Research on Inductance Calculations for Degaussing Windings of a Double-Layer Steel Cylinder

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ABSTRACT The inductance of degaussing windings is an important parameter for the dynamic current adjustment and overvoltage analysis of ship degaussing systems. This inductance depends not only on the shape, location, and turns of windings, but also on the distribution of the surrounding magnetic medium and its eddy current effect, leading to the difficulty of determining the self- and mutual inductances. To solve this problem, an AC inductance calculation method of degaussing windings considering the eddy current effect was first proposed. The relevant factors affecting calculation accuracy were then analyzed to provide a theoretical basis for the inductance calculation. Aiming at the accurate inductance calculation of a double-layer steel cylinder, a 3D numerical simulation model was established by ANSYS for frequency domain analysis at four different current frequencies (DC, 100 Hz, 1 kHz, and 10 kHz). The relationship between the current frequency and the mesh division in the shell thickness direction was analyzed. Effects of the outer shell on the inductance calculation and its mechanism were also analyzed. The comparative results of the measured and calculated inductance values show that the relative errors are less than 20%. Moreover, the maximum mutual inductance arrives at 21.6 µH, indicating a considerable value of the mutual inductance, which cannot be ignored in low-frequency equivalent circuit analysis.

INDEX TERMS Ship degaussing, inductance calculation, eddy current, current frequency, accuracy.

I. INTRODUCTION

With the rapid development of magnetic detection technology, the magnetic protection of steel-shell structures such as ships and underwater unmanned vehicles needs to be considerably improved. The degaussing systems are designed and applied to eliminate the magnetic field induced by the geomagnetic field around the steel shell, thus promoting magnetic protection [1], [2]. The inductance of degaussing windings is an important parameter for the dynamic current adjustment and overvoltage analysis [3]. Therefore, accurate calculation of inductance contributes to good performance and high efficiency of degaussing systems.

However, in the literature, only self-inductance of degaussing windings in air has been explored, whereas mutual inductance has been rarely reported in the field of ship degaussing [4]–[6]. Under special or extreme working conditions, such as when the degaussing power is suddenly turned on or off, the change in the self- and mutual inductances of the degaussing winding and its impact on the degaussing system need to be further studied. Moreover, the distribution of the surrounding magnetic medium and eddy current effect will also affect the inductance [7], [8], which makes calculating inductance accurately more difficult.

Therefore, this paper first proposed an AC inductance calculation method considering the eddy current effect. The relevant factors affecting calculation accuracy were analyzed to provide a theoretical basis for inductance calculations. A 3D numerical model of a double-layer steel cylinder was then established to conduct frequency domain analysis at different current frequencies. The effects of the current frequency and the outer shell on self- and mutual inductances were analyzed.
Finally, the measured and calculated inductance values were compared to verify the accuracy of the proposed inductance calculation method.

II. INDUCTANCE CALCULATION METHOD

A. PRINCIPLES

Under AC excitation, the impedance phasor of a degaussing winding is defined as follows:

$$
\dot{Z} = R + j\omega L
$$

(1)

Assuming that the excitation current phasor is \( \dot{I} \) and the terminal voltage phasor of the winding is \( \dot{U} \), the impedance \( \dot{Z} \) can be expressed by the real and imaginary parts of the voltage and current as follows:

$$
\dot{Z} = \frac{\dot{U}}{\dot{I}} = \frac{U_t + jU_i}{I_t + jI_i} = \frac{(U_t + jU_i) (I_t - jI_i)}{I_t^2 + I_i^2} = \frac{U_t I_t + U_i I_i}{I_t^2 + I_i^2} + j \frac{U_t I_t - U_i I_i}{I_t^2 + I_i^2}
$$

(2)

The symbol \( j \) represents the units of imaginary numbers. \( U_t \) and \( U_i \) are the real and imaginary parts of the voltage vector, respectively. \( I_t \) and \( I_i \) are the real and imaginary parts of the current vector, respectively.

From (1) and (2), we can obtain (3) as follows:

$$
L = \frac{U_t I_t - U_i I_i}{\omega (I_t^2 + I_i^2)}
$$

(3)

One can see that the AC inductance of the winding can be determined according to the real and imaginary parts of the excitation current and terminal voltage of the windings. If the excitation current and terminal voltage are on the same winding, then the inductance is called self-inductance. Otherwise, it is called mutual inductance.

