Analysis of eddy current loss in magnetic coupling based on three-dimensional finite element calculation

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Abstract. Considering the end effect, the three-dimensional finite element calculation model of the magnetic coupling is established. The three-dimensional distribution nephogram of the induced current and eddy current loss on the isolation cover is obtained, and the distribution trends of the two are consistent. The influence of size, material, and operating condition of magnetic coupling on eddy current loss is studied. The results show that the selection of isolation material with high resistivity and the reduction of isolation thickness are helpful to reduce the eddy current loss. The higher the rotating speed of the magnetic coupling, the greater the eddy current loss. At the same speed, the greater the load, the greater the magnetic declination, the smaller the eddy current loss. The research results can provide a reference for reducing energy loss and cooling structure design of magnetic coupling.

1. Introduction

The magnetic coupling uses inner and outer magnetic steel as the transmission parts, and the transmission fluid is completely enclosed inside the device with an isolating sleeve. So that the mechanical dynamic seal is changed into a static seal, and absolutely no leakage is achieved. Therefore, the magnetic coupling has been widely used in chemical, pharmaceutical, and other occasions with high requirements for the sealing of the transmission device\cite{1}. When the magnetic coupling is working, the isolation sleeve between the internal and external magnetic rotors cuts the magnetic induction line, and the induced current forms a closed loop on the surface of the isolation sleeve, resulting in eddy current loss. On the one hand, the reverse magnetic field generated by the induced current will weaken the original magnetic field of the magnetic coupling and reduce the transmission efficiency\cite{2}. On the other hand, eddy current loss dissipates in the form of heat, which increases the working temperature of the magnetic coupling. When the temperature exceeds the Curie temperature of the permanent magnet, the permanent magnet demagnetizes. Therefore, eddy current loss has an important influence on the reliable and efficient operation of magnetic coupling.

Many scholars have studied the eddy current loss of magnetic couplings. Among them, Shi, W.D., Zhao, K.Z. etc. summarized the empirical calculation formula of magnetic coupling eddy current loss based on their own research\cite{3}\cite{4}\cite{5}. Dai, W.Z., Wang, J.Q. summarized the eddy current loss characteristics of magnetic couplings from the perspective of two-dimensional finite element simulation and experiment\cite{6}\cite{7}. Tan, L.W., Liu, J.R. and others designed and studied the cooling channel for the eddy current heat problem of the magnetic coupling\cite{8}\cite{9}.
However, the above studies on the characteristics of eddy current loss all use 2D analysis and calculation, ignoring the end effect, and there is a problem of inaccurate calculation\(^\text{[10]}\). At the same time, the two-dimensional simulation cannot directly show the distribution of eddy current loss on the isolation cover. This paper uses 3D numerical simulation to study the eddy current loss characteristics of the isolation cover in the magnetic coupling, analyzes the influence of different structural parameters and operating conditions on the eddy current loss on the isolation cover, which provides a reference for reducing the energy loss of the magnetic coupling and designing the cooling structure.

2. Establish the 3D model of the magnetic coupling
Figure 2 is a 3D model of the magnetic coupling, and its structural parameters and materials are shown in Table 1:

The finite element calculation uses Maxwell software. Establish a three-dimensional model according to the parameters in the above table, the number of magnetic pole pairs is 16, the length of the magnet is 60mm, and the inner and outer magnets are both radially magnetized. The inner and outer magnetic rotors are respectively wrapped with air layers, which are defined as the rotation domain, the rotation direction is the positive direction of the z-axis, and the other areas are defined as the static domain. It should be noted that the rotating domain cannot intersect with any stationary objects. In the excitation options, add eddy current effects to the isolation cover. In addition, the isolation cover is in an alternating magnetic field and is affected by the skin effect. The induced current generated is
concentrated on the surface of the isolation cover. The surface current density of the isolation cover is large, and the internal current density is small. As a result, the resistance of the conductor increases. For this reason, when dividing the grid, the isolation cover needs to adopt the grid division based on the skin depth, and the skin depth is according to 
\[ d = \frac{2}{\omega \mu} \]
Where \( \omega \) is the angular frequency, \( \lambda \) is the conductivity of the conductor, and \( \mu \) is the magnetic permeability [11].

