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# Magnetic Circuit Design and Finite Element Analysis of Ferrofluid Seal of Engineering Machinery Hydraulic Cylinder

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**Abstract.** In order to solve the problem that the construction machinery hydraulic cylinder seal has a short life and cannot achieve zero leakage, This paper creatively applies ferrofluid sealing technology to engineering machinery hydraulic cylinders. In order to obtain the maximum magnetic energy product in the sealing gap of the ferrofluid sealing structure of the engineering machinery hydraulic cylinder, the pressure resistance performance and life expectancy of the ferrofluid seal of the engineering machinery hydraulic cylinder are improved. Based on the theory of magnetic circuit and the theory of ferrofluid seal, the magnetic circuit design of a ferrofluid seal structure with a uniform pole piece with eight magnetic sources is designed. The finite element analysis method was used to verify the pressure resistance of the ferrofluid seal of engineering machinery hydraulic cylinder, and the calculation results were analyzed and discussed. The results show: The design method of the magnetic circuit structure is reasonable and feasible, and has important reference significance for the design of the ferrofluid seal of the engineering machinery hydraulic cylinders.

**Key words:** Magnetic circuit; Engineering machinery hydraulic cylinder; ferrofluid; Seal; Finite element

## 1 Introduction

Ferrofluid sealing technology is widely used in aerospace, machinery, petroleum, chemical and instrumentation because of its advantages of zero leakage, long life and simple structure. However, the application of ferrofluid sealing technology in the field of engineering machinery hydraulic cylinders is also proposed for the first time. Due to the current low life of hydraulic cylinders and the inability to guarantee zero leakage, Therefore, improving the life of hydraulic cylinders is one of the current research focus. ferrofluid sealing technology is an effective way to improve the life of hydraulic cylinder seals. Studying the ferrofluid seal structure of hydraulic cylinders is of great significance for broadening the application field of ferrofluid seal technology[1-5].

Magnetic circuit design is the key to the design of ferrofluid seals for engineering machinery hydraulic cylinders. The use of magnetic circuit design ensures the reliability of sealing performance and reduces production costs. Although researchers have done a lot of research on the magnetic circuit design, magnetic field analysis and pressure resistance of ferrofluid seals, this is the first time to study the magnetic circuit design of the ferrofluid seal structure of engineering machinery hydraulic cylinders. The author designed the ferrofluid seal structure of engineering machinery hydraulic

cylinder by magnetic circuit design. The size of the magnetic source working at the position of the maximum magnetic energy product is obtained. And carried out finite element theory analysis and verification. Thereby providing a basis for the design of the ferrofluid seal of the engineering machinery hydraulic cylinder[6-7].

## 2 Ferrofluid seal theory

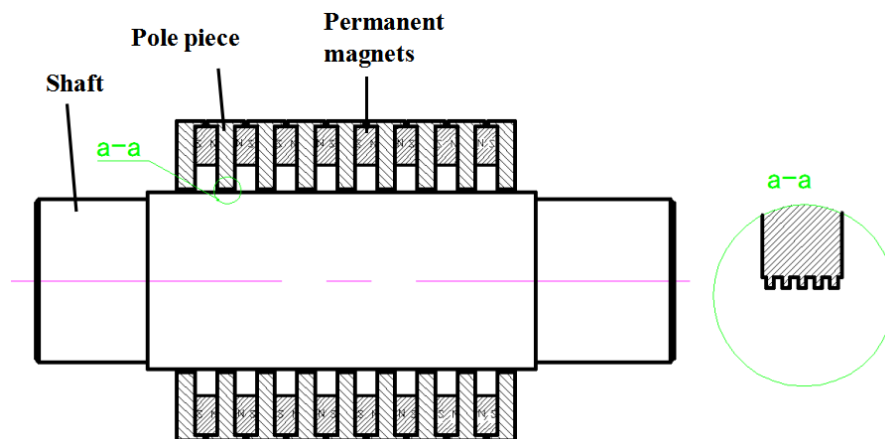
The total sealing capacity of the ferrofluid seal can be approximately expressed as

$$\Delta P = \int_{H_{i\min}}^{H_{i\max}} \mu_0 M dH \approx \sum_{i=1}^{i=N} M_s (B_{i\max} - B_{i\min}) \quad (1)$$

