ISSN (Print) 1226-1750
ISSN (Online) 2233-6656
Journal of Magnetics 27(1), 56-64 (2022) https://doi.org/10.4283/JMAG.2022.27.1.056

Analysis on Seal Capacity of Magnetic Fluid Seal Using Ring Magnet

Jiawei Liu[1] and Decai Li[1,2]*

[1]*School of Mechanical and Electronic Control Engineering, Beijing Jiaotong University, Beijing 100044,China*
[2]*Steta Key Laboratory of Tribology Tsinghua University, Beijing 100084,China*

(Received 26 November 2021, Received in final form 21 March 2022, Accepted 23 March 2022)

Magnetic fluid seal is one of the most mature applications of magnetic fluid. When the shaft has a large radial runout, the classical pole piece is easily damaged. Due to its small size, the commonly used pole piece structure harbors problems like poor seal performance under a large gap and poor processability. By exploring the distribution law of the magnetic field on the magnet's surface, we provided theoretical support for the magnetic fluid seal using axially-magnetized ring magnets. New structures for the magnetic fluid seal using axially-magnetized slotted ring magnets and the magnetic fluid seal using radially-magnetized ring magnets were proposed. Then, comparisons were made between the classical magnetic fluid seal and the magnetic fluid seal using ring magnets. The results revealed that the magnetic fluid seal using axially-magnetized slotted ring magnets and the magnetic fluid seal using radially-magnetized ring magnets exhibited a certain seal capacity, which could replace the classical magnetic fluid seal structure.

Keywords : magnetic fluid seal, finite element analysis, magnet ring, seal without magnetoconductive pole pieces

1. Introduction

Magnetic fluid is a new class of nano-functional materials, which exhibits two main characteristics–fluidity and magnetism. The former embodies the nature of fluid materials, while the latter embodies the nature of solid materials [1]. Magnetism enables it to respond to the effects of external magnetic fields, while fluidity allows it to form any shape to meet various requirements. Thereby, magnetic fluid has been extensively utilized in aerospace, military industry and petrochemicals [2-6].

There are two aspects concerning the optimal design of magnetic fluid seal: the optimal design of the permanent magnet area; the optimal design of the magnetoconductive pole piece area. Therefore, in the design of the magnetoconductive pole piece area, all designs are composed of pole piece structures, with the types, size and number of magnetoconductive pole pieces being the main differences. In publication [7], C. Du proposed the rectangular tooth structure for the multi-stage seal, generally using the rectangular tooth structure due to its remarkable seal capacity. As the seal capacity on both sides is identical and the rectangular tooth structure won't damage the bump and induce scratches, such structure has become the classic design for magnetoconductive pole pieces and pole pieces on magnetic fluid seals. The sealing gap between the relatively rotating shaft and the magnetoconductive pole pieces is the main working area of the magnetic fluid seal. To improve the seal capacity of magnetic fluid seals, smaller seal gaps are usually designed. However, the design will easily lead to the damage of bumps and cause scratches, leading to the decrease of seal capacity or leakage. Especially for the shaft with the big radial runout, the aforesaid structure is commonly unreliable. Most of the solutions solving this problem chose to increase the sealing gap between the relatively rotating shaft and the magnetoconductive pole pieces, whereas the seal capacity of the magnetic fluid sealing will decrease significantly. In publication [8], in order to solve such problem, X. Yang put forward a converging stepped magnetic fluid seal for the large sealing gap, which improved the seal capacity of the magnetic fluid sealing with a large gap. However, the complexity of the device and high requirements for installation reduced the reliability of the seal. In terms of the optimization of permanent magnets, most optimization are designed to avoid problems such as installation difficulties and the charge-magnetic imbalance of permanent magnets due to large diameter. In

*Corresponding author: Tel: +86-136-5120-6606
Fax: +86-136-5120-6606, e-mail: lidecai@tsinghua.mail.edu

publication [9], to avoid problems mentioned above, D. Li put forward a permanent magnet structure composed of many small cylindrical magnets and verified the sealing capacity by experiments. In publication [10], Szczech, M designed and analyzed the seal capacity of the magnetic fluid seal by experiments, whose magnetic source was made up of a cylindrical magnet, whereas he failed to propose the optimal design and the application conditions of the magnetic source. In publication [11], J. Liu proposed the optimized design and performed simulation analysis for the various structures of the permanent magnets through simulation analysis and provided a selection scheme for the magnetic source structure of large-diameter magnetic fluid seals.