For a winding with \( w \) turns, the inductance of the winding should be multiplied by the square of the number of turns based on (3) as follows:

$$
L = \frac{U_t I_t - U_i I_i}{\omega (I_t^2 + I_i^2)}
$$

(4)

B. EXAMPLE OF SELF-INDUCTANCE CALCULATION

AC inductance is equal to DC inductance at low current frequencies, meaning it can be calculated and compared to the analytical solution of DC inductance and the accuracy of the proposed method can be verified preliminarily.

The calculation of self-inductance is analyzed first. Assuming that the radius of a circular loop placed in a vacuum is \( R = 0.2 \) m and the radius of the conductor is \( r = 1 \) mm, as shown in Fig. 1, the self-inductance can be calculated using (5) [9]. Then, the analytical value of self-inductance can be obtained as \( 1.414 \mu H \).

$$
L = \mu_0 R \left( \ln \frac{8R}{r} - \frac{7}{4} \right)
$$

(5)

A numerical model in the frequency domain was established by commercial software ANSYS [10], as shown in Fig. 2. There is a gap of \( 1^\circ \) around the conductor, which is convenient for applying current excitation. An outer air layer close to the conductor is included to control mesh division and the outermost layer of air is set as a truncated boundary. By applying an excitation current in the loop direction with a current frequency of 1 Hz, the real and imaginary parts of current and voltage can be extracted and the self-inductance can be calculated using formula (3). The effects of mesh division and truncated boundary size on calculated inductance values are analyzed below.

1) MESH DIVISION

The mesh size of the outer air layer is maintained at 0.01 m, as shown in Fig. 3. The conductor is divided into 500, 1000, 1500, and 2000 segments along the loop direction, whereas it is maintained at four segments along the radial direction, as shown in Fig. 4.

The calculated results and simulation time for self-inductance with different loop divisions are listed in Table 1. With an increase in loop divisions, the calculated value of inductance moves closer to the analytical solution, but the calculated inductance becomes saturated and the relative error is always more than 5 % when the conductor is divided into more than 1500 segments. This indicates that the radial
division of the conductor or the outer air division has a greater influence on the calculated self-inductance.

To make sure the calculated results were valid, commercial software COMSOL was also adopted to calculate the self-inductance, and the results showed that the self-inductances calculated from COMSOL were very close to the results calculated from ANSYS. Furthermore, the simulation time of using COMSOL was much longer than that of using ANSYS (e.g. above 4.3 times for 2000 loop divisions), which indicates the validation and accuracy of the proposed method.

Next, the conductor was divided into 2, 4, 8, and 12 segments along the radial direction to analyze the effect of radial divisions on the inductance calculation, whereas the loop divisions was maintained at 1500 segments, as shown in Fig. 5. The mesh size of the outer air layer was maintained at 0.01 m.

The calculated results and simulation time for self-inductance under different divisions along the radial direction are listed in Table 2. Due to the low current frequency, the skin depth is much larger than the radius of the conductor, therefore, the radial divisions have almost no effect on the calculated value of self-inductance.

Next, the conductor is divided into 1500 and two segments along the loop and radial directions, respectively. The mesh size of the outer air layer is set to 0.01 m, 0.005 m, and 0.0033 m. Due to the continuity of meshing on the conductor surface, the mesh size of the outer air layer directly determines the meshing quality in the area around the conductor. As shown in Table 3, the calculated values of self-inductance are significantly affected by the mesh size of the outer air layer. When the mesh size is 0.0033 m, the relative error is only 2.2 %, indicating that the accuracy of the numerical model is significantly improved. However, the simulation time increases more than 25 times.

Based on the analysis above, it can be concluded that the accuracy of self-inductance calculation is highly dependent on the mesh size. Not only must the divisions along the loop direction of the conductor be sufficiently large, but the mesh size of the outer air layer must also be sufficiently small. However, because degaussing windings are very close to the hull, it is almost impossible to establish the outer air layer, and as a result, there may be some inevitable errors in self-inductance calculations of degaussing windings.

2) TRUNCATED BOUNDARY SIZE

Here, the conductor is divided into 1500 and two segments along the loop and radial directions, respectively. The mesh size of the outer air layer is set to 0.0033 m. The truncated boundary is set to be a cube with side lengths of 1 m and 2 m. In Table 4, one can see that the truncated boundary size should be 1 m, which is 2.5 times the diameter of the circular loop.

