Design of Magnetic Circuit and Simulation of Magnetic Fluid Sealing with Three Magnetic Sources

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Abstract. In order to obtain the maximum magnetic energy product in the sealing gap of the magnetic fluid sealing structure to improve the pressure capability of the magnetic fluid sealing, based on the magnetic circuit design theory and the magnetic fluid sealing theory, a parallel connection with three magnetic sources is provided. The magnetic fluid seal structure is designed for the magnetic circuit. The magnetic field in the magnetic fluid seal structure is calculated by the finite element method, and the pressure capability of the magnetic fluid seal is calculated. The results are analyzed and discussed. The results show that the magnetic flux leakage at the junction of the pole piece and the permanent magnet and the axial length of the intermediate pole pieces are short, which results in a nonlinear relationship between the magnetic induction strength difference between the two pole pieces and the sealing gap between the two pole pieces. The magnetic circuit method is lower than the magnetic fluid seal pressure capability calculated by the finite element method of the magnetic field.

1. Introduction
Magnetic fluid sealing technology is a new type of sealing technology, which has the advantages of zero leakage, long life, high reliability, good self-recovery characteristics, small torque variation at high and low temperatures, simple structure, and also can withstand high speed[1-5]. It is now widely used in aerospace, machinery and petroleum [6-8]. Magnetic circuit design is a key part of the magnetic fluid seal design, which ensures the reliability of the sealing performance and reduces the cost through the magnetic circuit design. Due to the complexity of the sealing structure, the diversity of the medium in the structure and the complexity of the boundary shape, the analytical method cannot calculate the magnetic field distribution in the sealing gap, and the finite element method is an effective tool for dealing with nonlinear problems and complex boundary conditions. Therefore, the magnetic field distribution in the sealing gap can be calculated [9, 11].

Sun Ming[10] calculated the magnetic field distribution of a magnetic fluid seal structure with three slots and four teeth by using the finite element method, and optimized the size of the pole teeth. But the magnetic energy product produced by a single permanent magnet is limited. In order to improve the pressure capability of the magnetic fluid seal, Yang Xiaolong[11] designed and calculated the magnetic circuit of a parallel magnetic fluid seal structure with two magnetic sources, but did not consider the influence of the pole teeth on the seal pressure capability. According to the magnetic circuit design and magnetic fluid seal theory, the magnetic circuit design of a parallel magnetic fluid seal structure with three magnetic sources is designed.
2. Design of magnetic circuit

2.1 Schematics of the multiple magnetic fluid sealing structure and equivalent magnetic circuit

It is a parallel type three-slot four-pole magnetic fluid sealing structure as shown in Fig. 1, and Fig. 2 is its equivalent magnetic circuit. It can be clearly seen from the figure that the magnetic circuit is mainly composed of a pole piece, a magnetic fluid, a permanent magnet and a shaft. The permanent magnet is a magnetic source of the magnetic circuit, and the magnetic field generated by the magnetic field in the radial sealing gap formed by the pole piece and the shaft.

2.2 Magnetic fluid seal pressure capability theory and calculation of magnetic circuit design

One of the most important parameters of a magnetic fluid seal is the critical pressure. Critical pressure can be calculated using the Bernoulli equation[5]:

\[
P + \frac{1}{2} \rho_f v^2 + \rho_f gh - \mu_0 \int H dM = C
\]

Where \( P \) is the composite pressure of magnetic fluids, \( h \), \( \rho_f \), \( V \) and \( M \) are the reference height, the density, the velocity and the magnetization of magnetic fluids, \( g \) is gravitational acceleration, \( \mu_0 \) is vacuum permeability, \( H \) is the external magnetic field strength, \( C \) is Constant. However, for static
pressure in a magnetic fluid seal, the effect of speed on the magnetic fluid seal can be neglected, and gravity in the seal gap can be ignored. Simplify the total sealing capacity of the magnetic fluid seal to (2):

$$\Delta P = \mu_0 M \sum_{i=1}^{N} (H_{\text{max}}^i - H_{\text{min}}^i) = M \sum_{i=1}^{N} (B_{\text{max}}^i - B_{\text{min}}^i)$$

(2)

Where $H_{\text{max}}^i$ and $H_{\text{min}}^i$ are the maximum and minimum magnetic field strengths under the i-th pole tooth respectively, $H$ is vacuum permeability. $B_{\text{min}}^i$ and $B_{\text{max}}^i$ are the maximum and minimum magnetic flux densities under the i-th pole tooth respectively, $M$ is the saturation magnetization of magnetic fluid under magnetic field. $N$ is total number of seals. The multi-stage magnetic fluid seal pressure resistance is the sum of the seal pressure resistance of each stage[12].

