The Analysis of Thermal Magnetic Coupling of Tubular Permanent Magnetic Coupler

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Abstract. Due to the existence of induced eddy current, the internal of the permanent magnet coupling’s temperature increases during the operation, which affects the performance of the permanent magnet coupling. In this paper, considering the influence of temperature on the remanence, coercive force of the permanent magnet, the conductivity of the conductor and steel frame. We analysed the coupling performance of thermodynamics and electromagnetism. Electromagnetic field simulated with ANSYS Maxwell and temperature field simulation with Workbench. The analysis results lay a foundation for the subsequent analysis of the thermomagnetic coupling of the permanent magnet couplings.

1. Introduction

Based on the magnetic field, the permanent magnet coupling uses the non-contact relative motion between the permanent magnet and the conductor to form the induced magnetic field. The interaction between the induced magnetic field and the original magnetic field produces the torque and realizes the torque transmit between the motor and the load section. The structure of the tubular permanent magnet coupler is shown in the Fig. 1, which is mainly made of inner and outer steel frames, permanent magnet blocks, aluminium yokes and conductor tubes. The magnetism of permanent magnet is directly related to the temperature, and the meaning high temperature will cause demagnetization, and at the same time the material performance parameters of components of permanent magnet coupler are also related to the temperature, such as the conductivity of conductor barrel, the remanence of permanent magnet, the coercive force of permanent magnet and the permeability of outer steel disk.

Fig 1. Structure diagram of tubular permanent magnet coupler.
2. Finite element simulation

2.1. Electromagnetic field finite element

We made finite element simulation \cite{1,2} with Ansys Maxwell, and made the finite element mode and establish the solution domain. The mathematical mode for searching the Magnetic vector potential \( A \) in the solution \( \Omega \):

\[
\Omega: \frac{\partial}{\partial x} \left( \beta \frac{\partial A}{\partial x} \right) + \frac{\partial}{\partial y} \left( \beta \frac{\partial A}{\partial y} \right) + \frac{\partial}{\partial z} \left( \beta \frac{\partial A}{\partial z} \right) = 0
\]  

(2.1)

The following three kinds of boundary conditions are mainly set up: the inner surface of the model is S1, the interface of different media is S2, and the side of the conductor along the radius direction of the driven rotor is S3. The expression of the three kinds of boundary conditions is shown in formula (2.2):

\[
\begin{align*}
S_1: & \quad A = 0 \\
S_2: & \quad \left( \beta \frac{\partial A}{\partial n} \right)_{x_2} = \left( \beta \frac{\partial A}{\partial n} \right)_{x_2} \\
S_3: & \quad \left( \beta \frac{\partial A}{\partial n} \right)_{x_2} - \left( \beta \frac{\partial A}{\partial n} \right)_{x_2} = J
\end{align*}
\]  

(2.2)

In the permanent magnet coupler, the main excitation is the rotation of the permanent magnet\cite{3}. The expression of the magnetic induction intensity of the permanent magnet is:

\[
B = \nabla \times A
\]  

(2.3)

By setting the rotating parameters of the permanent magnet disk, the relative slip between the permanent magnet disk and the conductor tube can be effectively simulated.

Setting the appropriate solution step and time, the convergence range and other parameters\cite{4}, the torque calculation equation of ANSYS Maxwell software is:

\[
T = \frac{1}{2} \int \left( \int_{r_1} r_1^2 J \times B \, dr \right) \, dV
\]  

(2.4)

The torque of each unit nodes can be obtained from equation 2.4. The integration is the torque of the whole permanent magnet coupling can be obtained from post-processing the relationship curve between different parameters, the magnetic induction intensity of each region, and the eddy current density distribution, etc.

2.2. Finite element simulation process

Established the finite element analysis model from the physical drawing of the permanent magnet coupler as shown in Fig. 2. The orange part is the conductor barrel, the red and blue parts are the permanent magnet blocks. The magnetization direction of the red permanent magnet block is opposite to the blue permanent magnet block are both along the radius direction\cite{5}.

In this paper, n42sh neodymium iron boron permanent magnet is used, which is composed of Nd2Fe14B. The maximum magnetic energy product is 398kJ / m3, the maximum remanence BR is 1.47t, and the maximum coercive force is 1000ka / m. The Curie temperature of neodymium iron boron permanent magnet is 310 ~ 410 °C, and due to the poorly stability of temperature, the remanence temperature coefficient is about - (0.095 ~ 0.15) % / K, and the coercive force temperature coefficient is about - (0.4 ~ 0.7) % / K. The temperature shadow should be taken into account when using Ring to avoid irreversible demagnetization.
Considering the influence of temperature, the material parameters of the permanent magnet coupling are set. Through the ANSYS Maxwell transient analysis function, the three-dimensional transient field of the permanent magnet eddy current coupling is analysed[6]. It is assumed that the permanent magnet and the outer steel frame are stationary, and it is relative to speed between the permanent magnet and the conductor barrel. The output variable is taken as the detection parameter of torque meshing and solved.

2.3 simulation result
In this paper, under the condition of 20rpm slip and 40rpm slip, the coupling is simulated by electromagnetics under 50% load and 100% load respectively. Taking 20rpm as an example, the finite element simulation results are introduced.