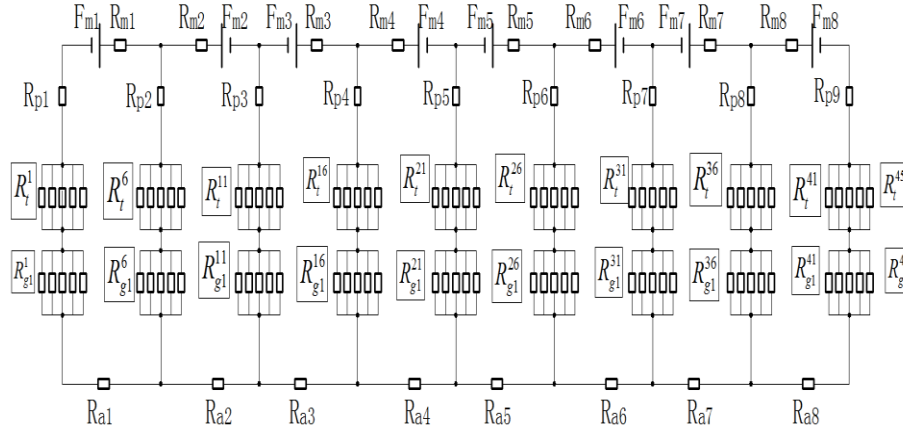
where  $\mu_0$  the permeability of vacuum,  $H_{i\min}$  and  $H_{i\max}$  are the minimum and maximum magnetic field strengths under the  $i$  pole tooth respectively,  $M$  the magnetization of ferrofluid,  $M_s$  the saturation magnetization of ferrofluid,  $N$  the number of pole tooth,  $B_{i\max}$  the maximum magnetic flux density under the  $i$  pole tooth, and  $B_{i\min}$  the minimum magnetic flux density under the  $i$  pole tooth. Under the condition of injecting a proper amount of ferrofluid into the sealing gap, The multi-stage ferrofluid seal pressure resistance is the sum of the seal pressure resistance of each stage[8-9].

## 3 Magnetic circuit design of ferrofluid seal of engineering machinery hydraulic cylinder

On the basis of the original hydraulic cylinder rubber seal, A ferrofluid seal structure of an engineering machinery hydraulic cylinder with eight magnetic sources was preliminarily designed. As shown in Figure 1, its equivalent magnetic circuit is shown in Figure 2.  $F_m$  represents the magnetic potential of the permanent magnet;  $R_m$  represents the reluctance of the permanent magnet;  $R_p$  represents polar resistance;  $R_t$  represents pole tooth reluctance;  $R_g$  represents the reluctance of the seal gap;  $R_a$  represents The reluctance of the shaft.



**Figure1.** A ferrofluid seal structure with eight magnetic sources



**Figure 2.** equivalent magnetic circuit of hydraulic cylinder ferrofluid seal

It can be concluded from Fig.2 that the multi-stage sealed magnetic circuit is mainly composed of pole piece, ferrofluid, permanent magnet and shaft. The permanent magnet is the magnetic source of the equivalent magnetic circuit. The magnetic field generated by the magnetic source firmly binds the ferrofluid in the radial sealing gap formed by the pole teeth on the pole piece and the shaft in the sealing gaps to form dense "protective film". The ferrofluid generates a magnetic field force that is resistant to the pressure difference between the two sides. Thereby achieving the effect of pressure seal.

There are two assumptions when designing the magnetic circuit for a ferrofluid seal structure of a construction machinery hydraulic cylinder: Ignore the effects of magnetic flux leakage and edge effects. According to the first law of the magnetic path Kirchhoff.

$$-\Phi_1 + \Phi_2 + \Phi_3 = 0 \quad (2)$$

The total magnetic flux that passes through (or enters) any of the closed faces is always equal to zero.  $\Phi_1, \Phi_2, \Phi_3$  are expressed as the magnetic flux in the magnetic pole, the intermediate magnetic pole, and Magnetic flux in the magnetic pole end of the atmospheric pressure. among them:

$$\Phi_1 = 5B_{g1}^1 S_{g1}^1 \quad (3)$$

$B_{g1}^1$  represents the magnetic flux density in the radial sealing gap between the first pole tooth and the reciprocating shaft;  $S_{g1}^1$  represents the annular area of the radial seal gap formed by the high-pressure measuring first pole tooth and the reciprocating shaft.

$$\Phi_2 = 5(B_{g1}^6 S_{g1}^6 + B_{g1}^{11} S_{g1}^{11} + B_{g1}^{16} S_{g1}^{16} + B_{g1}^{21} S_{g1}^{21} + B_{g1}^{26} S_{g1}^{26} + B_{g1}^{31} S_{g1}^{31} + B_{g1}^{36} S_{g1}^{36}) \quad (4)$$