C. EXAMPLE OF MUTUAL INDUCTANCE CALCULATION

The mutual inductance of coaxial windings is calculated and analyzed according to the distribution characteristics of degaussing windings, as shown in Fig. 6. The accuracy of the numerical model is validated by comparing the analytical solutions and numerical results.
We assume that the radii of the conductors are both 1 mm and the loop radii are $R_1 = 0.2$ m and $R_2 = 0.15$ m. Considering coaxial loops with an axial distance of 0.092 m, the mutual inductance of the coaxial loops can be calculated as follows [9]:

$$M = \frac{\mu_0}{4\pi} \sqrt{R_1 R_2 \lambda}.$$  \hfill (6)

Here, $\lambda = 9.074$, which is relevant to $((R_1 - R_2)^2 + x^2)/((R_1 + R_2)^2 + x^2)$ and can be obtained from a lookup table. The analytical solution for the mutual inductance can be calculated as $M = 157.16$ nH.

1) MESH DIVISION
Both conductors are divided into two segments along the radial direction, and into 150 and 300 segments along the loop direction, respectively. The mesh size of the outer air layer is 0.03 m. The calculated values for mutual inductance under different loop divisions are shown in Table 5. These results demonstrate that the accuracy of the numerical model is sufficiently high when the conductor is divided into 150 segments along the loop direction.

Next, the two conductors are divided into two segments along the radial direction and into 150 segments along the loop direction. The mesh size of the outer air layer is set to 0.03 m and 0.05 m. The calculated values of mutual inductance are listed in Table 6. One can see that the relative error increases significantly as the mesh size increases from 0.03 m to 0.05 m.

2) TRUNCATED BOUNDARY SIZE
The conductors are both divided into two segments along the radial direction and into 150 segments along the loop direction. The mesh size of the outer air layer is set to 0.03 m and 0.05 m. The calculated values of mutual inductance are listed in Table 7. When the truncated boundary size is greater than 1 m, the accuracy is sufficiently high. When the truncated boundary size is 0.5 m, the error increases significantly to 6%. Based on the fact that the size of the numerical model is 0.4 m, these results indicate that the truncated boundary size should be at least 2.5 times the size of the model.

### III. SIMULATION MODEL

#### A. STRUCTURE OF THE CYLINDER
The structure of the double-layer cylinder includes inner shell, outer shell, and ribs (see Fig. 7). The length of the cylinder is approximately 4700 mm. The outer diameters of the inner and outer shells are 450 mm and 570 mm, respectively. They are all made of marine steel. The thickness of the inner shell, outer shell, and ribs are 2 mm, 0.6 mm, and 6 mm, respectively. The degaussing windings are wounded along the circumferential direction of the cylinder with an axial distance of 250 mm between adjacent windings. The 18 windings are numbered with XQ1 $\sim$ XQ18 from the bow section to the stern section.

#### B. NUMERICAL MODEL

1) INNER AND OUTER SHELLS
The cylindrical section of the shells was mapped with hexahedrons, whereas the other sections were meshed with free tetrahedrons, as shown in Figs. 8(a) and 8(b).
Due to the skin effect, the eddy current at high frequency is mainly concentrated on the shell surface, which is equivalent to an increase in the impedance of the shell and a decrease in the eddy current, weakening the degaussing effect. To consider the skin effect, the element size in the shell thickness direction should not be larger than the skin depth $\delta$, which can be obtained from (7):

$$\delta = \sqrt{2/\left(\omega \mu \gamma\right)}$$  \hspace{1cm} (7)

where $\omega$ is angular frequency, $\mu$ is permeability, and $\gamma$ is conductivity. The relative permeability $\mu_r$ of ship steel in the range of 0~10 kHz is 132, and the conductivity $\gamma$ is $3.23 \times 10^6$ S/m. Then, the skin depth of the steel shell at different frequencies is calculated, as shown in Table 8. For the inner shell with 2-mm thickness, the skin depth at 100 Hz is larger than the thickness of the shell and there is no need to consider the skin effect. The inner shell needs to be divided into at least three and eight layers at 1 kHz and 10 kHz, respectively. Similarly, the outer shell with a thickness of 0.6 mm needs to be divided into at least three layers in the thickness direction when analyzing the inductance at 10 kHz.

### Table 8. Skin depth of ship steel under different current frequency.

| Frequency (Hz) | 100  | 1k   | 10k  |
|---------------|------|------|------|
| Skin depth $\delta$ ($\mu$m) | 2.4  | 0.77 | 0.24 |

IV. RESULTS OF AN APPLIED MAGNETIC FIELD

#### A. CURRENT LOAD

The time-harmonic magnetic field problem was solved by applying unit current to a certain winding using ANSYS. The element “solid97” was adopted, where the degrees of freedom consist of a vector magnetic potential $A$ and potential $\phi$. In the outermost air layer, the vector magnetic potential is $A = 0$, which is treated as a truncated boundary. The current density vectors are presented in Fig. 11 and they conform to the theoretical distribution, indicating the correctness of the current load.

