Analysis of Opening Angle for Radial Magnetic Field Compensation Windings of Double-layer Ferromagnetic Cylindrical Shells

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Abstract. A double-layer ferromagnetic cylindrical shell causes a magnetic anomaly in its surrounding space under the action of the geomagnetic field. Aiming at the problems of poor compensation uniformity and obvious local magnetization caused by the single-branch winding compensation method, a double-branch winding solution is proposed. By establishing a double-layer ferromagnetic cylindrical shell model, the radial magnetization characteristics of the cylindrical shell under the action of the vertical geomagnetic field was analyzed, and the opening angle of double-branch winding was studied. By optimizing the opening angle of compensation windings in the three proposed configuration schemes with respect to the minimum abnormal magnetic field, the optimal ranges of opening angle for the double-branch compensation windings were determined.

1. Introduction
Under the Earth's magnetic field, ferromagnets induce a magnetic field around themselves that exhibits abnormal characteristics. With the development of magnetic detection technology and torpedo and other weapons, the magnetic protection of cylindrical shell structures such as submarines, and underwater unmanned vehicles needs to be considerably improved. The radial induced magnetic field under the vertical magnetization of geomagnetism is crucial to measure the characteristics of magnetic anomalies. And the magnetic field induced by the ferromagnets is also an important direction for degaussing system design[1-3].

A double-branch compensation winding configuration scheme is proposed to achieve the best compensation effect, which can improve the compensation uniformity of the radial magnetic field outside the casing, reduce the peak value of magnetic anomalies observed. In order to achieve the best compensation effect, comparative results of optimal opening angles of double-branch windings under the three proposed configurations were analyzed. The proposed double-branch winding compensation scheme and optimization method can provide guidance for related engineering applications.

2. Radial Magnetic Field Compensation Model of Double-layer Cylindrical Shells
The degaussing windings used for magnetic field compensation are usually laid along the horizontal plane in case of a double-layer cylindrical shells in the vertical geomagnetic field. The single-branch windings are spread along the mid-plane, as shown in figure1 (a), while double-branch windings are parallel to the mid-plane, as shown in figure1 (b).
Considering that its axial size is considerably larger than its radial size, a double-layer cylindrical shells in a uniform magnetic field can be regarded as an infinitely long structure\(^{[4-7]}\). Therefore, its vertical two-dimensional section can be used for magnetization characteristic analyses. The three proposed configurations of double-branch windings are shown in figure2. figure2(a) shows that the double-branch windings are laid inside the inner shell; figure2(b) shows that the double-branch windings are laid between the inner and outer shells (close to the inner shell); figure2(c) shows that the double-branch windings are laid between the inner and outer shells (close to the outer shell).

\[
H = -\nabla \varphi
\]

(1)

When the compensation measures are added as shown in figure2, due to the existence of current, the vector magnetic potential \(\mathbf{A} = [A_x, A_y, A_z]\) should be introduced such that \(\mathbf{B} = \nabla \times \mathbf{A}\) and \(\nabla \cdot \mathbf{A} = 0\).

In the two-dimensional plane field, the vector magnetic potential \(\mathbf{A}\) and current density \(\mathbf{J}\) are parallel to each other and only exist in the direction perpendicular to the plane, that is, \(A_y = A_z = 0\), \(A_x = A\), \(J_y = J_z = 0\), and \(J_x = J\). The relationship between the magnetic potential and current density is as follows:

\[
\frac{\partial^2 A}{\partial y^2} + \frac{\partial^2 A}{\partial z^2} = -\mu J
\]

(2)

Because a ferromagnetic medium exists in the domain, the spatial magnetic field can be expressed as a superposition of three parts:

\[
\mathbf{H} = \mathbf{H}_J + \mathbf{H}_M + \mathbf{H}_B
\]

(3)
where $H_J$ is the magnetic field intensity generated by the current; $H_M$ is the magnetic field generated by the ferromagnetic material; and $H_B$ is the geomagnetic background magnetic field intensity.

For a multi-medium model, the boundary satisfies the continuous tangential component of the magnetic field intensity and the continuous normal component of the magnetic flux density on both sides of the interface. The magnetic field intensity distribution throughout the domain can then be obtained via numerical solutions such as finite elements method.

3. Example Analysis

3.1. Example Model and Optimal Opening Angle

To analyze the relationship between the compensation effect, compensation winding layout, and current configuration, the following example analysis models are established through the finite element simulation software COMSOL Multiphysics.

The section radius of the inner shell is 5 m; relative magnetic permeability, 100; The section radius of the outer shell is 6 m; relative magnetic permeability, 200; inner and outer shell thickness, 100 mm; number of winding layers, 2; the compensation effect is measured for the upper 20 m of the measurement line. The shortest distance between the winding arrangement and shell was fixed at Gap = 100 mm. The overall structure of the model is shown in figure2. Considering the opening angle of the winding with respect to the center of the circle as $\alpha$, the coordinates of the center of the incoming line on the upper left of the winding are \([r \cos(90° - \alpha/2), r \sin(90° - \alpha/2)]\); the coordinates of the remaining points can be obtained based on symmetry; and the vertical component of the geomagnetic field is considered as 30000 nT. Analyze the magnetic flux density $B$ of the double-branch windings in the space with different number of ampere-turns $I_A$ and open angle $\alpha$ through simulation.