In order to verify the accuracy of the finite element model, it was compared with the experimental data of magnetic coupling eddy current loss in practical application. The magnetic coupling used in the literature has 22 pole pairs and a rated torque of 100N·m. The experimental measurement of the eddy current loss under the working condition of rotation speed of 600rpm and slip angle of \( \frac{\pi}{m} \) [12]. The magnetic coupling is restored according to the parameters in the literature, and the three-dimensional finite element simulation is performed on it. The comparison between the simulation results and the experimental results is shown in the following table. The error is within the acceptable range, which proves the reliability of the finite element calculation results.

| Part             | Inner diameter (mm) | Outer diameter (mm) |
|------------------|---------------------|---------------------|
| Inner magnetic rotor | 90                  | 112                 |
| Outer magnetic rotor | 138                | 152                 |
| Isolation cover     | 124                 | 126                 |
| Inner magnet        | 112                 | 120                 |
| Outer magnet        | 130                 | 138                 |

3. Three-dimensional distribution of eddy current loss

Fig. 3 and Fig. 4 are respectively the induced current vector diagram and eddy current loss density distribution diagram on the isolation cover obtained by finite element calculation.

It can be seen that at any instant, the induced current generated by the metal isolation cover cutting the magnetic line of induction forms 16 closed loop areas on the isolation cover, and the current directions of the closed loops in the adjacent areas are opposite. And the density of the induced current also presents a staggered distribution of high density and low density. When the inner and outer magnets in the same magnetizing direction are aligned, the permanent magnet has the N pole facing the S pole. The magnetic induction lines start from the N pole of the magnet and pass through the isolation cover and return to the S pole. The corresponding isolation cover area cuts the magnetic induction line, so the induced current density generated here is high. When the inner and outer magnets in the opposite magnetizing direction are aligned, the permanent magnet has a situation where the N pole is facing the N pole and the S pole is facing the S pole. Only a small number of magnetic lines of induction pass through the isolation cover obliquely, and the corresponding isolation cover area performs weak cutting of the magnetic induction line, which can only generate less induced current, so the induced current density here is small. The inner and outer magnets rotate, and the induced current distribution on the isolation cover also moves with the inner and outer magnets.
Fig. 3. Induced current vector

The distribution of eddy current loss density is roughly the same as the distribution trend of induced current density. At any instant, there are 16 eddy current loss distribution areas on the isolation cover, and each area shows a trend of gradual increase in eddy current loss density from the surrounding to the center. The area with the largest eddy current loss density corresponds to the area with the largest induced current density. Affected by the end effect of the inner and outer magnets, the area of the isolation cover with eddy current loss is slightly larger than the area of the isolation cover corresponding to the inner and outer magnets. At different times, the distribution of eddy current loss also changes with the internal and external magnetic rotation.

Fig. 4. Eddy current loss density distribution

Table 2. Comparison of finite element calculation result and experimental result

| 3D FEC result | Experimental result | Relative error |
|---------------|---------------------|---------------|
| 181.69W       | 193.10W             | 5.9%          |
4. Analysis of Influencing Factors of Eddy Current Loss of Magnetic Coupling

The eddy current loss will reduce the working efficiency of the magnetic coupling, and the thermal effect produced by the eddy current loss will worsen the working environment of the magnetic steel. Therefore, understanding the influence of various factors on the eddy current loss and controlling the eddy current loss within a reasonable range is of great significance to the normal and stable operation of the magnetic coupling. The eddy current loss influencing factors of magnetic couplings can be summarized into three categories: material factors, size factors, and operating conditions. Based on the magnetic coupling model constructed above, the influence of various factors on the eddy current loss of the magnetic coupling is analyzed.