#### B. EDDY CURRENT DISTRIBUTION IN THE INNER SHELL

By considering the current load of XQ17 as an example, the eddy current on the inner shell at 100 Hz is presented in Fig. 12. One can see that there is an intensive eddy current in the inner shell under the excitation of the XQ17 winding,
V. EFFECTS OF THE OUTER SHELL

The eddy current effects of the outer shell will influence the inductance of the windings. In this section, an equivalent circuit model of the double-layer cylinder was first established to preliminary analyze the eddy current effects. Then, the calculated inductance of the windings with and without an outer shell was compared and analyzed.

A. EQUIVALENT CIRCUIT MODEL

In Fig. 15, the skin effect of the outer shell was ignored to simplify the equivalent circuit model. The self-inductance and resistance of the windings without considering the eddy current effects of the outer shell are assumed to be \( L \) and \( R \), respectively, whereas the inductance and resistance of the outer shell are assumed to be \( L_k \) and \( R_k \). They are connected in series. The mutual inductance between the windings and outer shell is assumed to be \( M \). The current and voltage of the windings are \( I_1 \) and \( U_1 \), respectively.

Then, the eddy current \( I_2 \) induced in the outer shell at a current frequency of \( \omega \) is

\[
I_2 = -\frac{j\omega M I_1}{j\omega L_k + R_k}
\]

(8)

The terminal voltage of the windings is

\[
U_1 = I_1 R + j\omega L I_1 + j\omega M I_2
\]

(9)

The impedance \( Z \) can be obtained using (8) and (9)

\[
Z = \frac{U_1}{I_1} = R + \frac{\omega^2 M^2 R_k}{R_k^2 + \omega^2 L_k^2} + j\omega \left( L - \frac{\omega^2 M^2 L_k}{R_k^2 + \omega^2 L_k^2} \right)
\]

(10)

The equivalent self-inductance \( L_{eq} \) of the windings considering the eddy current effects of the outer shell can be obtained from (10)

\[
L_{eq} = L - \frac{M^2 L_k}{\left( \frac{R_k}{\omega} \right)^2 + L_k^2}
\]

(11)

If the frequency is high enough, the conductor loop will be no longer a lumped inductance but a distributed LC network. Fortunately, the frequency of the degaussing current is far below 10 kHz and the lumped-element model is still valid. To analyze the eddy current effects more accurately, the skin effect of the shell is to be considered, then the resistance of the shell \( R_k \) is supposed to be frequency dependent. As we know, if the skin depth \( \delta \) is less than the thickness of the shell, the current can be approximated as flowing only at the skin depth. In this situation, \( R_k \) can be written as

\[
R_k = \frac{l}{\gamma S} = \frac{l}{\gamma \delta d} = \frac{l}{\gamma d \sqrt{2/(\omega \mu \gamma)}}
\]

(12)
where $l$ and $d$ is the perimeter and width of the shell, respectively. Substitute formula (12) into formula (11), we can obtain formula (13)

$$ L_{eq} = L - \frac{M^2 L_k}{2\pi l d \omega} + L_k^2 $$

(13)

According to (11) and (13), the eddy current effects of the outer shell on the inductance can be summarized as follows:

1. The equivalent self-inductance $L_{eq}$ decreases with an outer shell, indicating the degaussing effect of the eddy current.
2. The equivalent self-inductance $L_{eq}$ decreases as the current frequency $\omega$ increases. $L_{eq} \approx L - M^2/L_k$ when $\omega$ is sufficiently high.
3. When the resistivity of the outer shell increases, the resistance $R_k$ of the outer shell increases as well, which in turn decreases the degaussing effect of the outer shell. Thus, the equivalent self-inductance $L_{eq}$ increases.
4. When the windings move closer to the outer shell, the mutual inductance $M$ will increase and the equivalent self-inductance $L_{eq}$ will decrease.
5. When the permeability of the outer shell increases, $M$ and $L_k$ will both increase. The equivalent self-inductance $L_{eq}$ will decrease, indicating the enhancement of the degaussing effect of the eddy current.
6. Comparing formula (11) and (13), it can be concluded that, when the frequency is high enough, the skin effect will weaken the influence of the frequency on the inductance of the windings.