However, the optimization designs of the aforementioned scholars are limited to the classic structures of magnetic fluid seals. The poor sealing reliability and high scrap possibility caused by the shaft runout and installation difficulties are still unsolved. In publication [12], in order to solve the aforesaid problems, Karoen van der Wal proposed a magnetic fluid sealing structure, whose magnetic source was an axially magnetized ring magnet setting on the shaft. As shown in Fig. 1, the seal contained a nonmagnetic ring, an axially magnetized ring magnet and a nonmagnetic ring successively setting on the shaft. Although the design solved the problems mentioned above, the single-class ring magnet structure couldn't provide sufficient seal capacity. For the sake of elevating the seal capacity, based on the structure, the author decided to increase the number of ring magnets and set the groove structure in the inner surface of ring magnets, designing a novel magnetic fluid seal structure, which utilized radial-charge ring magnets as the magnetic source. Subsequently, these seal structures were calculated by Ansys Maxwell FEA and the seal capacity was compared under different circumstances. It was evidenced that two new types of magnetic fluid seals using ring magnets exhibited certain seal capacity, which provided better options for magnetic fluid seals with large gaps.

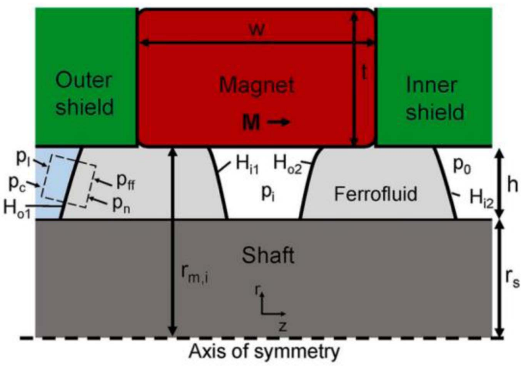


Fig. 1. (Color online) Magnetic fluid seal proposed by Karoen van der Wal etc [12].

2. Principles and Advantages of Magnetic Fluid Seals

The classical structure of the magnetic fluid seal is shown in Fig. 2, which comprises a nonmagnetic housing, ring magnet, magnetoconductive pole piece, magnetic shaft and magnetic fluid [13]. The magnetic fluid seal makes use of the response properties of the magnetic fluid to the magnetic field. After injected into the gap between the magnetic circuit formed by the magnetoconductive pole pieces and shaft, the magnetic fluid will become several "O" -shaped seals. The number of seal rings is also written as the seal stages. When the magnetic fluid is affected by the external pressure, it moves in the heterogeneous magnetic field, but the uneven magnetic field will create magnetic gradient to provide the magnetic force to fight against the external pressure, creating a new balance in the end [1, 14]. As the seal gap of the magnetic fluid seal is usually between 0. 05 to 0. 25 mm, we defined the seal gap smaller than 0.25 mm as the magnetic fluid seal with a small gap and the seal gap larger than 0. 25 mm as the magnetic fluid seal with a large gap [16].

Magnetic fluid sealing is extensively utilized, which can be applied in static seal, dynamic seal, rotary seal and reciprocating seal. Magnetic fluid seal presents the following advantages: zero leakage, long service life, high reliability, non-pollution, high speed resistance, optimal torque transfer and low viscosity friction. In some ways, due to the aforesaid advantages, it's irreplaceable compared with traditional seals. Therefore, magnetic fluid seal has been broadly leveraged in many fields.

