IOP Conference Series: Materials Science and Engineering

PAPER • **OPEN ACCESS**

Design of Magnetic Circuit and Finite Element Analysis of Stepped Ferrofluid Seal with Small Sealing Gap

To cite this article: Ruibo Zhang *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **692** 012017

IOP Conf. Series: Materials Science and Engineering **692** (2019) 012017 doi:10.1088/1757-899X/692/1/012017

Design of Magnetic Circuit and Finite Element Analysis of Stepped Ferrofluid Seal with Small Sealing Gap

Ruibo Zhang[1], Xiaolong Yang[1,*] and Guohong Wang[1]

[1]School of Mechanical Engineering, Guangxi University of Science and Technology, Liuzhou 545006, China

[*]Corresponding author e-mail: 09116324@bjtu.edu.cn

Abstract. For the sake of study the pressure capability of ferrofluid seals with small sealing gap, a diverging stepped ferrofluid structure with small sealing gap was designed according to the theory of stepped ferrofluid and magnetic path design, and the length and cross-sectional area of the permanent magnet (NeFeB) are obtained. On the basis of these parameters, the ferrofluid distribution of seal gap is calculated by using the magnetic ferrofluid element method, and the pressure capability is obtained, then the reliability of the magnetic path design is obtained according to the capability of withstand voltage. There are some findings as following after analysis and comparison. It is the magnetic flux leakage at the junction of the pole boot and NeFeB that cause pressure capability calculated by the magnetic path method is lower than that calculated by the finite element method.

1. Introduction

Ferrofluid seals is a kind of technology that ferrofluid seals generates sealing ring to the response characteristics of external magnetic field to achieve the function of resisting pressure difference on both sides of the sealing structure[1]. It is widely used in fields of aerospace, defense, machinery, chemical, petroleum, environment, instruments due to its advantages of zero leakage, long life and low friction[2-3]. At present, there are many researches on common ferrofluid seals in small gap. Research on vacuum, dustproof and small diameter magnetic liquid static sealing with low pressure capability and dynamic sealing technology with small sealing gap from 0.1mm to 0.3mm has been relatively mature, but the research on high pressure, high temperature, low temperature and high vacuum is few, which limits its application[4]. Wang Ruijin[5] et al summarized the general law of ferrofluid seals, and focused on the pressure capability of seal gap under different speeds and parts processing quality, then concluded that the seal gap is too small, which can not improve the pressure capability, but will decline. Gu Jianming[6] et al drew a conclusion that the sealing capability of the ferrofluid increases with the increase of seals, and decreases with rise the seal gap through experiments. Besides, the effect is better when the seal gap is 0. 05-0.20 mm, at the same time, the sealing series has an optimum value. Li Decai[7] et al numerically studied the pressure capability of small gap and concluded that sealing pressure capability is greatly decreases in rise sealing gap, but the sealing gap should not exceed 0.3 mm. These studies were only completed on the base of a non-stepped, but the study of stepped ferrofluid seals with small gap has not been carried out. In 2014, Yang Xiaolong and Li Decai et al began to carry out numerical analysis and experimental research on stepped ferrofluid seals with large sealing gap, and compared it with the pressure capability of ordinary ferrofluid seal, then came to a conclusion that the stepped ferrofluid seal is an effective method to improve the sealing performance of large gap ferrofluids. Yang Xiaolong and Chen Fan[8] demonstrated that the pressure capability of the diverging stepped ferrofluid seal with large sealing gap decreases with the increase of the radial seal gap width based on the theory and experiment of sealing. Yang Xiaolong et al drew a conclusion that the pressure capability of the diverging stepped ferrofluid seal decreases with the increase of the radial seal gap using the magnetic path design method and the finite element analysis method. However, there are no systematic studies about the sealing property of stepped ferrofluid seals with small sealing gap.

In order to improve the pressure capability of the stepped ferrofluid seals with small sealing gap, this paper designs a structure of the diverging stepped magnetic path with small sealing gap based on the theory of magnetic path design, and studies the effects of parameters such as the axial clearance, radial clearance, the number of axial teeth, the number of radial tooth on its sealing capability through finite element method. The research results provide important theoretical guidance for designing a high-reliability stepped ferrofluid seal structure with small gap.

