Magnetic Field Finite Element Analysis of a Novel Diverging Stepped Magnetic Fluid Seal

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Abstract: In order to improve the anti pressure capability of magnetic fluid seal under the large gap condition, a novel diverging stepped magnetic fluid seal was designed and set the pole teeth on the stepped shaft. The magnetic field distribution in the gap of diverging stepped magnetic fluid seal were numerical simulations by the finite element method of magnetic field. The effects of axial pole teeth number, radial pole number, radial sealing gap height and axial sealing gap on the anti pressure capability of a novel diverging stepped magnetic fluid seal were studied. The results show that the anti pressure capabilities of magnetic fluid seal increase with the increase of axial pole teeth numbers. The anti pressure capabilities of magnetic fluid seal firstly decrease and then increase with the increase of radial pole teeth numbers. The anti pressure capability of magnetic fluid seal firstly decrease and then increase with the increase of radial sealing gap height. The anti pressure capabilities of magnetic fluid seal decrease with the increase of axial sealing gap width.

1. Introduce

The magnetic fluid sealing technology utilizes the magnetization characteristics of a high-saturation magnetic fluid under the action of a magnetic field to form a sealing loop to seal the related equipment[1]. Compared to traditional seal, magnetic fluid seals are widely used in aviation, aerospace, chemical and petroleum industries as a result of their advantages of zero leakage, long life and no pollution[2-4]. However, the traditional magnetic fluid seal anti pressure capability tends to decrease significantly with the increase of the sealing gap, especially under the large gap condition where the sealing gap is more than 0.3 mm[5]. Therefore, it is of great engineering meaning to improve the anti pressure capability of magnetic fluid seals under large gap conditions.

Szczech experimented on the anti pressure mechanism of traditional magnetic fluid seal[6]. Radionov performs numerical analysis of magnetic fluid seals under small gap conditions[7]. Zhang and Li numerical analysis of the sealing characteristics of split magnetic fluid plane sealing[8]. Yang and Hao has carried out numerical and experimental studies on the anti pressure capability and leakage path of stepped magnetic fluid seal with large sealing gap[9]. The sealing devices of the above studies all have the pole teeth is set on the pole piece, but the magnetic fluid sealing structure with set the pole teeth on the stepped shaft is rarely studied.

In this paper, a novel diverging stepped magnetic fluid seal with single magnetic source is designed, and the set the pole teeth on the stepped shaft. Setting the pole teeth on the stepped shaft can effectively enhance the anti pressure capability of the magnetic fluid seal. The influence of the axial and radial sealing gaps of the magnetic fluid seal and the axial and radial number of pole teeth on the anti pressure capability is numerically calculated. It provides important theoretical guiding
significance for designing a novel diverging stepped magnetic fluid seal with single magnetic source.

2. Diverging stepped magnetic fluid seal formula

Normally, the Bernoulli equation for magnetic fluids can be expressed by the following equation[10]:

\[ P + \frac{1}{2} \rho \frac{V^2}{g} + \rho g h - \mu_0 \int_0^H M dH = C \]  

(1)

Where \( P \) is the pressure of magnetic fluid at a certain position; \( V \) is the velocity of magnetic fluid at a certain position; \( \rho \) is the density of magnetic fluid; \( h \) is the height of the magnetic fluid at a certain position; \( g \) is gravitational acceleration; \( \mu_0 \) is the vacuum permeability; \( H \) is external magnetic field strength; \( M \) is magnetization of magnetic fluid; and \( c \) is the constant. For the static pressure in magnetic fluid seals, the effect of velocity on magnetic fluid seals can be neglected and the gravity effect in the sealing gap should also be ignored. So, the total anti pressure capability of a magnetic fluid seal is reduced to the following expression:

\[ \Delta P = \mu_0 M_S \sum_{i=1}^{N} \left( H_{i \text{ max}} - H_{i \text{ min}} \right) \]

\[ = M_S \sum_{i=1}^{N} \left( B_{i \text{ max}} - B_{i \text{ min}} \right) \]  

(2)

where \( H_{i \text{ max}} \), \( H_{i \text{ min}} \), \( B_{i \text{ max}} \) and \( B_{i \text{ min}} \) are the maximum and minimum magnetic field intensities and the maximum and minimum magnetic flux densities under the \( i \)-th pole piece respectively. \( N \) is the total number of sealed pole pieces. We express the total anti pressure capability of the diverging stepped magnetic fluid seal as:

\[ \Delta P = \sum_{i=1}^{N} \left( P_{i r} + \lambda P_{i a} \right) \]  

(3)

In (3), \( P_{i r} \) and \( P_{i a} \) are the anti pressure capabilities of the magnetic fluid seal in the axial and in the radial sealing gaps formed by the \( j \)-th pole piece and the stepped shaft. We suppose that when \( P_{i r} < P_{i a} \) then \( \lambda = 1 \) and, when \( P_{i r} \geq P_{i a} \) \( \lambda = 0 \).