$B_{g1}^6 (B_{g1}^{11}, B_{g1}^{16}, B_{g1}^{21}, B_{g1}^{26}, B_{g1}^{31}, B_{g1}^{36})$  shows the magnetic flux density between the 6th(11th,16th,21th,26th,31th,36th) pole teeth on the 2th(3th,4th,5th,6th,7th,8th) pole piece and the radial sealing gap formed by the reciprocating shaft;  $S_{g1}^6 (S_{g1}^{11}, S_{g1}^{16}, S_{g1}^{21}, S_{g1}^{26}, S_{g1}^{31}, S_{g1}^{36})$  shows the annular area between the 6th(11th,16th,21th,26th,31th,36th) pole teeth on the 2th(3th,4th,5th,6th,7th,8th) pole piece and the radial sealing gap formed by the reciprocating shaft.

$$\Phi_3 = 5B_{g1}^{41} S_{g1}^{41} \quad (5)$$

$B_{g1}^{41}$  represents the magnetic flux density in the radial sealing gap between the 41st pole tooth on the 9th pole piece and the reciprocating shaft;  $S_{g1}^{41}$  represents the annular area in the radial sealing gap between the 41st pole tooth on the 9th pole piece and the reciprocating shaft. It is known by  $\Phi_{m1} = \Phi_1$ :

$$\Phi_{m1} = B_{m1} S_{m1} = 5B_{g1}^1 S_{g1}^1 \quad (6)$$

$\Phi_{m1}$ ,  $B_{m1}$  and  $S_{m1}$  respectively represent the magnetic flux, the magnetic flux density and the area of the first annular permanent magnet. It is known by  $\Phi_{m2} = \Phi_3$ :

$$\Phi_{m2} = B_{m2} S_{m2} = 5B_{g1}^{41} S_{g1}^{41} \quad (7)$$

$\Phi_{m2}$ ,  $B_{m2}$  and  $S_{m2}$  respectively represents the magnetic flux, the magnetic flux density and the area of the 8th annular permanent magnet. The total magnetic potential acting in any closed magnetic circuit is always equal to the algebraic sum of the magnetic field drop of each segmented magnetic circuit. Similar to Kirchhoff's second law in circuits, this law is called the Kirchhoff's second law of magnetic circuits. It is known by  $\sum_{k=1}^n H_k l_k = \sum N_k k$ :

$$F_1 = H_{m1} L_{m1} = 5B_{g1}^1 S_{g1}^1 \left[ R_{p1} + R_{a1} + R_{m1} + \frac{(R_t^1 + R_{g1}^1)}{5} \right] + 7 \times \left[ 5B_{g1}^6 S_{g1}^6 \left( R_{p2} + \frac{R_{t6} + R_{g1}^6}{5} \right) \right] \quad (8)$$

In the above formula,  $F_1$  represents the magnetic potential of the high-voltage side permanent magnet;  $H_{m1}$ ,  $L_{m1}$  represent the magnetic field strength and length of the first permanent magnet;  $R_{p1}$ ,  $R_{g1}^1$ ,  $R_{a1}$ ,  $R_{m1}$ ,  $R_t^1$  respectively represent the magnetic resistance of the first pole piece, the magnetic resistance of the radial sealing gap of the first pole tooth, Reluctance of the reciprocating shaft, The magnetic resistance of the first permanent magnet and the magnetic resistance of the first pole tooth.  $R_{p2}$ ,  $R_{g1}^6$ ,  $R_{t6}$  respectively represent the reluctance of the second pole piece, The magnetic resistance of the 6th pole tooth in the radial seal gap, and the reluctance of the 6th pole tooth.

$$F_2 = H_{m2} L_{m2} = 7 \times \left[ 5B_{g1}^6 S_{g1}^6 \left( R_{p2} + \frac{R_{t6} + R_{g1}^6}{5} \right) \right] + 5B_{g1}^{41} S_{g1}^{41} \left[ R_{p9} + R_{a8} + R_{m8} + \frac{(R_t^{41} + R_{g1}^{41})}{5} \right] \quad (9)$$