2. Design of magnetic path

Figure 1 is a diverging stepped ferrofluid seal structure, and its equivalent magnetic circuit is shown in Figure 2. It can be seen from the Figure 1 that the magnetic circuit is mainly composed of permanent magnet, pole piece, magnetic fluid and stepped shaft. The permanent magnet generates magnetic field which binds the magnetic fluid in the radial and axial sealing gap formed between the stepped shaft and the pole piece. The magnetic force on the magnetic fluid is to resist the pressure difference between the two sides of the seal structure and to achieve the purpose of blocking the leakage channel.

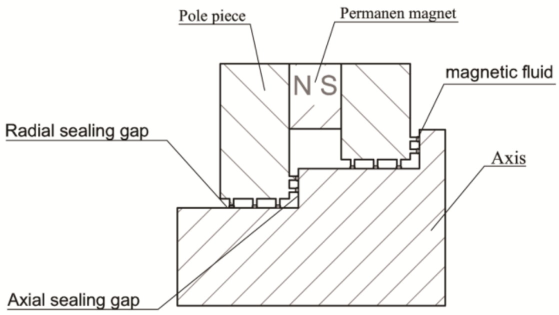

Figure 1. Structural Chart of Stepped ferrofluid Sea1

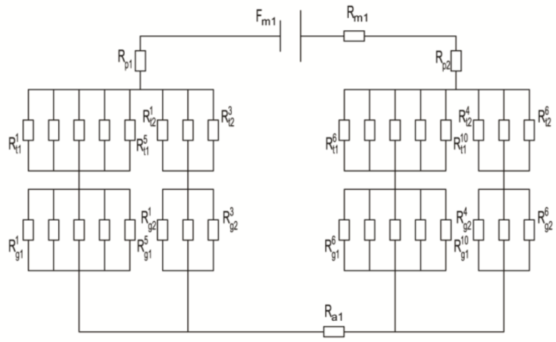

Figure 2. Diagram of equivalent magnetic path

It is assumed that the gravity of the ferrofluid is much smaller than the magnetic force, and the ferrofluid line can be replaced by an arc; the isomagnet line is considered to coincide with the ferrofluid line, and the surface tension of the ferrofluid can be ignored. Then the pressure capability of ferrofluid static seals can be approximately expressed by following formula

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

where $H_{max}^{i}$and H_{min}^{i} and B_{max}^{i} and B_{min}^{i} are, respectively, the maximum and minimum magnetic field strengths and the maximum and minimum magnetic flux densities under the ith is pole tooth, while N is the total number of sealed poles.

The total sealing capability of the converging stepped ferrofluid as:

$$\Delta P = \sum_{i}^{N} (P_{ia} + \lambda P_{ir}) \tag{2}$$

In(2), $P_{ia}$and $P_{ir}$are the pressure capabilities of the ferrofluid seal in the axial and in the radial sealing gaps formed by the ith pole piece and the stepped shaft.If P_{ia}<P_{ir} , then $\lambda = 1$, otherwise

$\lambda = 0$, P_{ia} and P_{ir} can be calculated by formula (1).

Two assumptions are contained in magnetic path design of parallel ferrofluid seals in this paper: first, ignore the magnetic flux leakage; second, ignore the edge effect. According to Kirchhoff's first law,

$$\sum \Phi_i = 0 \tag{3}$$

That is, at any point in the magnetic path, the sum of the magnetic flux algebra entering the region equals to the sum of the magnetic flux algebras leaving the region. According to the symmetry of the magnetic path structure,

$$\Phi_2 = \Phi_1 \tag{4}$$

Φ_1 and $\Phi_2$respectively represent the magnetic fluxes in the higher pressure side pole shoe and the atmosphere side pole shoe, among them

$$\Phi_1 = 5B_{g1}^1 S_{g1}^1 + 3B_{g2}^1 S_{g2}^1 \tag{5}$$

B_{g1}^1 and B_{g2}^1 respectively represents the first radial gap under the first pole teeth on the first pole shoe on the high voltage side and the magnetic flux density in the first axial gap under first pole teeth in first pole shoe, respectively; S_{g1}^1 and S_{g2}^1 denotes the annular area of the first radial gap under the first pole tooth and the first axial seal gap under the first pole teeth on the high pole side first pole shoe, respectively.

