Numerical analysis of magnetic grease seal pole teeth optimization based on pressure bearing capacity

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Abstract. The static magnetic field model of the magnetic grease seal was established by the nonlinear magnetic field finite element method. The influence of three typical pole teeth with different seal gaps, namely rectangular teeth, single-side trapezoid, and symmetrical teeth, on pressure bearing capacity was analyzed. The results show that the maximum pressure bearing capacity of the optimized structure is from large to small: symmetric trapezoid teeth, single-sided trapezoid teeth, rectangular teeth. The seal gap increased by 0.1 mm and pressure bearing capacity decreased by 12%. If the teeth width was doubled, the pressure bearing capacity can be increased by 17.8%, with an optimum range of 1.8 mm to 2.2 mm. The interval length of the teeth doubled, the pressure bearing capacity increased by 30.65%, and the optimum range for the interval length of the teeth was 1.8 mm to 2.0 mm. There was no significant correlation between teeth height and pressure bearing capacity. The study on the optimization of the teeth structure based on pressure bearing capacity could provide a reference for technical personnel to improve the efficiency and rationality of the design of the teeth for the sealing of the magnetic grease.

1. Introduction

The sealing of the fan is of great significance for safe production, energy-saving, and environmental protection[1-5]. The common sealing form at the fan shaft end is a labyrinth seal, and there was still a small amount of gas leakage[6]. Magnetic grease seal is a new type of seal, which has the advantages that other seals do not have, such as no leakage, low friction, long life, and high reliability. Suitable for fan shaft end sealing. The magnetic fluid seal similar to the magnetic grease seal was applied to the shaft end of the centrifugal fan with a good effect[7]. Compared with magnetic fluid, the saturation magnetization and initial viscosity of magnetic grease are higher, and it could still maintain pressure...
bearing capacity under vibration or impurity conditions [8, 9]. Therefore, the magnetic grease seal could be applied to the fan shaft end seal, and it is suitable for the sealing of the above extreme working conditions at the fan shaft end.

Research on the magnetic grease seal showed that the magnetic grease seal had strong developability and application value. The magnetic grease seal at the shaft end of the evaporative cooling motor had been tested and had a strong sealing ability [10]. Combining the brush seal with the magnetic grease seal, the flexible pole piece magnetic grease gas-phase seal met engineering needs [11]. Reports on the numerical calculation of the pressure-pressure bearing capacity of magnetic grease seals were rare, and the current seal structure urgently needs to be optimized.

Szczech used the nonlinear magnetic field finite element method to calculate the influence of different pole teeth types on the pressure bearing capacity of the seal. It was found that with the same pole teeth end width, the maximum pressure bearing capacity was arranged in order of symmetrical trapezoidal pole teeth. Single-sided trapezoidal pole teeth, rectangular pole teeth. And compared with experiments, the calculated values were all larger than the experimental values [12-15]. In the literature, the end width of the pole teeth was the same, and the volume of the trapezoidal pole teeth was significantly larger than that of the rectangular pole teeth. The influence of the volume of the pole teeth on the result cannot be ruled out, and supplementary research is needed.

![Figure 1. Schematic diagram of magnetic grease seals](image1)

![Figure 2. Magnetic field calculation model of magnetic grease seal](image2)

The pole teeth is an important structure of the magnetic grease seal. Under normal working conditions, the magnetic grease is maintained in the sealing gap formed by the pole teeth and the shaft. It is necessary to analyze the influence of the pole teeth structure on the pressure bearing capacity. This paper was based on the nonlinear magnetic field finite element method, based on the single factor principle, guided by the pressure-pressure bearing capacity, using the magnetic field force viewpoint to study the formation mechanism of the magnetic grease seal, and optimize the pole teeth structure concerning the numerical calculation results.
2. The principle of magnetic grease seal

As shown in Figure 1, the magnetic grease seal device is composed of a permanent magnet, magnetic pole, pole teeth, magnetic grease, and the rotation axis of the magnetic permeability, forming a magnetic circuit and having a high magnetic induction line density below the pole teeth. Under the action of non-uniform high gradient magnetic field force, magnetic fat is adsorbed on the end of pole teeth, forming a liquid "O" ring, and obtaining the sealing ability to resist pressure difference. Compared with magnetic fluids, magnetic grease has higher saturation magnetization, higher initial viscosity, and obvious non-Newtonian fluid properties. Therefore, magnetic grease has higher pressure bearing capacity at a low rotation speed.

