An optical method for research a magnetic track using speckles of the structure of scattered laser radiation

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Abstract. A new method for detecting a magnetic track from a moving magnetic object is presented. The features of the formation of a magnetic track from a moving object at a depth are determined. A technique has been developed to research the nature of changes in the magnetic field in a magnetic track using ferromagnetic fluid. The optimal sizes of the ferrofluidic cell and the parameters of laser radiation are established. The results of experimental research are presented.

Introduction

The development of scientific and technological progress, climate change on Earth, as well as the emergence in the modern world of new devices and systems constantly pose new challenges for scientists [1-9]. In some cases, to solve them, it is necessary to conduct new research of various physical phenomena [7, 9-15]. One of these phenomena is the magnetic field. With its use, a large number of instruments have been developed for studying various media [16–20]. These instruments are more accurate than optical measurements [21-24]. A sharp change in the parameters of the magnetic field, especially the Earth, leads to various disasters (earthquakes, etc.). A large number of magnetometers and variometers have been developed to measure magnetic field parameters. Among them, the most sensitive and accurate are quantum magnetometers [25-27]. All this made it possible to form a separate section of the physics of magnetic phenomena.

One of the least studied phenomena in the physics of magnetic phenomena is the magnetic track. Particularly great difficulties arise in the study of this phenomenon when it is formed from the movement of a moving object. It should be noted that research of magnetic tracks carried out by various scientists made it possible to establish the physical principle of its formation and some features. Our research have shown that the features of magnetic track formation depend on many factors [28-36]. In some cases, for example, in the air, a magnetic track exists for only a few seconds. At sea depths (more than 550 m), depending on the parameters of the marine object, the boundaries of the magnetic track are more pronounced compared to air. Changes in the magnetic field in the magnetic track at sea depth are more significant. Especially if the magnetic object has an impressive size and moves at high speed. Investigating a magnetic track at sea depths is a very expensive and complex process. Before full-scale tests, it is necessary to study the processes associated with the formation of a magnetic track in laboratory conditions, so that during field research under conditions of time limitation, the process of measuring magnetic field variations can be correctly implemented. Therefore, the development of various methods for conducting research of the magnetic track in laboratory conditions is an urgent task.
The method of magnetic track research
To conduct investigations of the magnetic track in laboratory conditions, we propose using the optical method that we previously developed to study the structure of magnetic field lines using scattered laser radiation and a ferrofluidic cell [28-36]. Figure 1 (top view) shows the experimental setup we developed for studying the magnetic track in the laboratory.

Figure 1. Structural scheme of experimental setup: 1 - power supply; 2 – solenoid; 3 - rectangular vessel; 4 – water; 5 - non-magnetic material; 6 - ferrofluidic cell; 7 – the body; 8 – the laser; 9 - diaphragm; 10 – the lens; 11 - photosensitive element; 12 - polarizer; 13 - processing device.

A magnetic fluid (an aqueous solution of hematite nanoparticles with a concentration of 0.03 - surfactant - oleic acid) is placed on a support of non-magnetic material 5 in a ferrofluidic cell 6. The cell is placed in the magnetic field of the solenoid 2. Induction of the magnetic field $B_0$ in the cell placement zone $68 \, \mu T$. A rectangular vessel 3 with a liquid medium 4 (water) is located between the solenoid and the ferrofluidic cell. Along the length of the vessel 3 moves the body 7, made of permalloy. Laser radiation with $\lambda = 632.8 \, \text{nm}$ enters through the diaphragm and lens onto the transparent surface of a quartz glass ferrofluid cell into which magnetic fluid is placed. Hematite nanoparticles are located in the field of magnetic field lines $B_0$. Scattered laser radiation from hematite nanoparticles that formed agglomerates near magnetic field lines is detected by the CCD camera 11 as speckle structures. With a high uniformity of the magnetic field $B_0$, the recorded diffraction image is symmetric with respect to the central maximum. When the body 7 appears in the magnetic field, the lines of force on it close. The recorded speckle pattern is changing. The rate of destruction of speckle images will depend both on the speed of the body 7, its size and the properties of the material from which it is made.

To register the reflected laser radiation from speckle structures, we use the optical image registration system developed by us [34-36].

The results of experimental research and discussion
In figure 2 shows the recorded images of reflected laser radiation from speckle structures formed by nanoparticles on the lines of force of the magnetic field of the solenoid at different positions of the body.

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Figure 2 (a, b, c). The diffraction pattern of the laser radiation in the case of the magnetic liquid placing: (a) in a uniform magnetic field; (b) a magnetic field force lines are closed on the body; (c) 2 minutes passed after the closure of all the magnetic field lines on the body.

In the absence of body 7 in the magnetic field of solenoid 2, the diffraction image is a symmetric structure (figure 2.a). After the field lines are closed to the body 7, the agglomerates are destroyed under the influence of thermal motion. The recorded speckle pattern is changing. Figure 2.b shows the image of the reflected radiation from the speckle pattern of nanoparticles through $t_z = 20$ s after the closure of the magnetic field lines of the solenoid to the body and at $t_z = 120$ s - figure 2.s The value $t_z = 120$ s is the average time the moving magnetic object passes through a space point at a depth in the zone of formation of the magnetic track. The longitudinal relaxation time $T_1$, which determines the process of magnetization of the substance, for water at a depth of less than 1 s. For complete magnetization of a liquid medium, $3T_1$ time is necessary [21-26].

It should be noted that a change in the magnetic field induction of a moving object also affects the process of magnetic track formation. As an example, Figure 3 shows the images of reflected radiation from the speckle pattern of nanoparticles after $t_z = 5$ s (Figure 3.b) after the magnetic field lines of the solenoid are closed to a moving object with induction $B_0 = 1.7$ mT (previously used permalloy), and at $t_z = 30$ s - figure 3.c.

Figure 3 (a, b, c). The diffraction pattern of the laser radiation in the case of the magnetic liquid placing: (a) in a uniform magnetic field; (b) a magnetic field force lines are closed on the body; (c) 2 minutes passed after the closure of all the magnetic field lines on the body.

A magnet made of a samarium-cobalt alloy was used as a moving object. The direction of the lines of force of the magnetic field of the solenoid and magnet coincide. Analysis of the results in figure 2 and 3 show a change in the nature of the optical image from speckle structures after the field lines are closed to a magnetic object. The process of destruction of speckle structures depends on the speed of
the object in all directions, the recorded image. This shows the possibility of recording changes in magnetic field variations by an optical sensor.

**Conclusion**

An analysis of the obtained diffraction images shows that the optical method we developed allows us to determine the presence of a magnetic track at a depth and to study its parameters depending on various factors. Using the method, we developed allows us to estimate the time of the magnetic track formation from a moving object with an error of no more than 30%.

In some cases, the sensitivity of the developed optical sensors to study the track parameters is not enough. Therefore, it is advisable to use a submersible quantum magnetometer when conducting research in the sea.

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