### B. WITHOUT AN OUTER SHELL

In this section, the inductance without an outer shell is first calculated and analyzed. The calculated values of self- and mutual inductances of each winding at different current frequencies are presented in Figs. 16 and 17. DC inductance was also calculated for comparison (very low frequency in simulations). Based on the calculated results, the following conclusions can be drawn:

1. The calculated value of XQ3 self-inductance at 10 kHz is 54.5 $\mu$H. If the skin effect is ignored, meaning the thickness direction of the inner shell is only divided into one layer, then the self-inductance value is only 27.4 $\mu$H. This indicates that the calculation of high-frequency inductance must account for the skin effects of eddy currents. Otherwise, calculated values will be significantly smaller than real values.
2. With an increase in current frequency, the self-inductance will decrease to a certain extent due to the degaussing effects of eddy currents. In the range of 0 to 100 Hz, the self-inductance decreases by over 20%. In the range of 100 Hz to 1 kHz, the self-inductance decreases by more than 50%, indicating that the degaussing effect of eddy currents is significant.
3. An increase in current frequency can significantly decrease the mutual inductance. When the frequency increases from 0 to 100 Hz, the mutual inductance decreases by several times. When the frequency increases from 100 Hz to 1 kHz, the mutual inductance is reduced by one order of magnitude. When the frequency increases to above 1 kHz, the mutual inductance is insignificant and can be ignored. Therefore, only the calculated values for DC and 100 Hz are presented in Fig. 18.
4. The maximum values of DC self- and mutual inductances arrive at 161.3 $\mu$H and 21.6 $\mu$H, indicating that the mutual inductance is considerable as compared with self-inductance. Therefore, the mutual inductance cannot be ignored in the analysis of low-frequency equivalent circuits.

### C. WITH AN OUTER SHELL

The calculated inductance values with an outer shell are presented in Figs. 16 and 17. The following conclusions can be drawn:

1. The existence of the outer shell has little effect on the AC self-inductance, but it does have a significant effect on
the mutual inductance and the DC self-inductance. With an outer shell, the mutual inductance significantly decreases by several times at 100 Hz, whereas DC self-inductance exhibits a certain degree of increase.

(2) The effects of the outer shell on the inductance of the windings are mainly reflected in two aspects: one is an increase in the permeability of the surrounding area, which leads to an increase in inductance, and the other is an increase in the degaussing effect of eddy currents, which leads to a decrease in inductance. When the current frequency is high, the degaussing effect of eddy currents is greater than the effect induced by increasing the permeability of the outer shell. Therefore, the inductance with an outer shell is slightly lower when the current frequency is greater than 1 kHz. When the current frequency is low, the former effect is dominant, meaning inductance increases when there is an outer shell. Overall, the self-inductance slightly increases at DC and 100 Hz, whereas the mutual inductance decreases. The decrease in the mutual inductance at low frequencies results from the magnetic shielding effect of the outer shell, as shown in Fig. 18. When the current frequency increases further, the magnetic shielding effect and degaussing effect of eddy currents produce a synergistic enhancement effect, leading to a decrease of several times in the mutual inductance at 100 Hz.

VI. COMPARISON OF CALCULATED AND MEASURED INDUCTANCE VALUES

A. WITHOUT AN OUTER SHELL
The calculated and measured inductance values of degaussing windings without a shell are analyzed and compared in this section. The relative error of self-inductance $e_{\text{RL}}$ is defined as follows:

$$e_{\text{RL}} = \frac{L_j - L_c}{L_c}$$  (14)

where $L_c$ and $L_j$ are the measured and calculated inductance values of the windings, respectively.

Mutual inductance is typically small and there are errors in measurement. The relative error of mutual inductance $e_{\text{RM}}$ is expressed as follows:

$$e_{\text{RM}} = \frac{M_j - M_c}{M_m}$$  (15)

where $M_m$ is the maximum measured value of mutual inductance. $M_m = 11 \, \mu\text{H}$ according to the measured results. $M_c$ and $M_j$ are the measured and calculated values of mutual inductance of two windings, respectively.

Figs. 19 and 20 show that the overall error of inductance calculation is small and the relative error is less than 20%. This indicates that the proposed method of inductance calculation is effective and can accurately calculate the changes in varying current frequencies. Additionally, most of the calculated self-inductance values are slightly higher than the measured values. This type of systematic error may be caused by discrepancies in material parameters.

B. WITH AN OUTER SHELL
Figs. 21 presents comparative results for calculated and measured self-inductance at different current frequencies with an outer shell. One can see that the majority of relative errors of calculated self-inductance are small (less than 10%). The self-inductance of the windings near the stern section suffers from greater relative errors (above 10% but less than 20%).