3. Structure design of a novel diverging stepped magnetic fluid seal

| Item                                | Value                      | Item                                | Value                      |
|-------------------------------------|----------------------------|-------------------------------------|----------------------------|
| Inner radius of the 1/2 pole piece(mm) | 26.1/29.8                 | Axial width of pole teeth(mm)       | 0.2                        |
| Outer radius of the 1/2 pole piece(mm) | 40                         | Axial sealing gap width(mm)         | 0.4/0.6/0.8/1.0            |
| Length of the pole piece(mm)        | 5                          | Radial sealing gap height(mm)       | 0.4/0.6/0.8/1.0            |
| Inner radius of permanent magnets   | 80                         | Slot depth(mm)                      | 0.7                        |
| Outer radius of permanent magnets   | 60                         | Permanent magnets length             | 5                          |
Figure 1. Schematic representation of a two-dimensional physical model of a novel diverging stepped magnetic fluid seal. The magnified region of the sketch without magnetic fluid, the figure on the right illustrates the terminology used for the axial and radial seal gaps used throughout this paper.

In order to study the effects of the key parameters of the stepped magnetic fluid seal on the anti-pressure capabilities, in this paper designs a novel diverging stepped magnetic fluid seal as shown in Fig. 1. Its structural parameters are as shown in Table 1. The permanent magnet material in the magnetic fluid seal is NdFeB and its coercive force and magnetic permeability are $1.356 \times 10^6$ A/m and 1.05 respectively. The material of the pole piece and the stepped shaft are both 2Cr13. The magnetic fluid uses an oil-based magnetic fluid having a saturation magnetization of $30.7$ KA/m.

Import the two-dimensional model of the diverging stepped magnetic fluid seal into the ANSYS finite element analysis software and select the magnetic field unit and. Assign material properties to individual components. The smart meshing and the accuracy of the mesh is 1. Set the magnetic field parallel boundary condition for the finite element model of a novel diverging stepped magnetic fluid seal. The magnetic induction in stepped magnetic fluid seal is obtained by the solver.

4. Results and discussion

In order to calculate the anti-pressure capability of the stepped magnetic fluid seal, it is essential to obtain the magnetic induction in stepped magnetic fluid seal. The magnetic induction in sealing gap of pole teeth number and sealing gap are obtained by finite element analysis when these parameters are respectively changed.

4.1 Effect of axial pole teeth number

When the number of radial pole teeth is 1 and the radial and axial sealing gaps are 0.4 mm, the magnetic induction in different number of axial pole teeth is shown in Fig. 2.

Fig. 2 show that the magnetic induction in radial sealing gap of the novel diverging stepped magnetic fluid seal decrease with increase of axial pole teeth numbers. This is because as the number of axial pole teeth increases, the increase of the magnetic resistance in the radial sealing gap leads to increase of the magnetic resistance in the entire magnetic circuit. Therefore, the magnetic induction in radial sealing gap of magnetic fluid seal will decrease. It is difficult found that the peak value of the magnetic induction in the axial seal gap of magnetic fluid seal increase with increase of the axial pole teeth number and the value of the magnetic induction changes little. This because the magnetism at the pole teeth is better and increase of the pole teeth number can effectively reduce the magnetic flux leakage.

Fig. 3 show that the anti-pressure capability of the novel diverging stepped magnetic fluid seal increase linearly with the increase of axial pole teeth numbers. This because the difference of magnetic induction in axial sealing gap of the diverging stepped magnetic fluid seal increase with increase of axial pole teeth numbers. Through the theory of anti-pressure capability of diverging stepped magnetic fluid seal, its anti-pressure capability is equal to the sum of the anti-pressure capability in axial and
radial sealing gaps.