It can be seen from Fig. 3 that the area with the largest magnetic induction intensity in the conductor barrel is the area where the permanent magnet maps to the conductor barrel, and with a maximum value of 1.84t. The magnetic induction intensity between the mapping areas of adjacent permanent magnets drops sharply. The direction of the magnetic induction intensity in the conductor barrel is the same as the magnetization direction of the permanent magnet. The direction of the magnetic induction intensity in the mapping area of adjacent permanent magnets is opposite, and the vector of the magnetic induction intensity is on Through the outer steel plates on both sides, a closed-loop curve is formed with each other.
It can be seen from Fig. 4 that the largest eddy current density in the conductor barrel is the area where the permanent magnet maps to the conductor barrel, and with the maximum value of $5.2 \times 10^4$ A/m$^2$. The eddy current circuit is formed in the mapping area of the conductor barrel, and the eddy current loss generated by the induced current has similar distribution trend in the current density. The largest eddy current loss density appears in the area where the permanent magnet maps to the conductor barrel, with the maximum value of $4.06 \times 10^3$ W/m$^3$.

3. Simulation of temperature field

3.1. Finite element analysis of temperature field.

The eddy current loss power can be obtained from the electromagnetic field simulation [7] in the previous section by taking the conductor barrel and the outer steel plate on the same side as the heat source of the system. The eddy current loss of the conductor barrel and the outer steel plate is completely dissipated through the heat generation; Therefore, the heat generation rate can be obtained according to formula 3.1 that the heat flow density is:

$$ q = \frac{P_{\text{loss}}}{V} $$

(3.1)

Where, $P_{\text{loss}}$ is eddy current loss power of conductor barrel or outer steel plate, unit: W, $V$ is volume of conductor barrel or outer steel plate, unit: m$^3$.

The thermal conductivity of each material of the permanent magnet coupler is shown in Table 1. To simplify the calculation, the fluid in the air gap is regarded as an entire object, and the equivalent thermal conductivity of the object is regarded as the effective thermal conductivity of the air gap $\lambda_{\text{eff}}$, which is used to represent the heat exchange capacity of the air gap[8], after simplification, the heat conduction can be used to equivalent the heat convection mode. According to the empirical formula, the small heat conduction coefficient of the permanent magnet coupler couple in this paper can be taken as $2W/(m\cdot K)$.

| Material                 | Pure copper | Aluminum101 | 45#Steel | Air | N42SHP Permanent magnet |
|--------------------------|-------------|-------------|----------|-----|------------------------|
| Thermal conductivity    | 386.4       | 151         | 50.2     | 2   | 9                      |

The cooling medium used in the permanent magnet coupler is air, which is driven by the rotation of the permanent magnet coupler during operation to conduct convection heat dissipation. If the influence of small parts on the heat dissipation surface is ignored, it can be approximately considered that the heat dissipation coefficient of each part of the permanent magnet coupler is only related to the air flow rate.
The heat dissipation coefficient of the permanent magnet coupler at room temperature is obtained from the empirical formula:

\[ h = h_0 \left( 1 + k \sqrt{v} \right) \]  

(3.2)

Where, \( h_0 \) is the natural heat dissipation coefficient of the object in the case of still air, \( v \) is the relative speed between the air and the surface of the object, unit is m/s, \( k \) is the influence coefficient of the heat dissipation efficiency in consideration of the air flow blowing. From the material of the permanent magnet coupler, \( h_0 = 14 \text{W/(m}^2 \cdot \text{K)} \), \( k \) is 0.5, and the heat dissipation coefficient is calculated according to the linear speed of each part, unit is \( \text{W/(m}^2 \cdot \text{K)} \).

Simplifying the three-dimensional model of the permanent magnet coupling to establish the finite element analysis mode, as shown in the Fig. 5. The conductor cylinder and the outer steel plate on the same side are set as the thermal load, assuming that the temperature distribution of the conductor cylinder and the outer steel plate is uniform, add internal \( h \) load to each generation and the surface heat transfer coefficient are meshed and analysed.

![FEM model](image1)

(a). The FEM model

![Dividing grid](image2)

(b). Dividing grid

Fig 5. Finite element mesh generation of temperature field

### 3.2. Simulation result

Fig. 6 is the simulation analysis result of temperature field of cylinder permanent magnet prototype, and under 20rpm normal temperature. It can be seen from Fig.6 that the temperature of conductor cylinder, inner aluminium yoke and permanent magnet is higher, and the temperature of outer aluminium yoke, permanent magnet and steel frame is lower.

![Temperature field distribution](image3)

Fig 6. Temperature field distribution of permanent magnet coupler.

### 4. Conclusion

This paper makes an electromagnetic field simulated analysis on the cylindrical permanent magnet coupling, the result comes out the largest area of the conductor tube eddy current density, and the largest area of the density of the eddy current loss. The simulation analysis on temperature field of the
A cylindrical permanent magnet prototype shows that under the condition of 20rpm of room temperature, the conductor tube, inside of the aluminium yoke and permanent magnet area temperature is higher; the outer aluminium yoke, permanent magnet and steel temperature is relatively low. The analysis results lay a foundation for the subsequent analysis of the thermo-magnetic coupling of the permanent magnet couplings.

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