4.1 The influence of material factors on eddy current loss

The main material factor that affects the eddy current loss of the magnetic coupling is the resistivity of the isolation cover. Metal materials are widely used in the production of isolation enclosures due to their good process performance, pressure resistance and high temperature resistance. The resistivity of the most commonly used isolation cover materials is shown in Table 2 [13]. Keep the operating conditions of the magnetic coupling unchanged, and perform finite element simulation calculations on the eddy current loss of the magnetic coupling under different isolation cover materials. The results are shown in Figure 5.

It can be seen from Figure 5 that the greater the resistivity of the isolation cover material, the smaller the eddy current loss on the isolation cover. If the isolation cover is made of non-metallic materials with no conductivity, the eddy current loss of the magnetic coupling can be completely eliminated, such as ceramics and some synthetic materials, which have been gradually applied to various magnetic coupling transmission devices. However, compared with metallic materials, non-metallic materials have poor strength and low rigidity, and their applicable occasions are limited. Therefore, in a working environment with low pressure, non-conductive non-metallic materials can be selected to avoid the generation of eddy current losses. In a high-pressure working environment, under the premise of meeting pressure requirements, selecting metal materials with high resistivity can reduce eddy current loss.

Table 3 Several commonly used isolation cover materials

| Material      | Resistivity (Ω·m) |
|---------------|-------------------|
| Hastelloy C   | 1.39×10^{-6}      |
| 304 stainless steels | 7.2×10^{-7}        |
| Titanium alloy | 8.3×10^{-7}       |
| 718 alloy     | 1.62×10^{-6}      |

Fig.5. The influence of resistivity on eddy current loss
4.2 The influence of size factor on eddy current loss
The size factor affecting eddy current loss of magnetic coupling is mainly the wall thickness of the isolation sleeve. Keeping the operating conditions and materials of the magnetic coupling unchanged, the eddy current loss of the magnetic coupling with different thickness isolators is simulated by the finite element method, and the curve of eddy current loss with wall thickness is obtained as shown in Fig. 6.

![Fig.6. The influence of isolation cover thickness on eddy current loss](image)

According to fig.6, the wall thickness of the isolation sleeve is proportional to the eddy current loss. The thicker the wall thickness of the isolation sleeve is, the greater the eddy current loss is. When the induced current is generated, the isolator is equivalent to the resistance, and the wall thickness determines the volume of the resistance. The thicker the wall thickness of the isolator is, the greater the resistance is, and the greater the eddy current loss caused by the induced current is. In order to reduce the eddy current loss on the isolation sleeve, the thickness of the isolation sleeve should be as thin as possible. Generally speaking, the thickness of metal isolation sleeve is in the range of 0.6 – 1.0 mm.

4.3 The influence of operating conditions on eddy current loss
The eddy current loss generated on the isolation cover of the magnetic coupling under different working conditions is also different. The operating conditions that affect the eddy current loss are mainly rotating speed and magnetic declination.

4.3.1 The influence of speed on eddy current loss.
Keeping the magnetic declination angle and coupling degree of the magnetic coupling unchanged, changing the rotation speed of the inner and outer magnetic rotors, the curve of the eddy current loss of the magnetic coupling with the rotation speed is shown in Figure 7.

It can be seen from the figure that the eddy current loss of the magnetic coupling increases with the increase of the speed. This is because the eddy current loss is caused by the continuous cutting of the magnetic lines of induction in the alternating magnetic field by the metal isolation cover, and the rotational speed affects the frequency of cutting the magnetic lines of induction. For a magnetic coupling with a fixed number of magnetic pole pairs, the isolation cover cuts the magnetic line of induction with a period of \( \frac{4\pi}{m} \). When the rotation speed is \( n \), the changing frequency of the alternating magnetic field of the isolation cover is \( \frac{nm}{120} \). The changing frequency of the magnetic field increases with the increase of the speed \( n \). The greater the frequency of the alternating magnetic field, the higher the eddy current loss. Therefore, it is very important to reasonably set the working speed of the magnetic coupling. For high-speed magnetic couplings, a cooling cycle should be set to prevent the magnetic steel from demagnetizing at high temperatures.
4.3.2 The influence of magnetic declination on eddy current loss