The magnetic circuit design of parallel type magnetic fluid seal for three magnetic sources studied in this paper contains two hypotheses: first, ignore the magnetic flux leakage; second, ignore the edge effect. According to Kirchhoff’s first law:

$$\sum \phi_i = 0$$

(3)

At any point in the magnetic circuit, the magnetic flux algebra entering there is equal to the sum of the magnetic flux algebras leaving it. According to the symmetry of the magnetic circuit structure, we can know:

$$\phi_1 = 2\phi_2 = 2\phi_3 = 2(5B_{i1}^S) = 2(5B_{i1}^S)$$

(4)

Where $\phi_1$, $\phi_2$, $\phi_3$ and $\phi_i$ represent the magnetic flux in the left pole piece, the left second pole piece, the left third pole piece, and the left fourth piece respectively. $B_{i1}^S$ and $B_{i1}^S$ represent the magnetic flux density of the radial seal gap of the first pole tooth of the left pole piece and the magnetic flux density of the radial seal gap of the first pole tooth of the left fourth pole piece respectively. $S_{i1}^t$ and $S_{i1}^t$ represent the annular area of the radial seal gap of the first pole tooth of the left pole piece and the annular area of the radial seal gap of the first pole tooth of the left fourth pole piece respectively.

Available from: $\phi_{i1} = \phi_{i1}$, we can know: $\phi_{i1} = B_{i1}^S S_{i1}^t$

(5)

According to Kirchhoff’s second law: $\sum H_{ij} = \sum N_i$, we can know:

$$F_i = H_{i1} L_{i1} = 5B_{i1}^S S_{i1}^t (R_{i1} + 3R_{i1}^t + 3R_{i1}^t + 3R_{i1}^t)$$

(6)

$F_i$ is the magnetic potential of the permanent magnet. $L_{i1}$ and $H_{i1}$ represent the length and magnetic field strength of the permanent magnet respectively. $R_{i1}$, $R_{i1}^t$, $R_{i1}^t$ and $R_{i1}^t$ represent the reluctance of the first permanent magnet on the left side, the reluctance of the radial seal gap of the first pole tooth on the left first pole piece, the reluctance of the first pole tooth on the left first pole piece and the reluctance of the first pole piece on the left respectively.

Multiply equation (5) by equation (6):

$$V_{i1} = S_{i1} L_{i1} = \frac{(5B_{i1}^S S_{i1}^t)^2}{[R_{i1} + 3R_{i1}^t + 3R_{i1}^t + 3R_{i1}^t]}$$

(7)

In order to reduce the volume and weight of the permanent magnet and increase the utilization of the permanent magnet, the permanent magnet should be operated at its maximum magnetic energy product. So there is:

$$V_{i1} = S_{i1} L_{i1} = \frac{(5B_{i1}^S S_{i1}^t)^2}{(BH)_{\text{max}}}$$

(8)

Divide equation (5) by equation (6):

$$S_{i1} L_{i1} = \frac{H_{i1}}{B_{i1} [R_{i1} + 3R_{i1}^t + 3R_{i1}^t + 3R_{i1}^t]}$$

(9)

Multiplying equation (8) by equation (9):
\[ S_{\text{ml}} = 5B_{\text{el}}^{l}S_{\text{el}}^{l} \left( \frac{H_{\text{el}}}{(BH)_{\text{max}}} \right) \]  

Dividing equation (8) by equation (9):

\[ L_{\text{ml}} = 5B_{\text{el}}^{l}S_{\text{el}}^{l} \left( R_{\text{ml}} + 3R_{\text{el}}^{l} + 3R_{\text{el}}^{l} + 3R_{\text{el}}^{l} \right) \left( \frac{B_{\text{el}}}{(BH)_{\text{max}}} \right) \]  

Since the magnetic permeability of the material of the pole piece and the rotating shaft is much larger than the magnetic permeability of the air and the permanent magnet, the magnetic capability of the pole piece and the rotating shaft can be neglected when calculating the length of the permanent magnet, that is:

\[ L_{\text{ml}} = 15B_{\text{el}}^{l}S_{\text{el}}^{l} \left( R_{\text{ml}} + 3R_{\text{el}}^{l} + 3R_{\text{el}}^{l} + 3R_{\text{el}}^{l} \right) \left( \frac{B_{\text{el}}}{(BH)_{\text{max}}} \right) \]  

3. Finite element analysis of magnetic field

The dimensions of each part of the magnetic circuit structure are as shown in Table 1. When the sealing gap is 0.3mm, if the sealing pressure capability is required to be not less than $1.8 \times 10^5$ Pa, the total magnetic induction difference in the sealing gap is 5.85T, which can be obtained by the formula (2). The length and cross-sectional area of the permanent magnet can be calculated from the symmetry of the parallel type magnetic fluid seal to be 6.3mm and 1187.522mm$^2$ respectively.