The pressure bearing capacity of the magnetic grease seal is related to the magnetization strength of magnetic grease, the difference of magnetic induction strength near the pole teeth, and the pressure resistance value of the carrier fluid. For the simplicity of the study, the liquid carrying pressure value of magnetic grease was ignored, and the effect of the magnetic field on pressure bearing capacity was considered only. Equation (1) represents the pressure bearing capacity of a single-pole tooth.

\[
\Delta p = M(\Delta H_1)B_1 - M(\Delta H_2)B_2
\]

\[
\Delta p = M_s\Delta B
\]

\[
\Delta p = \alpha M_s \sum_{i=1}^{N} \Delta B
\]

In the formula,
- \( \alpha \) Correction factor after superposition of seal pressure
- \( N \) The number of magnetic pole teeth
- \( M_s \) The saturation magnetization of magnetic lipid, kA/m
- \( \Delta B \) The magnetic induction intensity difference of the sealing gap, T

The magnetic induction near the pole teeth far exceeds the saturation magnetization of the magnetic grease. That is, the position of the magnetic grease in contact with the sealing medium satisfies the relation formula: \( M(\Delta H_1) = M(\Delta H_2) = M_\text{sat} \). Therefore, the maximum pressure difference formula of single-stage magnetic grease seal can be simplified as Equation (2). The sealing ability of the single-stage magnetic grease seal is limited. The sealing pressure ability is enhanced by increasing the number of pole teeth. The maximum pressure bearing capacity of a multi-stage magnetic grease seal can be calculated by Formula (3). According to the experimental results, the correction coefficient of multi-stage rectangular tooth pressure bearing capacity was \( \alpha = 0.88^{[15]} \). To verify the method, the saturation magnetization of magnetic fat was selected according to the literature and specified as \( M_\text{sat} = 37.8KA/m^{[16]} \).

3. Models and methods
3.1. Magnetic field models and materials
A magnetic grease seal magnetic field calculation model was established, as shown in Figure 2, including permanent magnet, magnetic pole, pole tooth, magnetic rotation axis, and external air. Under the action of the magnetic field, the magnetic induction intensity under the pole tooth was much higher than the saturation magnetization intensity of the magnetic grease, and its permeability was approximately equal to the vacuum permeability. Therefore, the air was applied to replace the magnetic fat in the model. Similarly, the air was also applied to replace the non-magnetic permeability of the sealed shell. To select the NdFeb magnet, brand N35, whose residual magnetic induction intensity was 1.2T, magnetized along the axis to the direction of the sealed cavity. The magnetic pole, pole tooth, and rotation axis were made of magnetic stainless steel material 12Cr13. The B-H curve of this material is shown in Figure 3.

![Figure 3. BH curve of magnetic material 12Cr13](image)

12Cr13 was an excellent magnetic stainless steel and a good material for magnetic grease seal fittings. Magnetic field intensity mode, magnetic induction intensity mode and relative permeability are obtained from the BH curve of the material. It was worth noting that the relative permeability refers to the slope of this curve, and the BH curve obtained by experimental measurement was usually a series of scatter points. Curve fitting was required to obtain an approximate function curve, and derivation of the slope of the curve was used as the relative permeability of this material. The process of curve fitting was omitted here. In fact, for the nonlinear static magnetic field finite element method, it is an important factor affecting convergence and should be paid attention to.

Table 1 listed the geometric parameters of the model. According to the principle of a single factor, the pressure bearing capacity of different seal clearance, the width of pole tooth, interval length of pole tooth, and height of pole tooth was calculated to optimize the structure of the pole tooth.

By using parametric modeling method, various sizes of polar teeth can be changed conveniently. The control variable method is used to study the effects of width, spacing distance, height and type of polar teeth on the bearing capacity of magnetic grease seal.

**Table 1. Geometric parameters of the magnetic field model**
### Parameters Values Meanings

| Parameters   | Values | Meanings                                      |
|--------------|--------|-----------------------------------------------|
| $R_{\text{axis}}$ | 35     | The radius of the rotation axis               |
| $gap$        | 0.1-1  | Sealing gap                                   |
| $h_m$        | 10.5   | The radial thickness of the magnet            |
| $l_m$        | 10     | Axial thickness of the magnet                 |
| $L_{\text{axis}}$ | 50     | Length of the axis                            |
| $h_l$        | 1.5-3.0| Height of pole teeth                          |
| $b$          | 1.4-2.8| Width of pole teeth                           |
| $h_p$        | 15     | The radial thickness of the magnetic pole     |
| $t_i$        | 1.4-2.8| Distance between pole teeth                   |
| $l_p$        | $3 \cdot b + 2 \cdot t_i$ | The thickness of pole teeth                   |

### 3.2. Mesh independence verification

To reduce the calculation result error caused by the mesh, the mesh in Fig 4 was divided. Permanent magnet, magnetic pole, pole tooth, axis, and external air domain use triangular mesh, and set the maximum unit size as 1mm; Quadrilateral mesh is used in the area near the pole tooth to correlate the maximum unit size with the seal clearance and set as 1/x of the seal gap. The number of triangular meshes is 17540, and quadrilateral meshes are the core area of the calculation. Table 2 shows the relationship between the number of quadrilateral meshes and the extreme value of the magnetic induction intensity of pole teeth.