However, the magnetoconductive pole piece structure

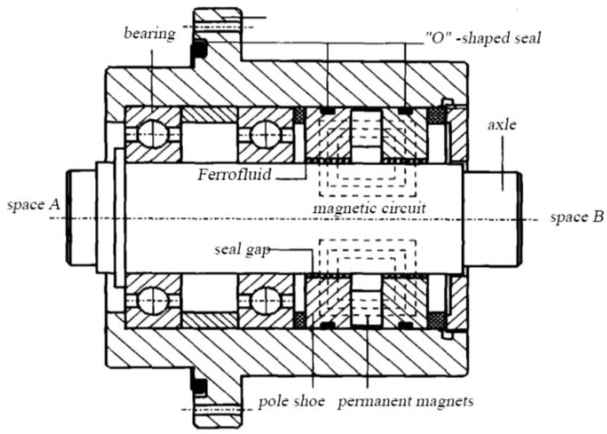


Fig. 2. Schematic diagram of magnetic fluid sealing.

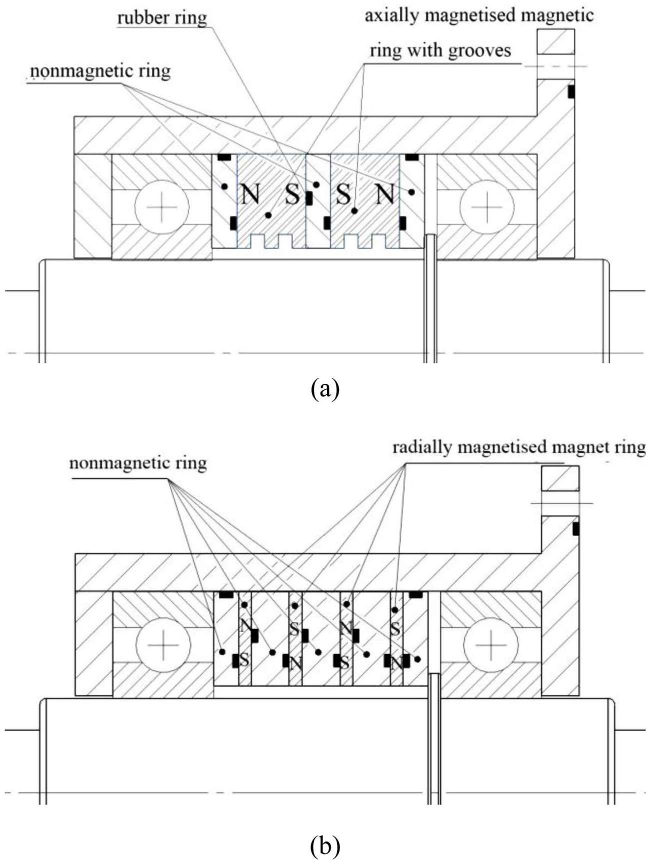


Fig. 3. Structural diagram of magnetic fluid seal using ring magnets (a) Magnetic fluid seal using axially-magnetized slotted ring magnets. (b) Magnetic fluid seal using radially magnetized ring magnets.

used harbors installation problems and is easily impaired by the radial runout of the shaft. But the ring magnet magnetic fluid seal perfectly solved these problems. As shown in Fig. 3, according to the optimization of the number and size of the ring magnet of the axially magnetized permanent magnet ring in Fig. 1, inspired by the pole tooth structure on the magnetoconductive pole piece, we proposed a new seal structure, which set the groove structure in the inner surface of the ring magnet to increase the seal capacity. Then, we proposed a new magnetic fluid seal structure that used a radially magnetized ring magnet as the magnetic source and replaced classic magnetoconductive pole pieces with a thin circular permanent magnet and a thick ring magnet successively set on the shaft. Under such conditions, the magnetic lines generated by the radially magnetized ring magnet could be regarded as going straight through the sealing gap. Similar to the magnetoconductive pole piece, this structure could also create magnetic gradient to provide the magnetic force and form "O"-shaped seals generated by the magnetic fluid in the seal gap to fight against the external pressure.