Creating a magnetic fluid-tight physical environment in the preprocessor of ANSYS finite element analysis software. The pole pieces and sealing shaft material are both 2Cr13, the magnetic fluid is oil-based, it’s saturation magnetization is 30.2KA/m. The saturation magnetization of the magnetic fluid is almost the same as that of the air, so the magnetic fluid can be treated as air.

Table 1. Items of parallel type magnetic circuit structure

| Item                          | Value       | Item                          | Value |
|-------------------------------|-------------|-------------------------------|-------|
| Inner radius of the pole piece (mm) | 25.3        | Width of pole teeth (mm)       | 0.2   |
| Outer radius of the pole piece (mm) | 40.3        | Sealing gap height (mm)        | 0.3   |
| Length of the pole piece (mm)   | 5           | Slot depth (mm)                | 0.7   |
| Radius of the shaft (mm)        | 25          | Slot width (mm)                | 1.0   |
| Number of teeth under the pole piece | 5           |                                |       |

4. Calculation results and analysis

Through the numerical analysis, the variation curve of the magnetic field strength Hsum and Bsum along the axial trajectory and the magnetic field distribution in the sealing gap can be obtained, as shown in Fig. 3 and Fig. 4.
Figure 3. Axial path $H_{\text{sum}}$ curve in the sealing gap

It can be seen from Fig. 3 that in the case of a sealing gap of 0.3mm, the maximum magnetic field strength in the sealing structure of the different pole pieces is located under the pole teeth of the middle two pole pieces, because the middle two pole pieces are teeth. The difference between the two magnetic fields is the sum of the magnetic induction, but the difference in the magnetic induction is not twice the difference in the magnetic induction between the two poles. This is due to the magnetic flux leakage at the junction of the permanent magnet with the pole piece and the short axial length of the intermediate pole piece.

According to Fig. 4 and the formula (2), when the sealing gap is 0.3mm, the sealing pressure capability of the magnetic fluid is calculated as:

$$\Delta P = 1.71 \times 10^5 \text{Pa}$$

The pressure capability of the parallel type magnetic fluid seal structure for three magnetic sources is calculated to be $1.71 \times 10^5 \text{Pa}$, which is slightly smaller than the seal pressure capability required by the magnetic circuit design of $1.8 \times 10^5 \text{Pa}$, but basically the same. This is because it is an ideal state in the design of the magnetic circuit assuming that the entire magnetic circuit is not magnetic leakage. There is no obvious magnetic flux leakage in the rest. Since the permanent magnet and the pole piece are generally in direct contact with the outer covering, in order to improve the accuracy of the magnetic circuit design and the pressure capability of the magnetic fluid seal, it is preferable to select a non-magnetic material as the outer covering and increase the axial length of the pole piece. And other methods to improve the utilization of magnetic energy of permanent magnets and reduce the leakage of magnetic energy.

5. Conclusion

Based on the classical magnetic circuit method, a parallel magnetic fluid seal structure for three magnetic sources is designed, and the magnetic field distribution of the parallel magnetic fluid seal structure is calculated by finite element method to calculate the theoretical seal pressure capability of the magnetic fluid. The following conclusions were drawn: The magnetic flux leakage at the junction of the pole piece and the permanent magnet and the axial length of the intermediate two pole pieces are short, resulting in a non-linear relationship between the difference of magnetic field strength in the sealing gap under the middle two pole pieces and the difference of magnetic field strength in the sealing gap under pole pieces of both sides. It also causes the magnetic circuit method to be lower than the magnetic field finite element method to calculate the pressure capability of the magnetic fluid seal. Due to the large magnetic field strength in the sealing gap of pole teeth on the two middle pole pieces, thereby causing the magnetic field strength differences in the sealing gaps of the pole teeth of the pole pieces on both sides to be approximately equal. If the outer covering material that directly contacts the permanent magnet and the pole piece is selected as a non-magnetic material, the magnetic flux leakage
can be effectively reduced, thereby improving the pressure capability of the magnetic fluid seal and the accuracy of the magnetic circuit design.

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