In the above formula,  $F_2$  represents the magnetic potential of the low-voltage side permanent magnet;  $H_{m2}$ ,  $L_{m2}$  represent the magnetic field strength and length of the 8th permanent magnet;  $R_{p9}$ ,  $R_{g1}^{41}$ ,  $R_{a8}$ ,  $R_{m8}$ ,  $R_t^{41}$  respectively represent the magnetic resistance of the 9th pole piece, The reluctance of the radial sealing gap of the first pole tooth of the 9th pole piece, Reluctance of the reciprocating shaft, The magnetic resistance of the 8th permanent magnet and the magnetic resistance of the 41th pole tooth. Since the shape, size and performance parameters of the permanent magnets used in the whole structure are the same, it can be known that:

$$F_1 = F_2 = H_{m2} L_{m2} = H_{m1} L_{m1} \quad (10)$$

It can be known that:

$$5B_{g1}^1 S_{g1}^1 \left[ R_{p1} + R_{a1} + R_{m1} + \frac{(R_t^1 + R_{g1}^1)}{5} \right] = 5B_{g1}^{41} S_{g1}^{41} \left[ R_{p9} + R_{a8} + R_{m8} + \frac{(R_t^{41} + R_{g1}^{41})}{5} \right] \quad (11)$$

Multiply equation (7) by equation (9):

$$V_{m2} = \frac{B_{m2} S_{m2} \times H_{m2} L_{m2}}{B_{m2} H_{m2}} = \frac{175B_{g1}^6 S_{g1}^6 B_{g1}^{41} S_{g1}^{41} \left( R_{p2} + \frac{R_{t6} + R_{g1}^6}{5} \right) + 25B_{g1}^{41} S_{g1}^{41} B_{g1}^1 S_{g1}^1 \left[ R_{p9} + R_{a8} + R_{m8} + \frac{(R_t^{41} + R_{g1}^{41})}{5} \right]}{B_{m2} H_{m2}} \quad (12)$$

In order to save costs, The thickness and length of the permanent magnets need to be minimized. Thereby obtaining a reduction in volume and weight, Improve the utilization rate of permanent magnets, The permanent magnet should be operated at the maximum magnetic energy product, It can be known that:

$$V_{m2} = \frac{B_{m2} S_{m2} \times H_{m2} L_{m2}}{B_{m2} H_{m2}} = \frac{175 B_{g1}^6 S_{g1}^6 B_{g1}^{41} S_{g1}^{41} \left( R_{p2} + \frac{R_t^6 + R_{g1}^6}{5} \right) + 25 B_{g1}^{41} S_{g1}^{41} B_{g1}^{41} S_{g1}^{41} \left[ R_{p9} + R_{a8} + R_{m8} + \frac{(R_t^{41} + R_{g1}^{41})}{5} \right]}{(BH)_{MAX}} \quad (13)$$

Equation (7) is divided by equation (9):

$$\frac{S_{m2}}{L_{m2}} = \frac{B_{g1}^{41} S_{g1}^{41}}{7 B_{g1}^6 S_{g1}^6 \left( R_{p2} + \frac{R_t^6 + R_{g1}^6}{5} \right) + B_{g1}^{41} S_{g1}^{41} \left[ R_{p9} + R_{a8} + R_{m8} + \frac{(R_t^{41} + R_{g1}^{41})}{5} \right]} \times \frac{H_{m2}}{B_{m2}} \quad (14)$$

Multiply equation (13) by equation (14):

$$S_{m2} = 5 B_{g1}^{41} S_{g1}^{41} \left( \frac{H_{m2}}{(BH)_{max} B_{m2}} \right)^{\frac{1}{2}} \quad (15)$$

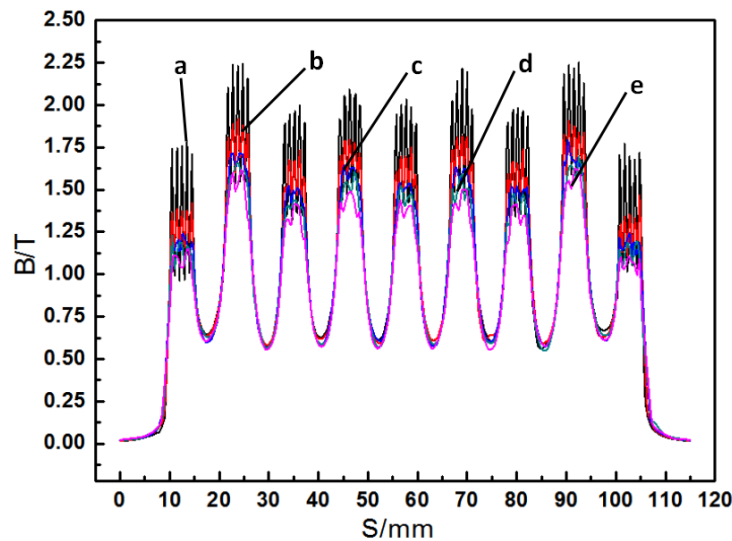
Equation (13) is divided by equation (14):

$$L_{m2} = F_2 \left( \frac{B_{m2}}{(BH)_{m2} H_{m2}} \right)^{\frac{1}{2}} = \left\{ 7 \times \left[ 5 B_{g1}^6 S_{g1}^6 \left( R_{p2} + \frac{R_t^6 + R_{g1}^6}{5} \right) \right] + 5 B_{g1}^{41} S_{g1}^{41} \left[ R_{p9} + R_{a8} + R_{m8} + \frac{(R_t^{41} + R_{g1}^{41})}{5} \right] \right\} \left( \frac{B_{m2}}{(BH)_{m2} H_{m2}} \right)^{\frac{1}{2}} \quad (16)$$

