Simulation of seawater eddy current loss in in-situ detection system for the magnetic properties of seabed sediments

Tianxue Zhao¹,² and Weidong Pan¹,²*

¹Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, China
²University of Chinese Academy of Sciences, Beijing, China
*Corresponding author’s e-mail: panwd@mail.iee.ac.cn

Abstract: This paper mainly simulates and analyzes the working conditions of the in-situ detection system for the magnetic properties of seabed sediments in the marine environment. Firstly, the causes and influencing factors of eddy current loss in seawater are analyzed. Secondly, the influence of seawater eddy current loss is equivalent to seawater impedance circuit, and the influence on coil resistance, inductance and magnetic field generated by the coil is qualitatively analyzed. Finally, a COMSOL simulation model is built to verify the mentioned-above theoretical analysis. The simulation results show that compared with those in the air environment, the equivalent resistance of the coil increases, the equivalent inductance decreases and the magnetic field generated by the coil decreases in the marine environment.

1. Introduction
At present, the marine environment magnetic field detection mainly includes satellite magnetic survey, underwater vehicle magnetic survey, scientific research ship magnetic survey and other methods. Satellite magnetic measurement refers to the placement of a magnetometer on a satellite to obtain the strength of the earth's magnetic field. This method can quickly obtain the information of the earth's magnetic field, detect the changes of the earth's magnetic field, and build a high-precision model of the earth's magnetic field. The seabed magnetic field distribution is obtained by inversion of the seabed magnetic field data measured by satellites; however, the local magnetic anomalies cannot be accurately obtained [1-2]. Underwater vehicle magnetic survey can go deep into the seabed, measure the seabed magnetic data easily. Although this method can measure the seabed magnetic data, it cannot measure the seabed magnetic properties [3]. The magnetic survey of the scientific research ship means that scientific research workers can directly observe the ocean, collect samples and perform analysis on the ship with special instruments and equipment. By collecting deep-sea rock samples and measuring them with a rock magnetic analyzer in the laboratory, the magnetic properties of seabed rocks can be obtained. Although this method can obtain the magnetic properties of seabed rocks, it is difficult to collect seabed samples and the samples are easy to lose direction information due to the limitation of deep-sea conditions.

In order to solve the limitations of the above methods, this paper proposes a magnetic properties detection system of seabed sediments. The system is to magnetize and demagnetize the seabed sediments by the pulsed and alternating magnetic field generated by the coil. Literature [4-5] has studied the eddy current loss in seawater with alternating magnetic field. Literature [6-7] has analyzed the influence of current and frequency on eddy current loss and transmission efficiency. They analyzed the influence of short-distance eddy current loss on transmission efficiency, but did not analyze the influence of eddy
current loss on the required magnetic field.

This paper introduces the principle of magnetic field generation of the in-situ detection system for the magnetic properties of seabed sediments. Through mathematical analysis, the relationship of the eddy current loss is derived from Maxwell's equation. The eddy current loss of seawater is equivalent to the resistance and inductance circuit, and the change of the coil resistance and inductance value and the influence of eddy current loss on the coil magnetic field are analyzed. According to the above theoretical analysis, a COMSOL simulation model for verification is established. Through the analysis, appropriate parameters can be selected to ensure the required magnetic field for the in-situ magnetic property detection system of seabed sediments.

2. Materials and Methods

2.1 Basic principle of in-situ detection system for the magnetic properties of seabed sediments

The in-situ detection system for the magnetic properties of seabed sediments is to perform in-situ magnetization and demagnetization of seabed sediments with different intensities through magnetization/demagnetization coils. It measures the corresponding magnetic field change information, thus to get the isothermal residual magnetization curves and corresponding demagnetization curves, and then determine the composition of the seabed sediment types [8-9].

