Features of the construction of the registration scheme of optical images in an autonomous quantum magnetic field sensor

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Abstract. The article describes the design of an autonomous quantum sensor for detecting variations of the magnetic field. The features of the regulation of the diffraction pattern of laser radiation using a ferrofluid cell placed in a uniform constant magnetic field are established. The optimal parameters for the design of the ferrofluid cell, magnetic fluid and laser radiation were determined. The experimental results of the study of the variation of the magnetic field from moving marine objects are presented.

1. Introduction

Currently, one of the urgent tasks is the control of various areas of the marine areas. The greatest interest in solving these problems is the determination of the presence in these areas of mobile marine objects, both surface and underwater [1-4]. Various methods and instruments developed on their basis are used to detect mobile marine objects.

The most effective of them are: acoustics, radar, satellite imagery in good weather, magnetic measurements and fiber-optic antennas [4-10]. It should be noted that devices developed on the basis of these physical phenomena have both advantages and disadvantages. All these devices and devices have proven themselves very well when used on ships and aircraft, where there are no restrictions on the consumption of electrical energy [4-12]. Power limitations when using these devices offline, for example, on a sea buoy (standalone sensor) become decisive. There are many problems with their long-term work offline, as the size and weight of the buoy is limited. It is not possible to place a large battery in it. At the big sizes - the buoy is well noticeable. It is extremely difficult to use such devices for covert monitoring of the state of the region.

It should also be noted that these autonomous devices should not respond to various electromagnetic disturbances that are specifically created to determine the position of such sensors in order to disable them or withdraw them from the water area [2-4, 12].

The most optimal solution for controlling the magnetic environment is the use of magnetometers [6, 7, 10, 13]. A moving magnetic object changes the structure of the magnetic field lines while moving. A variation of the magnetic field is created. The value of this variation can be defined as the presence of a magnetic object and the direction of its movement. Deciphering the map of variations in the magnetic field allows you to determine the configuration of the magnetic object (make it a preliminary identification). This is especially important when controlling movement in a given area of the marine
area of underwater objects. Modern magnetometers, which can record the variation of the magnetic field, for example, quantum or ferrozondovye, have average weight and size dimensions. But for their stable operation, high temperature stabilization in the sea buoy is required, which will require a large power consumption. In addition, they are very expensive, especially quantum, which are less sensitive to fluctuations in external temperature. Creating a system based on quantum magnetometers is only possible when monitoring critical areas or for solving exceptional problems.

Therefore, the development of compact, inexpensive and reliable sensors to solve the problems considered is extremely important. One of the possible directions of its solution may be quantum sensors based on a ferrofluid cell considered in our article. Quantum devices developed earlier by us using ferrofluidic cells have proven themselves well in monitoring the homogeneity of magnetic systems and visualization of magnetic fields [14–20]. When constructing quantum sensors on their basis, a number of features arise when registering optical images of scattered laser radiation. Detailed consideration of them is extremely necessary to create a reliable quantum sensor design for determining the position of a moving magnetic object.

2. The design of the quantum sensor and features registration of optical images.

Our earlier studies have made it possible to establish that if a ferrofluid cell with a ferromagnetic fluid is placed in a constant magnetic field, nanoparticles, for example, hematite, line up along its lines of force [15, 16, 19]. 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 bands 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 [15, 16, 19].

Studies have shown that it is most appropriate to use an aqueous solution of single-domain hematite nanoparticles with a volume concentration of 0.054 with a surface-active substance (surfactant) tetramethyl ammonium hydroxide as the magnetic fluid. We have also found that it is most effective to register diffraction images using laser radiation with λ = 613 nm with a high degree of coherence [18–23]. Specialized video cameras or photodetectors can be used to record image data [19–28].

All this allowed us to develop a design of an autonomous quantum sensor for placing it on various objects, for example, a sea buoy. In figure 1 shows a block diagram of a sensor developed by us with processing and control devices, and a signal transmission to an antenna placed on a buoy or in a block of commands that actuates various mechanisms.