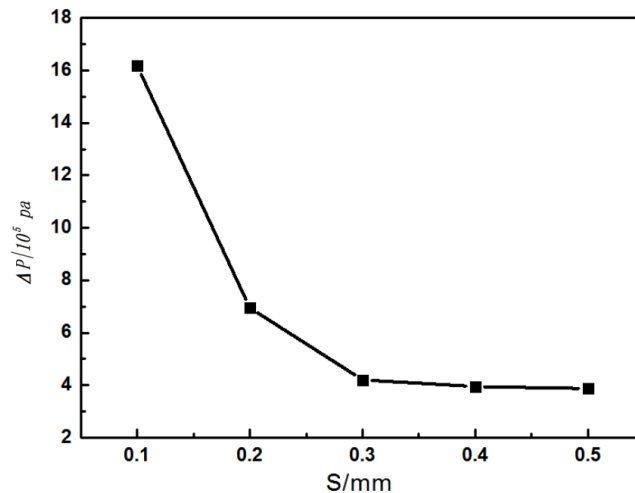
#### 4 Finite element analysis and its results

In the magnetic circuit of the ferrofluid seal structure, The permanent magnet material is selected from NdFeB. Its coercive force is  $H_c = 1.05 \times 10^6 A/m$ , The pole piece and the sealing shaft material are both 2cr13; ferrofluids are selected as ester based ferrofluid and its saturation magnetization is  $41.6 KA/m$ . The permanent magnet has a width of 6.3 mm and the inner (outer) radius of the pole piece is 25.1 (45) mm. According to the magnetic field distributions in the different sealing gaps of the ferrofluid seal which are shown in Fig.3. a, b, c, d, e denote magnetic distribution with 0.1mm, 0.2mm, 0.3mm, 0.4mm, 0.5mm sealing gap height.

It can be seen from Fig.3 that the pressure capabilities of the ferrofluid seal significantly decrease with the increase of the radial sealing gap. it can be found that In the structure of different sealing gaps, the maximum magnetic flux density is located under the second pole teeth on the left and right sides. And much higher than the magnetic flux of the left pole piece and the right first pole piece. This is because the left and right first pole pieces are only powered by a single permanent magnet. The middle pole piece is supplied by a magnetic field from the left and right permanent magnets. The magnetic flux in the middle pole piece is the part of the sum of the magnetic fluxes generated by the permanent magnets on both sides. When the radial sealing gap is changed, the pressure resistance of the ferrofluid seal under different sealing gaps can be calculated which is shown in Fig.4.



**Figure 3.** Magnetic field distributions of the ferrofluid seal with different gaps conditions



**Figure 4.** sealing capability ( $\Delta P$ ) under different sealing gap

As can be seen from the above figures, the pressure resistance of the ferrofluid seal of the hydraulic cylinder is continuously decreasing as the clearance increases. This is because the larger the sealing gap is, the larger the magnetic resistance of the sealing gap is. According to the magnetic circuit law. The magnetic flux density in the sealing gap is reduced, and the magnetic induction intensity is correspondingly reduced. This results in a decrease in the pressure resistance of the hydraulic fluid seal of the hydraulic cylinder. At the same time, it can be seen that when the sealing gap is 0.1 and 0.2 mm, the model sealing pressure resistance is higher. Therefore, when the processing conditions permit, try to keep the sealing gap below 0.3mm.

## 5 Conclusions

Based on the classical magnetic circuit method, the ferrofluid seal structure of engineering machinery hydraulic cylinder is designed. The finite element analysis was carried out and the following conclusions were drawn:

- 1) The pressure resistance of the ferrofluid seal of the hydraulic cylinder is continuously decreasing as the clearance increases.
- 2) According to the magnetic circuit method, the detailed parameters of the permanent magnet working at the position of the maximum magnetic energy product are obtained. That is, the thickness of the permanent magnet is 6.3 mm.
- 3) The test results show that the magnetic circuit design method is feasible. It provides the basis for

the design of the magnetic fluid seal of engineering machinery hydraulic cylinder.

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