When the magnetic coupling is at rest, the N (S) pole of the outer magnet and the S (N) pole of the inner magnet are attracted to each other and aligned. When the magnetic coupling is in operation, it is subjected to a load, and a magnetic declination will be generated between the inner and outer magnets. The size of the angle is affected by the load. The greater the load, the greater the magnetic declination angle, which can reach a maximum of $\frac{\pi}{m}$. Beyond this angle, the internal and external magnetic components will relatively slip off, and the magnetic coupling will no longer operate normally. Keep the rotation speed of the inner and outer magnets unchanged, change the magnetic declination angle between the inner and outer magnets, simulate the eddy current loss of the magnetic coupling with different magnetic declination angles, and the calculated curve is shown in Fig. 8.

![Graph showing the influence of magnetic declination on eddy current loss](image)

**Fig. 8. The influence of magnetic declination on eddy current loss**
It can be seen from Figure 8 that as the magnetic declination angle between the inner and outer magnets increases, the eddy current loss of the magnetic coupling gradually decreases. This is because when the magnetic declination angle is 0°, the N(S) poles and S(N) poles of the inner and outer magnets are attracted and aligned with each other. The magnetic line of induction starts from the N pole of the inner(outer) magnet, passes through the isolation cover and returns to the S pole of the outer(inner) magnet. At this time, the magnetic flux passing through the isolation cover is the largest, and the magnetic induction intensity is the largest, so the eddy current loss at this time is also the largest. When the inner and outer magnets generate a magnetic deflection angle, the N and S poles of the inner and outer magnets are offset, the number of magnetic lines of induction passing through the isolation cover is reduced and the magnetic lines of induction are inclined. At this time, the magnetic flux passing through the isolation cover is reduced, the magnetic induction intensity is reduced, and the eddy current loss on the isolation cover is also reduced. Figure 9 is obtained by simulating and calculating the magnetic induction intensity on the isolation cover at different magnetic declination angles. The trend of the magnetic induction intensity decreasing with the increase of the magnetic declination angle also proves the correctness of the above analysis. It can be seen that the magnetic declination has a significant effect on the eddy current loss of the magnetic coupling. When the magnetic coupling is working, the load should be matched with the rated load of the magnetic coupling to keep the magnetic declination angle at a larger angle. This can not only make the best use of the magnetic coupling, but also reduce the eddy current loss on the isolation cover.

5. Conclusion
Aiming at the problem of inaccurate results caused by end effects that are ignored in the analysis and calculation of 2D eddy current loss, this paper establishes a 3D finite element calculation model of the magnetic coupling. The 3D distribution cloud diagram of the induced current and eddy current loss on the isolation cover is obtained, and the distribution trends of the two are consistent.

At the same time, the influence of eddy current loss is analyzed from three aspects: material factors, size factors, and operating conditions of the magnetic coupling. It is concluded that the smaller the resistivity of the isolation cover material, the greater the eddy current loss. The thicker the wall thickness of the isolation cover, the greater the eddy current loss. The greater the speed of the magnetic coupling, the greater the eddy current loss. The larger the magnetic declination angle of the inner and outer magnets, the smaller the eddy current loss.

According to the above conclusions, the following measures can be taken to reduce the eddy current loss of the magnetic coupling. In the case of meeting the strength requirements, select the isolation cover material with high resistivity, and reasonably reduce the isolation cover wall thickness. In the case of meeting the working requirements, reasonably reduce the speed, and set a cooling device for the high-speed magnetic coupling. When selecting the magnetic coupling, select the one that matches the load.
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