3. Relevant Theoretical Analysis

3.1. Theoretical analysis of magnetic fluid seal

From the Bernoulli equation of the magnetic fluid and the corresponding assumption, each level of the magnetic fluid seal can be expressed as [1, 2]:

$$p_i = \mu_0 M_s (H_{i\max} - H_{i\min}) = \mu_0 M_s \Delta H_i \quad (1)$$

where $H_{i\min}$ and $H_{i\max}$ are the minimum and maximum magnetic field strengths under the stage i pole tooth respectively, ΔH_i denotes the difference between the maximum and minimum magnetic field strengths at the stage i pole piece, μ_0 is the permeability of vacuum, M_s reflects the saturation magnetization of the magnetic fluid, p_i denotes the seal capacity of stage i of the magnetic fluid seal ring. The seal capacity provided by each seal stage could be approximately considered identical. The total seal capacity of the magnetic fluid seal can be approximately expressed as [17-21]

$$p = \sum_{i=1}^{n} p_i = \sum_{i=1}^{n} \mu_0 M_s \Delta H_i \quad (2)$$

where n is the number of seal stages.

3.2. Magnetic Tip Effect

The tip effect is a general rule of the charge distribution on the surface of the conductor. It shows that when the charge distribution of a conductor reached the balance, regardless of its own shape and the distribution of conductors and mediums around, the sharper the parts of the conductor and the bigger the surface curvature was, the more charge distribution it had. And the smoother the parts of the conductor and the smaller the surface curvature was, the less charge distribution it had [22]. This is the interpretation of the tip effect from the university physical. According to the relevant knowledge and experience of magnets, similar tip effect was found in the distribution of the magnetic field around the permanent magnet boundary. Since the permanent magnet is usually unidirectional charged, we took the small cylindrical microelements along the magnetic charging direction from the magnet boundary to finish our analysis. Assuming that the magnetic lines were emitted from the bottom surface to the top surface, after applying Gauss theorem to the magnet boundary, we could obtain an equation to analyse the tip effect [23]

$$\int_{S_1} H_1 \cdot n_1^0 \mathrm{d}S = \int_{S_2} H_2 \cdot n_2^0 \mathrm{d}S \quad (3)$$

where n_1^0 and n_2^0 are the outer normal vector of the bottom and top surfaces respectively, S_1 is the magnet microelement area of the bottom surface, H_1 is the magnetic field strengths going into the bottom surfaces, S_2 is the magnet microelement area of the top surface, H_2 is the magnetic field strengths going out the top surfaces. To sum up, the smaller the surface area of the permanent magnet, such as the sharp angle and the edge of the magnet, the denser the magnetic field. Correspondingly, the magnet produced a stronger magnetic field near the sharp surfaces than other flat surfaces. Hereafter, we called the theory the tip effect of permanent magnets. From formula (2), the larger the magnetic field strength gradient, the greater the seal capacity of the magnetic fluid seal.

To sum up, we provided a theoretical support for the axially magnetized magnet fluid sealing. Hereafter, the author applied this principle to the design, optimization and simulation of the magnetic fluid seal structure.

4. Maxwell Analysis of Magnetic Fluid Seal

4.1. Design scheme

As shown in Fig. 4(a), it was a classic rectangular teeth structure of magnetic fluid seal whose seal gap was L_g=0.1mm. With this gap confirmed, we acquired the magnetoconductive pole piece width L_t, magnetoconductive pole piece distance L_s and magnetoconductive pole piece height L_h, which were respectively 0.2 mm, 0.8 mm, and 0.7 mm. The design theory was successfully applied for the magnetic fluid sealing in small gaps [8, 24], which was well sealed and highly reliable under many circumstances. But the magnetic fluid seal is easily damaged by the radial runout of shaft. Due to its small size, the magnetoconductive pole piece usually harbors the problems of poor processability and poor sealing performance under the large gap. However, without the structure of magnetoconductive pole pieces, the magnetic fluid seal using ring magnets could well solve these problems. According to Maxwell FEA, the author offered the design scheme of the magnetic fluid seal using ring magnets. As shown in Fig. 3(b), the adjacent permanent magnets were charged reversely, where the thickness of the permanent magnet ring and the thickness of the nonmagnetic ring were L_{h1} and L_{h2} respectively. Then, we used the simulation results to finish comparative analysis on the magnetic fluid seal capacity.