$$\Phi_2 = 5B_{g1}^6 S_{g1}^6 + 3B_{g2}^4 S_{g2}^4 \tag{6}$$

B_{g1}^6 and B_{g2}^4 respectively represents the sixth radial gap of sixth pole tooth on the atmospheric side pole shoe and the magnetic flux density in the fourth axial gap of the fourth pole teeth on the middle pole shoe; S_{g1}^6 and S_{g2}^4 denotes the annular area of the sixth radial seal gap under the sixth pole teeth on the atmospheric side pole shoe and the fourth axial seal gap under the fourth pole tooth on the atmosphere side, respectively.

$$\Phi_{m1} = B_{m1} S_{m1} = \Phi_2 = 5B_{g1}^6 S_{g1}^6 + 3B_{g2}^4 S_{g2}^4 \tag{7}$$

Where Φ_{m1} B_{m1} and S_{m1} represent the magnetic flux, magnetic flux density and annular area of NeFeB on the atmospheric pressure side respectively.

According to Kirchhoff's second law, $\sum H_i l_i = \sum N_i i$

$$\begin{aligned} F_1 = H_{m1} L_{m1} = &\left(5B_{g1}^6 S_{g1}^6 + 3B_{g2}^4 S_{g2}^4\right)\left[R_{p2} + \frac{\left(R_{t1}^6 + R_{g1}^6\right)\left(R_{t2}^4 + R_{g2}^4\right)}{3\left(R_{t1}^6 + R_{g1}^6\right) + 5\left(R_{t2}^4 + R_{g2}^4\right)}\right] + \\ &\left(5B_{g1}^1 S_{g1}^1 + 3B_{g2}^1 S_{g2}^1\right)\left[R_{p1} + R_{a1} + R_{m1}\frac{\left(R_{t1}^6 + R_{g1}^6\right)\left(R_{t2}^1 + R_{g2}^1\right)}{3\left(R_{t1}^1 + R_{g1}^1\right) + 5\left(R_{t2}^1 + R_{g2}^1\right)}\right] \end{aligned} \tag{8}$$

Wherein F_1 represents the magnetomotive force of the NeFeB; H_{m1}, L_{m1} represent the ferrofluid strength and length of the NeFeB; R_{p1}、R_{a1} and R_{m1} represent the first pole piece, the stepped shaft, and the NeFeB, respectively. R_{t1}^6, R_{g1}^6, R_{t2}^4, R_{g2}^4 respectively represent the magnetic drag of the sixth radial pole tooth on the atmospheric side pole shoe and the sixth radial seal gap of the sixth radial pole tooth, and the atmospheric side pole shoe ,The magnetic drag of the fourth radial seal gap of the upper fourth axial pole teeth and the fourth radial pole tooth.

Equation (5) multiply (6)

$$V_{m1} = L_{m1} S_{m1} = \frac{F_1 \Phi_{m1}}{B_{m1} H_{m1}} \tag{9}$$

In order to reduce the volume and weight of the NeFeB and improve the utilization rate of the NeFeB, the NeFeB should be operated at its maximum magnetic energy product, and therefore,

$$V_{m1} = L_{m1}S_{m1} = \frac{F_1\Phi_{m1}}{(BH)max} \tag{10}$$

Divide equation (5) by equation (6)

$$\frac{S_{m1}}{L_{m1}} = \frac{\left(5B_{g1}^1S_{g1}^1 + 3B_{g2}^1S_{g2}^1\right)H_{m1}}{F_1B_{m1}} \tag{11}$$

Equation (8) Multiply (9).

$$S_{m1} = \left(5B_{g1}^1S_{g1}^1 + 3B_{g2}^1S_{g2}^1\right)\sqrt{\frac{H_{m1}}{(BH)_{max}B_{m1}}} \tag{12}$$

Divide equation (8) by equation (9)

$$L_{m1} = F_1\sqrt{\frac{B_{m1}}{(BH)_{max}H_{m1}}} \tag{13}$$

Since the magnetic permeability of the material of the pole shoe and rotating shaft is much larger than that of the air and the NeFeB, the obstruction of the pole shoe and the rotating shaft can be neglected when calculating the length of the NeFeB.