The in-situ detection system for the magnetic properties of seabed sediments consists of three parts: DC high-voltage power supply, capacitor and magnetization/demagnetization coil, as shown in Figure 1. Here is the principle of the magnetic field generated by the coil: First, close the switch $S_1$ to charge the capacitor $C$ through DC high-voltage power $U$. When the voltage at both ends of the capacitor is $V$, the capacitor energy storage is shown as in Equation (1):

$$W = \frac{1}{2} CV^2$$

(1)

After charging is completed, open switch $S_1$ and close switch $S_2$, the capacitor discharges to the magnetization/demagnetization coil, and obtains the discharge current $i(t)$:

$$i(t) = \frac{V}{\omega R} e^{\frac{Rt}{2L}} \sin(\omega t)$$

(2)

Where $V$ is the charging voltage at both ends of the capacitor $C$; $R$ is magnetization/demagnetization coil resistance; $L$ is the magnetization/demagnetization coil inductance; $r$ is the average radius of magnetization/demagnetization coil; $\omega$ is the resonant angular frequency of the discharge circuit. At the time $t(\omega)$,

$$t_0 = \frac{1}{\omega} \tan^{-1} \frac{2L\omega}{R}$$

(3)

The discharge current reaches the maximum value, $i_{max}$:

$$i_{max} = \frac{V}{\sqrt{L}} e^{\frac{R}{2L\omega\tan^{-1} \frac{2L\omega}{R}}}$$

(4)

And the central magnetic field of the magnetization/demagnetization coil $B$ is

$$B = \frac{\mu_0 N i_{max}}{2r}$$

(5)
2.2. Seawater eddy current loss analysis

As the conductivity of air is 0 S/m, there is no need to consider the effect of the loss of the system in the air. However, as the conductivity of seawater is approximately 3 S/m ~ 5 S/m, the eddy current loss in seawater should be taken into account for the in-situ detection of need to consider magnetic properties of seabed sediments. According to Faraday’s law of electromagnetic induction, the time-varying magnetic field may generate eddy electric current in the conductor and therefore cause eddy current loss. Eddy current loss will reduce the working efficiency of the coil, thus affecting the magnetic field of the coil. In order to analyze the causative factors of eddy current loss further, Maxwell’s equations on electromagnetic field theory are shown as follows [10]:

\[ \nabla \times \bar{E} = -\frac{\partial \bar{B}}{\partial t} \]  \hspace{1cm} (6)
\[ \nabla \times \bar{H} = \bar{J}_e + \sigma \bar{E} \]  \hspace{1cm} (7)
\[ \bar{B} = \mu \bar{H} \]  \hspace{1cm} (8)
\[ \bar{J}_e = \sigma \bar{E} \]  \hspace{1cm} (9)

Where \( E \) is the electric field intensity; \( B \) is the magnetic induction intensity; \( H \) is the magnetic field strength; \( J_c \) is the excitation current density; \( J_e \) is the eddy current density; \( \mu \) is the permeability; \( \sigma \) is the electrical conductivity. Pulse current generated by the in-situ detection system is \( i(t) = \sqrt{2} I_1 e^{-at} \sin(\omega t + \phi) \). In order to facilitate the analysis, set the coil radius \( r \), the pulse current as sinusoidal current \( \sqrt{2} I_1 \sin(\omega t + \phi) \), the amplitude of sinusoidal current is the same as the maximum amplitude of pulse current, which does not affect the analysis of the magnetic field when the coil produces the maximum current.

According to the boundary conditions of the electric field intensity, the constraint equation is obtained as:

\[ \nabla^2 E + k^2 E = 0 \]  \hspace{1cm} (10)

Where \( k^2 = \omega^2 \mu \varepsilon - j \omega \mu \sigma \). Based on the spherical coordinate system, the Helmholtz equation is [11]:

\[ \frac{\partial^2 E}{\partial \rho^2} + \frac{1}{\rho} \frac{\partial E}{\partial \rho} + \frac{\partial^2 E}{\partial z^2} + \left( k^2 - \frac{1}{\rho^2} \right) E = 0 \]  \hspace{1cm} (11)