![Figure 1. Block diagram of the laboratory layout of a quantum sensor: 1 - semiconductor laser; 2 - laser power supply; 3 - inductor; 4- stabilized current source; 5 - ferrofluid cell; 6 - specialized camera; 7 is a processing circuit; 8 - data transmission scheme; 9 - power supply; 10 - battery.](image-url)
To create a constant magnetic field, a specialized solenoid 3 is used. By varying the voltage on the power source 10, it is possible to control the induction of the field $B_0$ from zero to 2.4 mT. This allows, when the solenoid is turned on, to fix the nanoparticles on the magnetic field lines and form a diffraction grating. Further, the magnetic induction decreases to $B_0 = 0.206$ mT. With this induction value, the field inhomogeneity is $10^{-5}$ cm$^{-1}$. The diffraction pattern from the laser radiation transmitted through it, recorded by a specialized camera, is symmetrical about the central maximum.

The appearance near the solenoid of a magnetic object, which, when moving, creates its own magnetic field with certain variations in different directions. It will lead to the fact that the magnetic field from the moving object will violate the homogeneity of the weak magnetic field of the solenoid. In this case, the diffraction pattern will become non-symmetrical. Fixing the difference between the two recorded images, you can determine the appearance of a moving magnetic object at a certain distance from our quantum sensor. The buoy body is made of non-magnetic durable material, which is now produced quite a lot [29, 30].

Our studies allowed us to establish the following feature for recording images of a diffraction pattern from a ferrofluid cell placed in a magnetic field. Magnetic fluid in the case of placing the ferrofluid cell in a vertical state in a magnetic fluid under the action of gravity with time, most of the nanoparticles are placed at the bottom of the cell. Therefore, a layer of magnetic fluid in the direction of propagation of laser radiation, which should be placed on the line passing through the center of the Earth, should not exceed 2-3 mm. The opaque ends of the ferrofluid cell should be located perpendicular to the magnetic field lines of the solenoid. To determine the direction of motion of a magnetic object, the variation of the magnetic field, which is created when it moves, must be recorded in three directions (X, Y, and Z). It is impossible to locate the ferrofluid cell in the solenoid in order to register the diffraction image from the laser radiation passing through it in three directions. It is possible only in two. Therefore, for reliable operation of a quantum sensor, if a solenoid is placed to create a magnetic field in the direction of the Earth’s radius (OZ axis), the image of the diffraction pattern is recorded in the reflected radiation. In some cases, the variation of the magnetic field from a moving magnetic object has a significant impact on the structure of the force lines only in the OZ direction.

Therefore, we considered two variants of the formation of diffraction maxima for the recorded image from the transmitted and reflected laser radiation.

In figure 2 shows the propagation of laser radiation through a ferrofluid cell in a magnetic field $B_0$.

![Figure 2](image_url)

**Figure 2.** The pattern of propagation of laser radiation in a ferrofluid cell during the registration of a diffraction pattern in transmitted light: 1 - walls of a ferrofluid cell; 2 - a layer of magnetic fluid in the direction perpendicular to the magnetic field, with a thickness equal to $dr$; 3 - screen.
At the boundaries of the media, 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 double-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 in place of 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:

\[ \frac{a_1^2 - \lambda^2 k_1^2}{\lambda^2 k_2^2} \Delta Y^2 + 2L \left( \frac{k_1^2 - k_2^2 \lambda^2}{k_2^2} \right) \Delta Y + 4L^2 \left( \frac{k_1^2 \lambda^2}{a_1^2 - k_2^2 \lambda^2} \right) = 0 \]  

(1)

where L is the distance between the ferrofluid cell and the chamber; \( k_1 \) and \( k_2 \) are the orders of the diffraction maxima (\( k_2 > k_1 \)).