3. Finite element analysis of the ferrofluid

The dimensions of each part of magnetic path are shown in table 1. If the sealing pressure capability is required to be not less than 2×10^5 Pa , we know that the total static magnetic induction difference in the sealing gap is 6.5T according to the general static sealing withstand voltage formula. The length of NeFeB is 5.6 mm, the cross-sectional area is 243 mm^2 according to the symmetry of magnetic path and the design of the parallel ferrofluid seals.

Table 1. Parameter of converging stepped ferrofluid seals.

Item	Value	Item	Value
Inner radius of the 1/2 pole piece (mm)	17/21	Number of radial teeth under the 1/2 pole piece	2
Outer radius of the 1/2 pole piece (mm)	30		
Length of the 1/2 pole piece (mm)	5.3	Width of pole teeth (mm)	0.3
Number of axial teeth under the 1/2 pole piece	3	Axial sealing gap width (mm)	0.1
Slot width(mm)	0.7	Radial sealing gap height (mm)	0.1
Slot depth (mm)	0.8		

Create a physical environment of ferrofluid-tight in the preprocessor of ANSYS finite element analysis software. Due to the symmetry of the structure, the three-dimensional axisymmetric problem of the ferrofluid seals can be simplified to a two-dimensional one. NdFeB magnet is chosen as the NeFeB of diverging stepped ferrofluid seals structure with small gap, the coercive force H_c is 1.356×106 A/m, the magnetic permeability is 1.05. The material of the pole shoe and the stepped shaft are 2Cr13, and oil-based ferrofluid, with saturation magnetization of 30.7 KA/m is selected as ferrofluid. Since the ferrofluid strength generated by the NeFeB in the gap under each pole piece is greater than the saturation magnetization of the ferrofluid, the ferrofluid is saturated and magnetized. The saturation magnetization of the ferrofluid is almost the same as that of the air, so the ferrofluid can be treated as air. Each part is endowed with corresponding material properties, and Smart Meshing, with the accuracy of 4, is selected; A boundary condition that parallels with lines of force is applied to the model boundary.

