in size, and variations in magnetic fields no longer have a significant impact on the location of the maxima in the diffraction image.

The experiments carried out and the results of their analysis showed that the information presented in this form is not very convenient for the operation of electronic systems for processing and transmitting information. Therefore, a row is selected in the registered diffraction pattern (according to the width or height of the diffraction cell). This line is used to construct the distribution of the intensity $I$, of the detected laser radiation. In figure 4, as an example, presents the distribution data in the diffraction pattern for the laser radiation transmitted through the ferrofluid cell.
In one case, the created magnetic field had a high value of homogeneity in the area of placement of the inductance coil with a ferrofluidic cell. In another case (figure 4(b)), the magnetic field uniformity in the solenoid deteriorated due to the placement of the optical sensor in the magnetic track. The intensity distribution I corresponds to the diffraction pattern recorded at a certain point in time $t$. For example, when the distortion of the structure of the power lines in the inductor reached its maximum value.

Studies have shown that changing the position and amplitude of the maxima in the recorded diffraction pattern (figure 4(b)) depends on the time from the formation of the magnetic track, and on the motion parameters of the magnetic object and its mass-dimensional characteristics. This requires a large number of experiments that are not included in the problems solved in this work.

4. Conclusion
The results of experimental studies have shown that the measured values of the position of the diffraction peaks in the recorded images of laser radiation passing through a ferrofluidic cell can determine the presence of a magnetic track in the marine area. A new method for processing dispersion of magnetic waves allows, with an error of less than 10%, to reconstruct the moment of their formation and the technical characteristics of the physical body that participated in the process of forming a magnetic track.

The development of our proposed method for determining and studying the characteristics of a magnetic track can be useful for conducting studies of underwater currents of the seas and oceans at deep water.

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