Due to the advantages of zero leakage and high reliability, the classical structure of the magnetic fluid seal has been widely used in recent decades. We took a seal applied for many years in engineering applications as a calculation example. The seal shaft diameter was 15 mm; the seal gap was 0.1 mm; the seal stage was 8; the axial length of the pole piece was 5mm; and the size of the circular magnet was Φ20 mm × 32 mm × 6 mm. We used this structure to perform Maxwell FEA and comparative analysis. The core part of the magnetic fluid seal using ring magnets consisted of ring magnets and nonmagnetic rings installed without clearance. The inner diameter and outer diameter of ring magnets, the thickness of ring magnets and nonmagnetic ring thickness, the width of magnetic rings were respectively D_1, D_2, L_{h1}, L_{h2}, and L_{h3} ($L_{h3}=(D_1-D_2)/2$). Other parts had the same size as the seal calculation example.

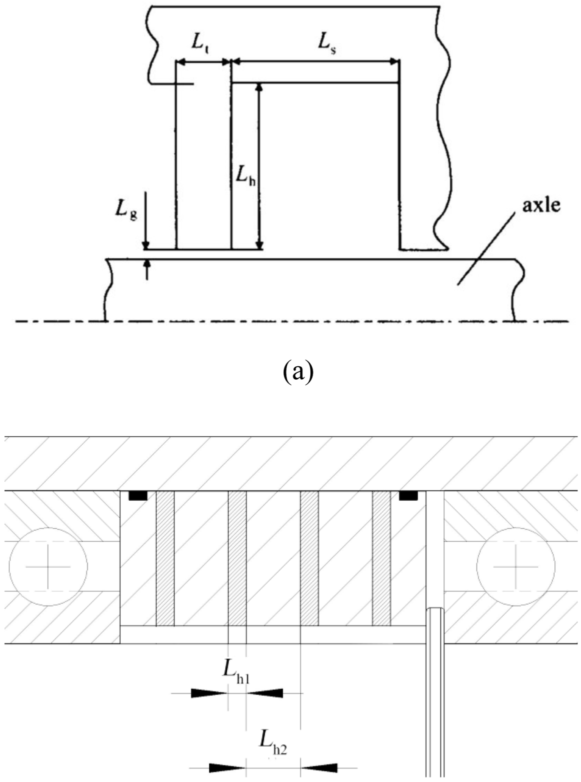


Fig. 4. Schematic diagram of magnetoconductive pole piece structure and ring magnet structure (a) Structure of magnetoconductive pole piece (b) Magnetic fluid seal using ring magnets.

Regarding the material choice, magnetic sections, such as the axle and the magnetoconductive pole pieces, were made of magnetic permeability materials, like 2Cr13. Nonmagnetic sections, such as the nonmagnetic rings and the shell, were made of nonmagnetic materials, like 304 stainless steel. Permanent magnets were made of N35H rubidium ferroboron magnets, which had the largest maximal

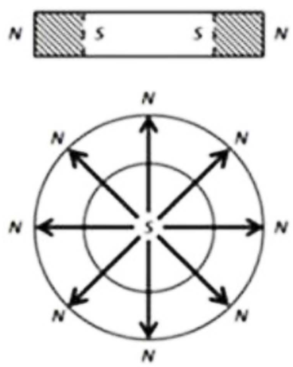


Fig. 5. Magnetization of axially magnetized ring magnet.

magnetic energy product. The axially magnetized ring magnets and radially magnetized ring magnets were N35H magnets charged in different ways, whose H_{cb}=860 kA/m. The magnetization of the axially magnetized ring magnets is shown in Fig. 5.

In this paper, we considered the seal target insoluble with the magnetic fluid, which was supposed to be nitrogen. Thereby, we could use ester-based magnetic fluid here, whose saturation magnetization M_s was 20 kA/m [27, 28]. Its M_s increased with the magnetic field intensity of the seal gap. And it almost stopped increasing when the magnetic field intensity H in the seal gap reached 200 kA/m. Therefore, in order to fully use the magnetic field intensity of the sealing gap, the H in the seal gap should be larger than 200 kA/m.