The measured diffraction pattern is measured by \( \Delta Y \) (the distance between the maxima of the peaks) for the corresponding values of \( k_1 \) and \( k_2 \). From the measured \( \Delta Y \) value, using (1), the \( dr \) value is determined — the order of the diffraction grating (the distance between the field lines in this interpolar plane of the magnetic system).

In figure 3 shows the propagation of laser radiation reflected from a ferrofluid cell in a magnetic field \( B_0 \).

![Figure 3](image)

**Figure 3.** The pattern of propagation of laser beams in a ferrofluid cell when registering a diffraction pattern in reflected light: 1 - walls of a ferrofluid cell; 2 - a layer of magnetic fluid in the direction perpendicular to the magnetic field, with a thickness equal to \( dr \); 3 - screen.

Further, the radiation after refraction on the walls of the cell and fell on the diffraction grating formed by nanoparticles with a period of \( dr \). The structure of the diffraction grating from which the “reflection” occurs is located at a distance \( dk \) from the inner wall of the ferrofluid cell. In this case, to determine the value of \( \Delta Y \), we obtained the following relation (2).

The analysis of the obtained dependences shows that the position and nature of the change in maxima from the variation of the magnetic field, the recorded images will differ. This will need to be taken into account during processing and comparisons.
In addition, the experimental results obtained allowed us to establish another feature. The degree of contrast of the diffraction pattern from the laser radiation transmitted through the ferrofluidic cell is several times higher than that in the recorded diffraction pattern in the reflected radiation. To increase the contrast degree of the recorded diffraction pattern in the reflected radiation, one of the faces of the ferrofluid cell, which is parallel to the face on which the laser radiation is incident, must be made of an opaque material with a low reflection coefficient. This will increase the sensitivity of the quantum sensor to variations in the external magnetic field.

3. The results of experimental studies and their discussion

To test the performance of the quantum sensor we developed, the following was done. The role of a moving magnetic object was performed by a permanent magnet with induction Bm. When it moves at different distances from the solenoid 3 (Figure 1), the position of the central maximum shifts, the shape of the maxima in the diffraction pattern changes, and its symmetry is violated. In figure 4, as an example, is a view of a diffraction pattern recorded by a camera placed in the zone where screen 3 was located (Figure 2). Figure 4.a corresponds to the absence of a magnetic object near the solenoid 3, in which the ferrofluid cell is placed. The magnetic field in the ferrofluid cell is uniform. Figure 4.b corresponds to one of the moments of motion near the solenoid 3 of the magnetic object. Diffraction patterns in Figure 3 are presented after computer processing.

The result obtained in Figure 4 shows that the magnetic field created by the moving object made a change in the structure of the magnetic field lines of the solenoid in which the ferrofluid cell is placed.

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

\[ + L \cdot \left[ \frac{\sqrt{n_k^2 - n_m^2 \left( 1 - \frac{t_2^2}{d_r^2} \right)}}{\sqrt{1 - \left( n_k^2 - n_m^2 \left( 1 - \frac{t_2^2}{d_r^2} \right) \right)}} \right] \] 

(2)

\[ t_1 = (2k_1 + 1) \cdot \lambda/2; \ t_2 = (2k_2 + 1) \cdot \lambda/2 \] 

(3)

where \( n_m \) is the refractive index of the magnetic fluid, \( n_k \) is the refractive index of the transparent glass wall of the cell, \( d_k \) is the distance from the cell wall to the first layer of nanoparticles in the magnetic fluid that forms the diffraction grating, \( k_1 \) and \( k_2 \) are orders of diffraction maxima (\( k_2 > k_1 \)).

The heterogeneity of the magnetic field in the area of the location of the ferrofluidic cell has changed significantly. The symmetry of the diffraction pattern is broken. The experiments performed and the results of their analysis showed that the information presented in this form is not very convenient for the operation of electronic information processing and transmission systems. Especially for the case when the quantum sensor will be placed on an autonomous object, for example, an underwater buoy. Therefore, in the registered diffraction pattern, a row is selected (according to the width or height of the diffraction cell).
Figure 4. Diffraction pattern of laser radiation in the case of placement of a magnetic fluid: (a) in a uniform magnetic field; (b) in a magnetic field with variations from the external magnetic field of a moving magnetic object.