The objective function of the best compensation is the minimum value of the maximum magnetic anomaly on the observation line, as shown below:

$$
\left\{ \begin{array}{l}
\text{Objective} = \min \left\{ \max \left[ \text{abs} \left( B^i_1(\alpha, I_1) - B^i_2 \right) \right] \right\}, \ i \in l \\
\text{Constra int} = \alpha \in [10°, 170°], \ step = 0.25° \ \\
\text{Constra int} = I_1 \in [100, 300], \ step = 0.25°
\end{array} \right.
$$

where $B^i_2$ is the vertical component of the magnetic flux density $B$ at each point on the observation line, which can be solved by finite element simulation; $B^i_1$ is the vertical component of the geomagnetic flux density of the corresponding point, that is, 30000 nT in this example; $i$ is the number of each point on the observation line, and $l$ represents the measurement line.

The variables are the relative opening angle $\alpha$ and the number of ampere-turns of the winding. To determine the best solution, a genetic algorithm is selected to realize parameter optimization\(^{[8-10]}\). For the parameter optimization, the number of iterations was set to 50; number of populations per generation, 80; range of the number of ampere-turns for each winder layer, 100 ~ 300; and range of opening angle $\alpha$, 10~170°. Considering the practical feasibility, both variables are selected in 0.25 steps.

**Case 1**: The double-branch windings are laid inside the inner shell. The vertical magnetic anomaly increases and then decreases with the increase in the opening angle of the windings. The final optimization result is that the number of ampere-turns for each branch of the double-branch windings is 907, and the opening angle $\alpha$ is 119°; further, the maximum magnetic anomaly value of the measuring line at 20 m was 0.21 nT, as shown in figure3.

**Case 2**: The double-branch windings are laid between the inner and outer shells (close to the inner shell). The final optimization result is that the number of ampere-turns for each branch of the double-branch windings is 293, and the opening angle $\alpha$ is 118.5°; further, the maximum magnetic anomaly value of the measuring line at 20 m was 0.76 nT, as shown in figure4.

**Case 3**: The double-branch windings are laid between the inner and outer shells (close to the outer shell). The final optimization result is that the number of ampere-turns for each branch of the double-
branch windings is 278.8, and the opening angle \( \alpha \) is 118°; further, the maximum magnetic anomaly value of the measuring line at 20 m was 1.21 nT, as shown in figure 5.

![Figure 3](image3.png)

**Figure 3.** Maximum magnetic anomaly and ampere-turns for different opening angle \( \alpha \) in case 1.

![Figure 4](image4.png)

**Figure 4.** Maximum magnetic anomaly and ampere-turns for different opening angle \( \alpha \) in case 2.

![Figure 5](image5.png)

**Figure 5.** Maximum magnetic anomaly and ampere-turns for different opening angle \( \alpha \) in case 3.

3.2. Performance Improvement Analysis

To verify the improvement in the performance of the double-branch windings configuration scheme over that of the traditional method, the current configurations of single- and double-branch windings
were optimized for the same double-layer cylindrical shell model. Table 1 compares the compensation effects of the single- and double-branch winding schemes.

**Table 1. Comparison of the compensation effects.**

| Case     | Total ampere-turns(A) | Maximum magnetic field(A/m) | Magnetic anomaly(nT) |
|----------|-----------------------|-----------------------------|----------------------|
| **Case 1** |                       |                             |                      |
| Single-branch | 1559                 | 231                         | 12.5                 |
| Double-branch | 1815                 | 86                          | 0.2                  |
| Comparison | 16%                   | -63%                        | -98%                 |
| Single-branch | 512                  | 74                          | 29.7                 |
| **Case 2** |                       |                             |                      |
| Double-branch | 586                  | 39                          | 0.8                  |
| Comparison | 14%                   | -47%                        | -97%                 |
| Single-branch | 487                  | 48                          | 32.6                 |
| **Case 3** |                       |                             |                      |
| Double-branch | 557                  | 24                          | 1.2                  |
| Comparison | 14%                   | -50%                        | -96%                 |

As summarized in table I, when the double-branch windings scheme is adopted for the three cases, the total ampere-turns increase by 16%, 14% and 14%, respectively, while the maximum magnetic field decreases by 63%, 47% and 50%, respectively. Furthermore, the magnetic anomaly drops by 98%, 97% and 96%, respectively.

Comparing to single-branch winding scheme, the maximum compensation magnetic field for the double-branch winding scheme decreases significantly, due to more distributed current for the double-branch winding scheme. The magnetic anomaly value of double-branch winding scheme drops significantly in comparison with single-branch winding scheme, because the double-branch winding scheme exhibits better fitting freedom of the spatial magnetic field, the optimal compensation effects can be achieved by adjusting the opening angle $\alpha$.

4. Conclusion

Aiming at the magnetic anomaly induced by the geomagnetic field magnetization for the double-layer ferromagnetic cylindrical shells, the optimal opening angles of the double-branch degaussing winding scheme in three cases were compared and analyzed. The optimal opening angle of the double-branch winding scheme ranges in $118^\circ$~$119^\circ$, in which cases the compensation effects have been significantly improved. For the double-branch winding scheme, the magnetization effect of the ferromagnetic cylindrical shells was weakened due to more distributed current. In addition, the magnetic anomaly after compensation drops over 96% due to better fitting freedom of the spatial magnetic field.

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