Figs. 22 presents comparative results for calculated and measured mutual inductance at different current frequencies with an outer shell. The calculated mutual inductance agrees well with the measured values. The relative errors are less than 20%. Compared with the calculated values without an outer shell, the mutual inductance decreases slightly at 100 Hz with an outer shell because the outer shell is composed of several pieces and does not form a complete loop in the circumferential direction. Therefore, there is a slight degaussing effect leading to a small decrease in mutual inductance.
VII. CONCLUSION

(1) A calculation method for AC inductance considering the degaussing effects of eddy currents was proposed in this paper. The accuracy of the calculation method at low frequency was verified using a small model, and the effects of mesh size and truncated boundary size on the inductance calculation were analyzed. The maximum relative errors of self- and mutual inductances calculations at different current frequencies are less than 20%, indicating the high accuracy of the proposed method.

(2) The inductance of degaussing windings without an outer shell was calculated, and the results demonstrated that the calculation of high-frequency inductance must account for the skin effect of eddy currents. Otherwise, the calculated inductance will be significantly lower. With an increase in current frequency, self-inductance will decrease a little for frequency in the range $0 \sim 100$ Hz, whereas it will decrease by more than 50% for frequency in the range $100$ Hz $\sim 10$ kHz. In addition, the current frequency has a greater effect on mutual inductance. With an increase in current frequency, the mutual inductance decreases by several times for frequency in the range $0 \sim 100$ Hz, decreases by an order of magnitude for frequency in the range $100$ Hz $\sim 1$ kHz, and decreases to very close to zero for frequency above $1$ kHz.

(3) The inductance of degaussing windings with an outer shell was calculated, and the results demonstrated that the existence of an outer shell has an effect on DC self-inductance and mutual inductance. The effects of the outer shell on inductance are reflected in two aspects: one is an increase in the permeability of the surrounding area, leading to an increase in inductance, and the other is an increase in the degaussing effect of eddy currents, leading to a decrease in inductance. The former effect is dominant when the frequency is low ($\leq 100$ Hz), meaning inductance increases when there is an outer shell. When the frequency is high ($\geq 1$ kHz), the degaussing effect of eddy currents is dominant and the existence of an outer shell leads to a decrease in inductance.

(4) The maximum values of DC self- and mutual inductances arrive at 161.3 $\mu$H and 21.6 $\mu$H, indicating that the mutual inductance is considerable as compared with self-inductance and cannot be ignored at low-frequency circuit analysis.

REFERENCES

[1] G. Chengbao and Z. Weichang, “Numerical simulation and verification of magnetic signatures of ship degaussing coils,” Acta Armamentarii, vol. 38, no. 10, pp. 1988–1994, 2017.

[2] L. Shengdao, W. Wei, and X. Cunlong, “Calibration of a degaussing system coils’ ampere-turns for low magnetic steel ship,” Mar. Electr. Electron. Eng., vol. 33, no. 4, pp. 25–27, 2013.

[3] W. Zhifei, “Overview on the ship degaussing system,” Mar. Electr. Electron. Eng., vol. 40, no. 9, pp. 4–7, 2020.

[4] S. Ji and N. Shifeng, “Inductance computation of ship degauss coil,” Ship Sci. Technol., vol. 38, no. 8, pp. 100–103, 2016.

[5] T. Guanhan and K. Jianhua, “A fast calculating method for magnetic field of solenoid,” Trans. China Electrotech. Soc., vol. 8, no. 4, pp. 36–40, 1993.

[6] Z. Xinghui, H. Yu, and X. Kexing, “The mutual inductance of two coaxial circular coils and the magnetic field distribution,” College Phys., vol. 26, no. 7, pp. 21–24, 2007.

[7] T. H. Fawzi and P. E. Burke, “The accurate computation of self and mutual inductances of circular coils,” IEEE Trans. Power App. Syst., vol. PAS-97, no. 2, pp. 464–468, Mar. 1978.

[8] W. Sunan, “Inductance calculating table for air cored cylindrical coils,” J. Zhengzhou Univ., vol. 24, no. 3, pp. 106–112, 2003.

[9] C. T. Kalantarov, Handbook of Inductance Calculation. Beijing, China: China Machine Press, 1992.

[10] X. Longhan and L. Jiehong, ANSYS Electromagnetic Field Analysis. Beijing, China: Electronic Industry Press, 2015.

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