4.2 Effect of radial pole teeth number
When the number of axial pole teeth is 1 and the radial and axial sealing gaps are 0.4 mm, the magnetic induction in different number of axial pole teeth is shown in Fig. 4.

Fig. 4 show that the maximum magnetic induction of the novel diverging stepped magnetic fluid seal does not change much with increase of radial pole teeth numbers. This because the magnetic flux leakage in the radial sealing gap will decrease with the increase of radial pole teeth number.

Fig. 5 show that the anti pressure capability of the novel diverging stepped magnetic fluid seal decrease firstly and then increase with the increase of radial pole teeth numbers. The anti pressure capability decrease firstly is because the difference of magnetic induction in the radial sealing gap is greater than the axial sealing gap. Therefore, through the theory of anti pressure capability of diverging stepped magnetic fluid seal, its anti pressure capability should be equal to the anti pressure capability in the radial sealing gap when the anti pressure capability of the radial sealing gap is greater than the axial sealing gap. The anti pressure capability increase later is because as the number of radial pole teeth continues to increase, the difference of magnetic induction in the radial sealing gap increases.

Figure 2. Magnetic field distributions for different axial pole teeth number. (a), 1; (b), 2; (c), 3.
Figure 3 Critical leakage pressure $\Delta P$ as a function of the number of the axial teeth.

Figure 4. Magnetic field distributions for different radial pole teeth number. (a), 1; (b), 2; (c), 3, (d), 4.
Figure 5 Critical leakage pressure $\Delta P$ as a function of the number of the radial teeth.
4.3 Effect of radial sealing gap height

When the number of axial and radial pole teeth is 3 and 4 respectively, the axial sealing gaps are 1 mm and the magnetic induction in different radial sealing gap height is shown in Fig. 6.

Fig. 6 show that the magnetic induction in axial sealing gap of the novel diverging stepped magnetic fluid seal increase with the increase of radial sealing gap height. This because as the increase of radial sealing gap, the magnetic resistance in radial sealing gap will increase and it will lead to the magnetic resistance increase of the whole magnetic circuit. Therefore, the magnetic potential in the axial sealing gap will increase and the magnetic flux in axial sealing gap will decrease. It is difficult found that the magnetic induction in radial sealing gap of the magnetic fluid seal decrease with the increase of radial sealing gap height. This because with the increase of magnetic resistance in entire magnetic circuit will cause the magnetic induction in entire magnetic circuit to decrease.

Fig. 7 show that the anti pressure capability of the novel diverging stepped magnetic fluid seal decrease firstly and then increase with the increase of radial sealing gap height. The anti pressure capability decrease firstly is because the difference of magnetic induction in the radial sealing gap is increase with the increase of radial sealing gap height. The anti pressure capability increase later is because the increase of the magnetic induction in the axial sealing gap is greater than the decrease of the magnetic induction in the radial sealing gap.

4.4 Effect of axial sealing gap height

When the number of axial and radial pole teeth is 3 and 4 respectively, the radial sealing gaps are 1 mm and the magnetic induction in different axial sealing gap height is shown in Fig. 8.

Fig. 8 show that the magnetic induction in axial sealing gap of the novel diverging stepped magnetic fluid seal decrease with the increase of axial sealing gap width. This is because as the increase of axial sealing gap width, the magnetic resistance in axial sealing gap will increase. Therefore, the magnetic induction in axial sealing gap will decrease.

Fig. 9 show that the anti pressure capability of the novel diverging stepped magnetic fluid seal decrease with the increase of axial sealing gap width. This is because the difference of magnetic induction in the radial sealing gap is increase with the increase of radial sealing gap height and the magnetic induction in the radial seal gap does not change much.
5. Conclusion

In this paper, a novel diverging stepped magnetic fluid seal is designed and the magnetic field distribution within the seal has been analyzed by means of the finite element method. The effects of axial pole teeth number, radial pole number, radial sealing gap height and axial sealing gap on the anti pressure capability of a novel diverging stepped magnetic fluid seal were studied. The results show that the anti pressure capabilities of magnetic fluid seal increase with the increase of axial pole teeth numbers. The anti pressure capabilities of magnetic fluid seal firstly decrease and then increase with the increase of radial pole teeth numbers. The anti pressure capability of magnetic fluid seal firstly decreases and then increase with the increase of radial sealing gap height. The anti pressure capabilities of magnetic fluid seal decrease with the increase of axial sealing gap width.

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