Use the method of separating variables to solve this equation. Suppose \( E(\rho, z) = R(\rho)T(z) \), the following equation is:
\[
\left( \frac{1}{R} \frac{\partial^2 R}{\partial \rho^2} + \frac{1}{R \rho} \frac{\partial R}{\partial \rho} - \frac{1}{\rho^2} \right) + \left( \frac{1}{T} \frac{\partial^2 T}{\partial z^2} + k^2 \right) = 0 \tag{12}
\]

Defining the separation constant as \( \tau \); the following equation is:

\[
\frac{1}{T} \frac{d^2 T}{d \rho^2} + k^2 = \tau^2 \tag{13}
\]

\[
\rho^2 \frac{d^2 R}{d \rho^2} + \rho \frac{d R}{d \rho} + \left( \tau^2 - 1 \right) R = 0 \tag{14}
\]

The general solution to the equation is:

\[
E(\rho, z) = \int_0^\infty \left[ C_1 J_1(\tau \rho) + C_2 Y_1(\tau \rho) \right] \left( C_3 e^{\sqrt{\tau^2 - k^2}z} + C_4 e^{-\sqrt{\tau^2 - k^2}z} \right) d\tau \tag{15}
\]

Where \( C_1, C_2, C_3, C_4 \) are the undetermined coefficients, \( J_1(\tau \rho) \), \( Y_1(\tau \rho) \) are Bessel function of the first kind and Bessel function of the second kind. According to the boundary conditions of electric and magnetic fields, we can deduce that [11]:

\[
E(\rho, z) = -\frac{\mu_0 I r \tau}{2} \int_0^\infty \frac{\tau}{\sqrt{\tau^2 - k^2}} J_1(\tau r) J_1(\tau \rho) e^{-\sqrt{\tau^2 - k^2}z} d\tau \tag{16}
\]

According to the definition of eddy current loss, the loss generated by the coil in seawater is:

\[
P = \int |E|^2 dv \tag{17}
\]

According to (16) and (17), the eddy current loss of seawater \( P \) increases with the rise of either conductivity \( \sigma \), current \( I \) or resonant angular frequency \( \omega \).

2.3. Seawater impedance equivalent circuit

According to the loose-coupling transformer model proposed by Bihan et al [12], the seawater medium is equivalent to a circuit with certain impedance characteristics, which is composed of the equivalent resistance of seawater \( R_1 \) and the equivalent inductance \( L_1 \), as shown in Figure 2. Where \( R_1 \) is the resistance equivalent to the active power loss generated by eddy current in seawater, and \( L_1 \) is the inductance equivalent to the magnetic effect generated by eddy currents [7].

Based on the above principle, the equivalent resistance \( R' \) and the equivalent inductance \( L' \) of the circuit for the coil are:

\[
R' = R + \frac{\omega^2 M^2 R_1}{R_1^2 + \omega^2 L_1^2} = R + R_1' \tag{18}
\]

\[
L' = L - \frac{\omega^2 M^2 L_1}{R_1^2 + \omega^2 L_1^2} = L - L_1' \tag{19}
\]

Figure 2. Effects of seawater on the in-situ detection system for the magnetic properties of seabed sediments.
Where $M$ is the mutual inductance between seawater and magnetization/demagnetization coil. As shown in (18) and (19): in the marine environment, the equivalent resistance of the coil $R'$ increases and the equivalent inductance $L'$ decreases, and the equivalent resistance $R'$ goes up with $\omega$ and the equivalent inductance $L'$ goes down with $\omega$.

2.4. Changes in coil magnetic field in seawater

According to the equivalent circuit of the above analysis, we can obtain the equivalent circuit of the in-situ detection system as shown in Figure 3.

When the voltage $V$ at both ends of the capacitor remains unchanged and the resistance $R$ becomes $R'$, the current $I$ in the capacitor $C$ discharge loop decreases. According to (5), the magnetic field $B$ generated by the coil decreases. Therefore, the eddy current loss of seawater reduces the generated magnetic field $B$.

