Research on Magnetic Flux Detection Technology for Shallow Sea Moving Targets

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Abstract. The ocean moving target is covered by the vast ocean, and it is highly concealed. In order to effectively detect the moving target in the ocean, based on the theory of magnetic flux induction, the characteristics of the detected target are analysed, the equivalent magnetic model of the target is established, and the rectangular induction coil structure is designed. The coil structure was optimized by studying the effects of coil size parameters and moving target motion parameters on induced electromotive force. Finally, through field trials, using induction coils to collect and analyse the signals of wooden boats, speedboats and kayaks, the feasibility of the detection technology was verified, which provided a new way for the detection of shallow sea moving targets.

1. Introduction
The ocean is a very important stage in modern warfare. Various types of underwater and surface moving targets, such as speedboats and unmanned submarines, have played an important role. They have the characteristics of flexibility and concealment. The research on the detection of the characteristics of speed, height and magnetic moment of these magnetic moving targets has become the object of great concern. Among them, the detection technology based on the principle of magnetic flux induction has been widely used in some fields as one of the important methods [1-2].

In this paper, according to the characteristics of the moving target, the magnetic flux detection technology is used to detect the moving target, the equivalent magnetic model of the target is established, the structure of the induction coil is designed, and the response relationship of the detection signal to the target's motion characteristics is simulated and calculated. By analysing the influence of coil parameters on the detection signal, the structure of the induction coil is optimized. The feasibility of the detection technology was verified through field marine experiments, which provided a reference for the detection and tracking of shallow sea moving targets.

2. Detection principle and analysis
Shallow sea moving targets always have certain magnetic properties in the design and manufacturing stages. The main sources of magnetic moments are: the permanent magnetic material's own magnetic moments, the magnetic moments generated by various current loops, etc. The existence of these magnetisms makes it possible for the magnetic flux method to detect moving targets. The basic principle of flux sensing is based on Faraday's law of electromagnetic induction: for a sized static closed coil, when a magnetic moving target passes through it, it will cause a change in magnetic flux,
which in turn induces an electromotive force. And the induced electromotive force is linear with the negative value of the magnetic flux change rate of the coil circuit. By quantitative calculation and analysis of the induced electromotive force, certain magnetic characteristic parameters of the moving target can be reversed.

Firstly, derive the magnetic induction of the magnetic dipole at a certain point in space. The magnetic moment of the magnetic dipole is $m$, which is convenient for deriving the analysis, and the magnetic dipole is simplified into a circular current with radius $R$ [3-4]. Set the space where the magnetic dipole is filled with a magnetic permeability of $\mu$, according to Biot-Savar's law [5], and deduce the three-component expression of the magnetic induction intensity of the spatial point $E(r, \varphi_0, \theta_0)$.

\[
\begin{align*}
B_x &= \frac{3\mu}{8\pi} \frac{m}{(R^2+r^2)^2} \frac{r^2\sin 2\varphi_0 \cos \theta_0}{(R^2+r^2)} \\
B_y &= \frac{3\mu}{8\pi} \frac{m}{(R^2+r^2)^2} \frac{r^2\sin 2\varphi_0 \sin \theta_0}{(R^2+r^2)} \\
B_z &= \frac{\mu}{2\pi} \frac{m}{(R^2+r^2)^2} \left(1 - \frac{3}{2} \frac{r^2\sin^2 \varphi_0}{R^2+r^2}\right)
\end{align*}
\] (1)

The change in the magnetic flux caused by the magnetic moving target passing over the rectangular detecting coil is now derived. From the magnetic flux expression $\Phi = \oint \vec{B} \cdot \vec{S}$, the magnetic flux inside the rectangle can be obtained by integrating the plane around the coil.

Assuming that the direction of the magnetic moment of the target $Q (x_q, 0, z_q)$ is the positive direction of the $x$-axis, the length of the detection coil is $a$, the width is $b$, the magnetic flux of the rectangular coil can be obtained as [6]

\[
\Phi = \int_{-a/2}^{a/2} \int_{-b/2}^{b/2} B_z dx dy = -\frac{3\mu m}{4\pi} \int_{-a/2}^{a/2} \int_{-b/2}^{b/2} \left[(x - x_q)^2 + y^2 + z_q^2\right]^{-\frac{3}{2}} \cdot (x - x_q) \cdot z_q dx dy
\] (2)

According to Faraday's law of electromagnetic induction, the magnetic flux caused by the movement of the magnetic dipole in the rectangular coil is differentiated from the time $t$ to obtain the induced electromotive force at that moment.

3. Analysis of influencing factors of induction signal

The motion parameters and coil size of the moving target will affect the magnitude of the induced electromotive force. To simplify the calculation, let the direction of the magnetic moment of the magnetic dipole be along the positive direction of the $x$-axis.