This is a traditional method of processing optical images, which is used by many scientists in conducting scientific research using diffraction and interference phenomena [29–34]. The use of other methods for processing images obtained by us, which are used in photonics and computer optics [29, 30, 35-38], as experiments have shown, is not advisable. This line is used to construct the distribution of the intensity $I$, of the detected laser radiation. In figure 5, as an example, presents the distribution data in the diffraction pattern for laser radiation transmitted through a ferrofluid cell. In one case, the magnetic object was absent in the area of the inductance with the ferrofluid cell. In another case (Figure 5.b), it made a movement. 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.

In order to more reliably identify the presence of a moving magnetic object in this area, it is necessary to establish the degree of influence of each of its magnetic field components on the distortion of the structure of the lines of force. This is due to the fact that a moving object has a magnetic field with a different distribution of the values of induction and inhomogeneity along the $x$, $y$ and $z$ planes. Therefore, earlier in the work, two ways of registering images from the structure of magnetic field lines are considered. When a magnetic object moves, its position changes relative to the direction of the magnetic field in the magnetic system in which the ferrofluidic cell is located. The influence of the components of the magnetic field vector on the recorded image changes.

In figure 6 shows, after computer processing, diffraction patterns of recorded images during the motion of a permanent magnet, which has been rotated 90 degrees. All other motion parameters of the magnetic object, including the trajectory, were saved.
Figure 5. The dependence of the intensity I on the distance between the magnetic field lines: a) in a uniform field $B_0$; b) the magnetic field $B_m$ from the moving object is additionally present in the inductance coil.

Figure 6. Diffraction pattern of laser radiation in the case of placement of a magnetic fluid: (a) in a uniform magnetic field; (b) in a magnetic field with variations from the external magnetic field of a moving magnetic object.

In figure 7 shows 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 5.b and 7.b) depends on the trajectory of the magnetic object relative to the position of the ferrofluid cell in the inductor. The greatest influence on the position of the maxima in the recorded diffraction pattern is exerted by the magnetic field lines of a moving object, which are located in the same plane with the power lines of the inductance coil.

Therefore, in the final version of the quantum sensor, it is most expedient to register the image of the diffraction pattern along the OX and OY planes from the laser radiation passing through the ferrofluidic cell. In the plane OZ from the reflected - radiation. A sharp change in the magnetic field from a moving magnetic object in this direction will be when it makes a maneuver with ascent from depth.

In subsequent studies, it is necessary to establish the degree of influence of the speed of a moving magnetic object on the distortion of the form of lines of force. This is due to the fact that magnetic particles have inertia and for their redistribution requires a certain time.
4. Conclusion

The results of the experiments showed that the quantum sensor developed by us, which takes into account the established features of the registration of the image of the diffraction pattern, allows us to determine the presence of a moving magnetic object in a given zone of the sea. Using for these purposes the recorded changes in the structure of the diffraction pattern of laser radiation associated with a change in the magnetic field gradient eliminates measurement error. In the course of the experiments, it was found that the long-term presence of the cell with its correct location, which we determined for various cases, in a constant magnetic field does not affect the sensitivity of the device.

It should also be noted that the electronics used in this device is compact. Low power consumption of component elements allows this device to operate continuously in autonomous mode from batteries (depending on battery life) for up to three years.

As a result of the experiments, we found that electromagnetic radiation when scanning the radiation pattern of various types of radar stations, which are currently used to solve various problems in water areas [2-4, 12], does not cause distortions in the structure of the lines of force in the ferrofluid cell, which would correspond to finding a magnetic object not far from it. This shows a high degree of noise immunity of the quantum sensor developed by us.

5. References

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