![Figure 3. The equivalent circuit of the in-situ detection system for the magnetic properties of seabed sediments.](image)

2.5. Simulation validation

In order to analyze and verify the correctness of the above theory, the coil parameters are chosen as shown in Table 1. We use COMSOL to build a 3D model of the coil in seawater. Considering the skin depth of seawater, we set the radius of seawater at 100 m and the magnetic field at the boundary of seawater is 0, as shown in Figure 4:

| Table 1. Coil parameters.                  |
|-------------------------------------------|
| **Turns per coil** | 100 Turns |
| **Coil diameter** | 0.3m |
| **Coil sectional area** | 53mm×44.8mm |
| **Wire sectional area** | 23.744mm² |
| **Conductor conductivity** | $6\times10^7$S/m |
Due to the complexity of seawater environment, it is difficult to calculate the effects of eddy current loss of seawater on the magnetic field generated by the coils. Therefore, we analyze the effects of eddy current loss $P$ on magnetic field $B$ using the simulation model. From the analysis, the eddy current loss $P$ increases with the rise of resonant angular frequency $\omega$, so we can analyze the changes of magnetic field $B$ in different resonant angular frequency $\omega$. We randomly select three different points (0,0,0), (0,3,0) and (0,10,0) in the coil, and analyze the magnetic field $B$ generated by the coil in air and seawater under different conductivity conditions and analyze the variation relationship of the coil magnetic field $B$ with angular frequency $\omega$ at three points.

3. Results & Discussion

3.1. Effects of current, frequency and conductivity on eddy current loss
When the conductivity $\sigma$ is 3S/m, 4S/m, 5S/m and $\omega$ or $I$ is fixed, the curve of the eddy current loss $P$ with the current $I$ or the frequency $\omega$ are as shown in Figure 5 and Figure 6, respectively.

Figure 5. Relationship between eddy current loss $P$ and current $I$. 
As shown in Figure 5 and Figure 6: The simulation results are consistent with the analysis principle of (16) and (17) above. It is verified that the eddy current loss of seawater $P$ increases with the rise of either conductivity $\sigma$, current $I$ or resonant angular frequency $\omega$.

### 3.2. Effects of eddy current loss on coil resistance and inductance

As shown in Figure 7, the resistance of the coil $R$ in the air does not change with the $\omega$, while in the seawater $R$ increases with the rise of $\omega$. Consistent with (18), it is validated that the resistance of the coil $R$ increases with the rise of $\omega$ in seawater environment. It is also observed that when $\omega \leq 10^4$ rad/s, the change of coil resistance $R$ can be ignored.

Figure 8 shows that the change of coil inductance is not significant in the air, while in seawater $L$ decreases significantly with the rise of $\omega$. Consistent with (19), it is validated that the inductance of the coil $L$ decreases with the rise of $\omega$. It can also be seen that when $\omega \leq 10^4$ rad/s, the variation of the coil inductance $\Delta L \leq 27.9 nH$. Compared with the initial value of the inductance, the variation value can be ignored.
Figure 8. Relationship between coil inductance $L$ and frequency $\omega$.

Coil resistance value and inductance value change in line with the relationship between eddy current loss $P$ with frequency $\omega$ change, when $\omega$ is small, $R$ and $L$ change less.

3.3. Effects of eddy current loss on coil magnetic field

As shown in Figure 9, at the center of the coil (0,0,0), the magnetic field $B$ generated by the coil in the air is 1.019336T. The magnetic field generated by the coil in the seawater is become smaller. At the same conductivity $\sigma$ in seawater, $B$ decreases with the rise of $\omega$. As $\omega$ is the same, $B$ decreases with the rise of $\sigma$.

As shown in Figure 10, at the point (0,3,0), the magnetic field $B$ generated by the coil in the air is $1.276 \times 10^{-4}$T. The magnetic field generated by the coil in the seawater is become smaller. At the same conductivity $\sigma$ in seawater, $B$ decreases with the rise of $\omega$. As $\omega$ is the same, $B$ decreases with the rise of $\sigma$.