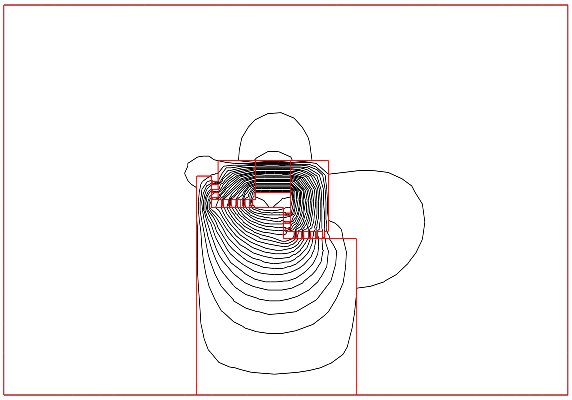

Figure 3 Distribution of magnetic line of force

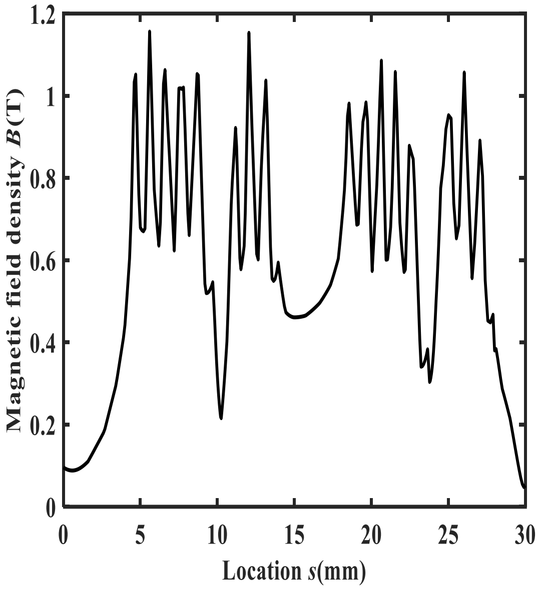

Figure 4 Axial path BSUM curves

Figure 3 and **Figure** 4 of magnetic flux density curve are obtained by finite element analysis., verify the accuracy of the magnetic path design according to the withstand voltage formula of stepped ferrofluid seals, the data of the Table 1 and **Figure** 4, the NeFeB data calculated by magnetic path design, So sealing pressure capability Δp is

$$\Delta P = \mu_0 M_s \sum_{i=1}^{N}(H_{max}^{i} - H_{min}^{i}) = M_s \sum_{i=1}^{N}(B_{max}^{i} - B_{min}^{i}) = 0.307 \times 5.8631 = 1.8 \times 10^5 \text{pa} < 2 \times 10^5 \text{ Pa}$$

Therefore, it is calculated that the pressure capability of the diverging ferrofluid seals structure is less than that required by the magnetic path design, 2×10^5 Pa, through the finite element method. Magnetic flux leakage，which is caused by the direct contact of magnet, pole piece and shell, is the main reason for this phenomenon. In order to improve the accuracy of the magnetic path design and the pressure capability of the ferrofluid seals, it is possible to select a non-magnetically conductive housing and increase the axial length of the intermediate pole piece to reduce the leakage magnetic energy.

4. Conclusion

- The finite element analysis results verify the reliability of the magnetic path design method.
- The pressure resistance of divergent stepped ferrofluid seal calculated by magnetic path design method is slightly larger than that of finite element analysis, mainly due to magnetic leakage at the direct contact between NeFeB and pole shoe and shell.
- We can reduce the leakage of magnetic energy by choosing non-permeable shells.

Acknowledgments

The authors gratefully acknowledge the support of the National Nature Science Foundation of China (Grant No. 51905114), the support of the Science and Technology Project of Guangxi Province (Grant No. 2016GXNSFBA380213), the support of the Innovation Project of GuangXi University of Science and Technology Graduate Education (Grant No. GKYC201901) and the support of the Science and Technology Project of Liuzhou (Grant No. 2017BC20204).

Reference

[1] Rosensweig R E 1997 Ferrohydrodynamics(New York: Dover Publications)

[2] Urreta H, Aguirre G, Kuzhir P, Lopez de Lacalle LN. 2018 Seals based on ferrofluids for high precision spindles of machine tools. *Int J Precis Eng Manuf* (Volume 19(4)) PP.495-503.
[3] Y.B Chen,D.C Li and Y.J Zhang Numerical Analysis and Experimental Study on Ferrofluid Reciprocating Seals *IEEE Trczns Magn* , (Volume 55(1)) PP.495-503.
[4] Yan C and Decai L 2011 Design and Experiments for Ferrofluid Seal of Tank Panoramic Mirror *Acta Armamentarii* (Volume 32(11)) PP 1428-1432.
[5] Ruijin W, Yunhong L and Ming Z 2001 Effect on pressure tight capacity for gap of ferrofluid seals *Vacuum* (2) PP 42-44
[6] Jianming G and Yongxing X 1999 Effect of the Gap of Ferrofluid Seal on Seal apacity *JOURNAL OF SHANGHAI JIAOTONG UNIVERSITY* (Volume 33(3)) PP 136-138
[7] Mingli K and Decai L Numerical Simulation for Ferrofluid Sealing Device *Journal of Beijing Jiaotong University* (Volume 32(1)) PP 116-118
[8] Xiaolong Y, Peng S, Fan C, Fuxiang H, Decai L and Peter J T 2019 Numerical and Experimental Studies of a Novel Converging Stepped Ferrofluid Seal *IEEE TRANSACTIONS ON MAGNETICS*(Volume 55(3))