![Figure 4. meshes of calculation area (a) global mixed mesh (b) quadrilateral mesh near pole teeth](image)

![Figure 5. Calculation results of the magnetic field](image)
The fraction of the minimum unit size in the seal clearance was no more than 0.2, the mesh precision met the calculation requirements, and there was no obvious correlation between the calculation results and the mesh.

Table 2. The corresponding relationship between the number of meshes and the magnetic induction intensity of the first pole teeth

| Proportion | Maximum units size [mm] | Meshes numbers | Maximum of B [T] | Minimum of B [T] |
|------------|-------------------------|----------------|------------------|------------------|
| 1          | 0.5                     | 508            | 0.815            | 0.509            |
| 0.8        | 0.4                     | 809            | 1.063            | 0.502            |
| 0.6        | 0.3                     | 1541           | 1.005            | 0.489            |
| 0.4        | 0.2                     | 3409           | 0.985            | 0.490            |
| 0.2        | 0.1                     | 12700          | 0.987            | 0.489            |
| 0.1        | 0.05                    | 50800          | 0.987            | 0.489            |

3.3. Results validation

Fig. 5 showed the calculation results of the sealed static magnetic field. There was a strong magnetic induction intensity near the pole tooth. The black curve represented the magnetic induction lines, which were concentrated near the pole teeth, proving the magnetic gathering effect of the pole tooth. The maximum magnetic induction intensity near the pole tooth was about 1.2T, and the minimum magnetic induction intensity of the teeth groove was about 0.2T. The pressure bearing capacity of magnetic grease seal can be calculated by simplifying the pressure bearing capacity formula (3).

\[ F_m = M_s \cdot \nabla B \] (4)

Figure 6. Axial magnetic force in sealing gap of the pole tooth

The axial magnetic force of seal clearance was shown in Fig. 6. The magnetic force had obvious peaks and valleys, and the negative sign only represents the direction. The magnetic force is calculated according to Formula (4):

Figure 7. Comparison with existing literature data
The magnetic field was a potential field, with directional, magnetic field force, and magnetic induction intensity gradient was proportional, so there would be a sign of difference.

Fig 7 showed the difference of the pressure bearing capacity. Compared with the data given in the literature, the same material and structure parameters were used to calculate the sealing pressure capacity of magnetic grease. When the sealing clearance was 0.5mm, the pressure bearing capacity of the single-pole tooth calculated in this paper was 21.56kPa. Compared with 19.5kPa given in the literature[16], the result was 10.56% higher than the experimental data 0.022mpa, 2% lower[17]. The magnetic materials were nonlinear and had different permeability under different magnetic induction intensity, which might result in the difference between the calculated results and the literature data. Through comparative analysis, the numerical calculation method proposed in this paper was more accurate.

4. Result and discussion

4.1. Effect of pole tooth type on bearing capacity

The bearing capacity of single-pole teeth was studied when the pole tooth was a rectangular shape, single-side trapezoid, and symmetric trapezoid. The relationship between the bearing capacity and gap of different types of pole teeth is shown in Fig. 8.

The pressure bearing capacity of the three types of pole teeth was consistent with the changing trend of seal clearance, and the pressure bearing capacity decreased with the increase of the sealing gap. When the sealing gap changed from 0.1mm to 1mm, the change rate of pressure capacity was the same, which was about -12%, that was if the seal clearance increased by 0.1mm, the pressure capacity decreased by about 12%.

Among the three typical pole teeth, symmetrical trapezoidal pole teeth had the highest bearing capacity, followed by single-side trapezoidal pole teeth and rectangular pole teeth. With the same tooth root width, the end area of the trapezoidal pole tooth was less than the root area, and the magnetic induction line density was higher, that was, the greater the magnetic induction intensity was, the higher the bearing capacity was.
The order of bearing capacity with the same width of the tooth root was studied, which verified the correctness of the conclusion in the literature[12] between 0.1mm and 1mm in the sealing gap. No matter the width of the tooth root or the width of the tooth end was the same, the trapezoidal pole teeth had higher bearing capacity.

4.2. Effect of pole tooth width on bearing capacity
The rectangular pole tooth was selected and the remaining parameters were kept unchanged to study the change in the bearing capacity caused by the change in the width of the pole tooth. The comprehensive bearing capacity of the level-6 pole tooth was shown in Fig. 9.