Figure 9. Relationship between $B$ and $\omega$ at point (0, 0, 0).
As shown in Figure 11, at the point (0,10,0), the magnetic field $B$ generated by the coil in the air is $3.68 \times 10^{-6} \text{T}$. The magnetic field generated by the coil in the seawater is become smaller. At the same conductivity $\sigma$ in seawater, $B$ decreases with the rise of $\omega$. As $\omega$ is the same, $B$ decreases with the rise of $\sigma$. When $\omega \leq 10^4 \text{rad/s}$, the change in $B$ is negligible.

4. Conclusions

Based on the theoretical derivation and COMSOL simulation analysis of seawater eddy current loss and its equivalent circuit, it is concluded that the eddy current loss of seawater shows effects on the in-situ detection system for the magnetic properties of seabed sediments. In the marine environment, the eddy current loss $P$ is mainly affected by the current $I$, conductivity $\sigma$ and resonance angular frequency $\omega$: when $\sigma$, $\omega$ is constant, $P$ increases with the rise of $I$; when $I$, $\omega$ is constant, $P$ increases with the rise of $\sigma$; when $I$, $\sigma$ are both constant, $P$ increases with the rise of $\omega$. The equivalent resistance of seawater eddy current loss increases with the rise of $\omega$, and the equivalent inductance decreases with the rise of $\omega$. As the eddy current loss of seawater $P$ may reduce the magnetic field $B$, it suggests that the resonant angular frequency can be set at $10000 \text{rad/s}$ to reduce the effects of eddy current loss in seawater for the in-situ detection system for the magnetic properties of seabed sediments.

Acknowledgments

We thank Huiwen Xiao for assisting simulation of eddy current loss. This research was supported by the Chinese Academy of Sciences A Strategic Pilot Science and Technology special project (XDA22020603) and the National Natural Science Foundation of China (31870367, 31670855).
References

[1] Rae, K. H., Von, F.R.R.B., Taylor, P.T., et al. (2010) Improved magnetic anomalies of the Antarctic lithosphere from satellite and near-surface data. J. Geophysical Journal International (1): 119-126.

[2] Wang, K., Shen, J.S., Zhang, Z., et al. (2017) Summarization of Papers Published in Hydrographic Surveying and Charting in 2016. J. Hydrographic Surveying and Charting.

[3] Fang, C., Anstee, S. (2010) Coverage path planning for harbour seabed surveys using an autonomous underwater vehicle. Oceans. IEEE.

[4] Kojiya, T., Sato, F., Matsuki, H., et al. (2004) Automatic power supply system to underwater vehicles utilizing non-contacting technology. Oceans. IEEE.

[5] Meginnis, T., Henze, C. P., Conroy, K. (2008) Inductive Power System for Autonomous Underwater Vehicles. OCEANS 2007. IEEE.

[6] Zhou, W.Q. (2008) Study on the characteristics and design of inductively coupled power transmission system. D. Zhejiang University.

[7] Zhou, J. (2014) Study on the Optimization of non-contact power Transmission efficiency in seawater environment. D. Zhejiang University.

[8] B, D.J.A, A, L.X., C, Q.H., B, K.X.A., et al. (2018) Scanning SQUID microscope with an in-situ magnetization/demagnetization field for geological samples - ScienceDirect. J. Physica C: Superconductivity and its Applications, 547, 1-6.

[9] Abnormal isothermal remanence and reverse magnetization after heat treatment of siderite. J. Journal of Peking University: Natural Science edition.

[10] Duan, L.J. (2020) Research on two-way Radio Energy Transmission technology of autonomous Underwater Vehicle. D.

[11] Lei, Y.Z. Analytical method of time-harmonic electromagnetic field. Science Press, Beijing.

[12] Bihan, Y.L. (2003) Study on the transformer equivalent circuit of eddy current nondestructive evaluation. J. Ndt & E International, 36(5): 297-302.