3.1. Effect of coil size on induced electromotive force

From the theoretical analysis, when the coil size and the target height are of the same order, the larger the size, the greater the induced electromotive force. The simulation results are shown in Fig.1.
3.2. Effects of target motion parameters on induced electromotive force

Simulate and analyse the influence of target altitude on the induction signal respectively. The results are shown in Fig.2.

As can be seen from Fig.2 that with the increase of the target height, the peak value of the induced electromotive force in the rectangular coil is decreasing, and the peak value has a power exponential relationship with the height.

4. Shallow sea test verification

The experiment area is selected in the shallow sea area with a water depth of about six meters. The detection coil is placed in the designated sea area. The coil frame size is 100cm×150cm, the thickness is 10cm, and the number of copper wire turns is 500. Use various ships to go back and forth through the coil to obtain various test data. In addition, different test conditions are simulated by changing the
number of coils and the series-parallel relationship. The magnetic flux detection system used in the experiment is shown in Fig.3.

In order to obtain the magnetic flux signal induced when the target with different magnetic characteristics and different motion states passes through the detection coil. In this test, various types of ships were selected including iron ships, wooden boats, speed boats, rubber boats, etc, as shown in Fig.4.

4.1. Analysis of wooden boat magnetic flux signal extraction results
The wooden boat is used to go back and forth over the detection coil multiple times to obtain the induction signal. The wavelet threshold filtering method is used to process the generated magnetic flux signal, and the low-frequency part of the magnetic flux signal and the high-frequency part after thresholding are reconstructed respectively [7]. The processing result is shown in Fig.5.
It can be seen from the figure that the waveform change of the target flux signal is obvious, but some local features are masked by the background noise. Further analysis shows that the low frequency part of the signal is induced by the background magnetic field when the wooden boat passes by. As can be seen from the signal waveform, the magnetic characteristics of the wooden boat background magnetic field are more obvious. The high-frequency part of the signal fluctuates periodically, through spectrum analysis, it can be found that the signal is stronger between 13-14Hz which may be related to the rotation of the wooden boat engine.

4.2. Analysis of speed boat magnetic flux signal extraction results
The speed boat is used to go back and forth over the detection coil multiple times to obtain the induction signal. The wavelet threshold filtering method is used to process the generated magnetic flux signal, and the low-frequency part of the magnetic flux signal and the high-frequency part after thresholding are reconstructed respectively. The processing result is shown in Fig.6.

![Speed boat magnetic flux signal extraction results.](image)

It can be seen from the figure that the waveform change of the speed boat magnetic flux signal is obvious, but some local features are masked by the background noise. Further analysis shows that the low frequency part of the signal is induced by the background magnetic field when the speed boat passes by. As can be seen from the signal waveform, the magnetic characteristics of the speed boat background magnetic field are more obvious. The high-frequency part of the signal fluctuates periodically, through spectrum analysis, it can be found that the signal is stronger between 18-19Hz which may be related to the rotation of the speed boat engine.

4.3. Analysis of rubber boat magnetic flux signal extraction results
The rubber boat is used to go back and forth over the detection coil multiple times to obtain the induction signal. The wavelet threshold filtering method is used to process the generated magnetic flux signal. The processing result is shown in Fig.7.

![Rubber boat magnetic flux signal extraction results.](image)
It can be seen from the figure that the waveform change of the rubber boat magnetic flux signal is obvious, but some local features are masked by the background noise. Further analysis shows that the low frequency part of the signal is induced by the background magnetic field when the rubber boat passes by. The high-frequency part of the signal fluctuates periodically, through spectrum analysis, it can be found that the signal is stronger between 40Hz which may be related to the rotation of the rubber boat engine.

The difference in magnetic flux signals induced by several different types of ships is very obvious, which makes it possible to use the magnetic flux detection system to distinguish different targets.

5. Conclusion
In this paper, the magnetic dipole model is established for the ocean moving target, the coil structure size is designed, the magnetic flux change caused by the magnetic dipole movement in the rectangular coil and the magnitude of the induced electromotive force are deduced, and the effects of various parameters on the electromotive force are analysed. Through research, we can find that within a certain range, the peak value of induced electromotive force increases with the increase of the coil size, the target motion speed and the induced electromotive force increase linearly, and the distance between the induced signal and the coil shows a decreasing exponential change. Finally, the signals of different ships were detected and analysed in shallow waters, which verified the feasibility of magnetic flux detection technology. The research will further improve the magnetic theory model of the moving target, establish a rich database, and invert the available information of the target by detecting the signal characteristics of the moving target.

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