With the increase of pole tooth width, the bearing capacity increased from 92.187kPa to 108.56kPa, increasing by 17.8%. With 0.2mm as the change interval, the change rate of bearing capacity at each pole tooth width was calculated, decreasing from 4.5% to 1%. This indicated that when the pole tooth width exceeded 2.2mm, the rate of change decreases significantly.

As the width of the pole tooth increases, the magnetic induction line was more likely to pass through the pole tooth, causing the magnetic induction intensity under the pole tooth to rise. According to formula 3, the sealing bearing capacity increased. However, the magnetic energy product of a permanent magnet was determined, so the rate of change of bearing capacity caused by increasing the width of the pole tooth decreased gradually. Compared with six single-stage, pressure bearing ability of multistage pole tooth was small, this was because the multistage pole tooth magnetic induction intensity distribution influenced each other, caused the magnetic induction intensity in the teeth groove minimum increased, according to the formula (3), the bearing capacity was not only related to the maximum, also related to the minimum value, so the bearing capacity to reduce. At the same time, it was noted that the increase of the width of the pole tooth would increase the volume of magnetic grease in the sealing gap. Considering the machining economy and bearing capacity, the optimal range of the width of the pole tooth was 1.8mm to 2.2mm.

4.3. Effect of interval length of pole tooth on bearing capacity
The rectangular pole teeth were selected and the remaining parameters were kept unchanged to study the change in the bearing capacity caused by the change in the spacing of the pole teeth. The comprehensive bearing capacity of the level-6 pole teeth was shown in Fig. 10.

With the increase of interval length of the pole tooth, the pressure bearing capacity increased from 87.318kPa to 114.08kPa by 30.65%. The mutation rate increased to 9.46% when t1=1.8mm, and then dropped to about 2.5%. The magnetic field of tooth groove position of was very small compared with the sealing gap magnetic field, increasing pole tooth interval length, caused by alveolar lines of magnetic induction, magnetic induction line easier to gather at the bottom of the pole tooth, tooth loss of magnetic induction intensity tooth at the bottom of the magnetic induction intensity increased, thereby increasing the bearing pressure ability. Due to the abrupt change in the rate of change, the bearing capacity was greatly improved after this pole tooth interval length. The pole tooth interval exceeding 1.8mm had no great influence on the overall sealing structure, and the optimal range of the pole tooth interval was 1.8mm to 2.0mm.

4.4. Effect of pole tooth height on bearing capacity
The rectangular pole tooth was selected and the remaining parameters were kept unchanged to study the change in the bearing capacity caused by the change in the height of the pole tooth. The comprehensive bearing capacity of the level-6 pole tooth was shown in Fig. 11.

![Figure 10. Effect of interval length of pole tooth on bearing capacity](image)

![Figure 11. Effect of pole tooth height on bearing capacity](image)

The influence of pole tooth height on the bearing capacity was relatively weak compared with the width and interval length of pole teeth. When the pole tooth height was increased, the bearing capacity was approximately equal to 102.3 kPa, which only changed in a small range and the rate of change was always less than 1%. Therefore, it can be considered that the pole tooth height did not influence the bearing capacity. This was because the bearing capacity was related to the magnetic induction intensity and the difference of the magnetic induction intensity, and the pole tooth height did not significantly affect the magnetic induction intensity distribution near the pole tooth. The seal structure design selected many kinds of pole tooth depth, the bearing capacity does not change basically, had the larger design flexibility.

5. Conclusion
In this paper, the nonlinear magnetic field finite element method was adopted to obtain the magnetic induction intensity distribution of the sealing structure according to the single factor principle. Based on the magnetic field force point of view, the sealing mechanism was described, and the influence of the pole tooth structure on the bearing capacity of the magnetic grease seal was studied. The following findings were found:

The order of bearing capacity of three typical pole teeth from large to small was symmetrical trapezoidal pole teeth, single side trapezoidal pole teeth, and rectangular pole teeth. The structure of the pole tooth was able to generate a non-uniform magnetic force, and the maximum magnetic force of the rectangular pole tooth is located at the right angle of the pole tooth.

For every 0.1 mm increase in the sealing gap, the pressure bearing capacity decreased by 12%; The pole tooth width increased from 1.5 mm to 3 mm, and the bearing capacity increased by 17.8%. The pole tooth interval length increased from 1.5 mm to 3 mm, and the bearing capacity increased by 30.65%. With the increase of pole tooth height, the pressure bearing capacity had little change.
Through the numerical calculation of pole tooth optimization, the better pole tooth parameters were obtained, and the sealing pressure capacity is improved. This study could guide the design of the magnetic grease seal, optimize the structure of pole teeth, save the space of seal, and improve the bearing capacity of the seal.

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