4.2. Modeiling and simulation

We used SolidWorks to draw the core of the seal device of the above structure scheme. Then, we imported it to the Maxwell FEA module and set the geometry module as cylinderical about Z. The magnetization direction of the axially magnetized ring magnets and radially magnetized ring magnets were respectively z and r in the cylindrical coordinate system. According to the Maxwell FEA, we could optimize the seal structure. The simulation structure of the classical structure of the magnetic fluid seal is shown in Fig. 6(a). The simulation structure of the magnetic fluid seal using axially magnetized ring magnets is shown in Fig. 6(b). According to Maxwell FEA, we set the thickness of ring magnets and nonmagnetic ring thickness and the width of magnetic rings respectively as L_{h1}=2 mm, L_{h2}=2 mm, and L_{h3}=2 mm. The simulation structure of the magnetic fluid seal using axially-magnetized slotted ring magnets is shown in Fig. 6(c). Setting the groove structure in the inner surface of the ring magnet could increase the seal capacity by adding the amount of magnetic fluid rings. Due to the design of the grooves, it's hard to set nonmagnetic rings into the gap of grooves.

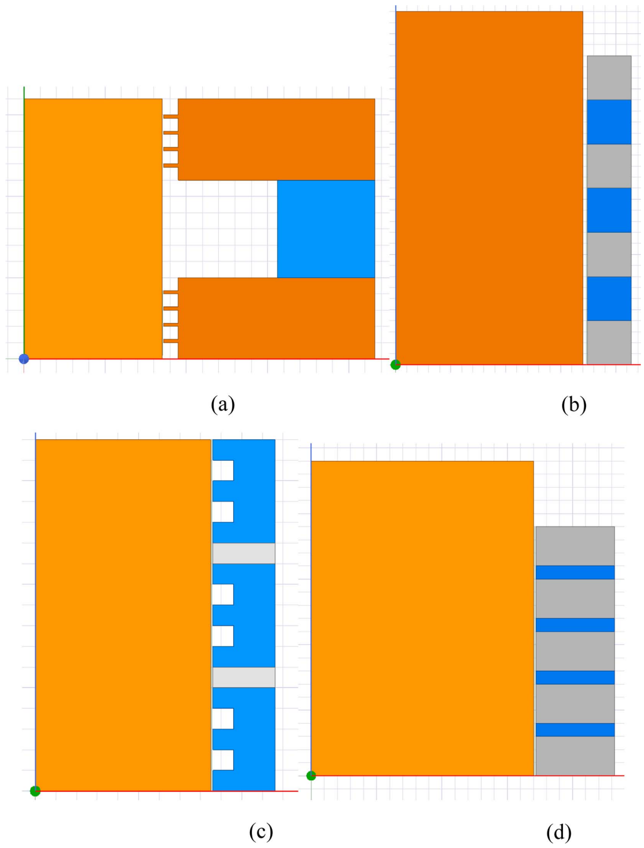


Fig. 6. (Color online) Illustration of seal model (a) classical structure of magnetic fluid seal (b) Magnetic fluid seal using axially-magnetized ring magnets (c) Magnetic fluid seal using axially-magnetized slotted ring magnets (d) Magnetic fluid seal using radially-magnetized ring magnets.

According to the demagnetization knowledge of magnets, we could set the working sections of magnets as rectangular to minimize the demagnetization. According to Maxwell FEA, we set L_{h1}=5 mm, L_{h2}=1 mm, and L_{h3}=3 mm. The optimal value of the height, thickness and distance of the groove was 1 mm. The simulation structure of the magnetic fluid seal using radially magnetized ring magnets is shown in Fig. 6(d). According to Maxwell FEA, we set L_{h1}=0.5 mm, L_{h2}=1.5 mm, and L_{h3}=3 mm.

The contour plots of the magnetic flux density of the classic structure of the magnetic fluid seal, the magnetic fluid seal using axially-magnetized ring magnets, the magnetic fluid seal using axially-magnetized slotted ring magnets and magnetic fluid seal using radially-magnetized ring magnets are shown in Fig. 7. The magnetic line distribution of the magnetic fluid seal, the magnetic fluid seal using axially-magnetized ring magnets, the magnetic fluid seal using axially-magnetized slotted ring magnets and magnetic fluid seal using radially-magnetized ring magnets is shown in Fig. 8. Due to the magnetoconductive

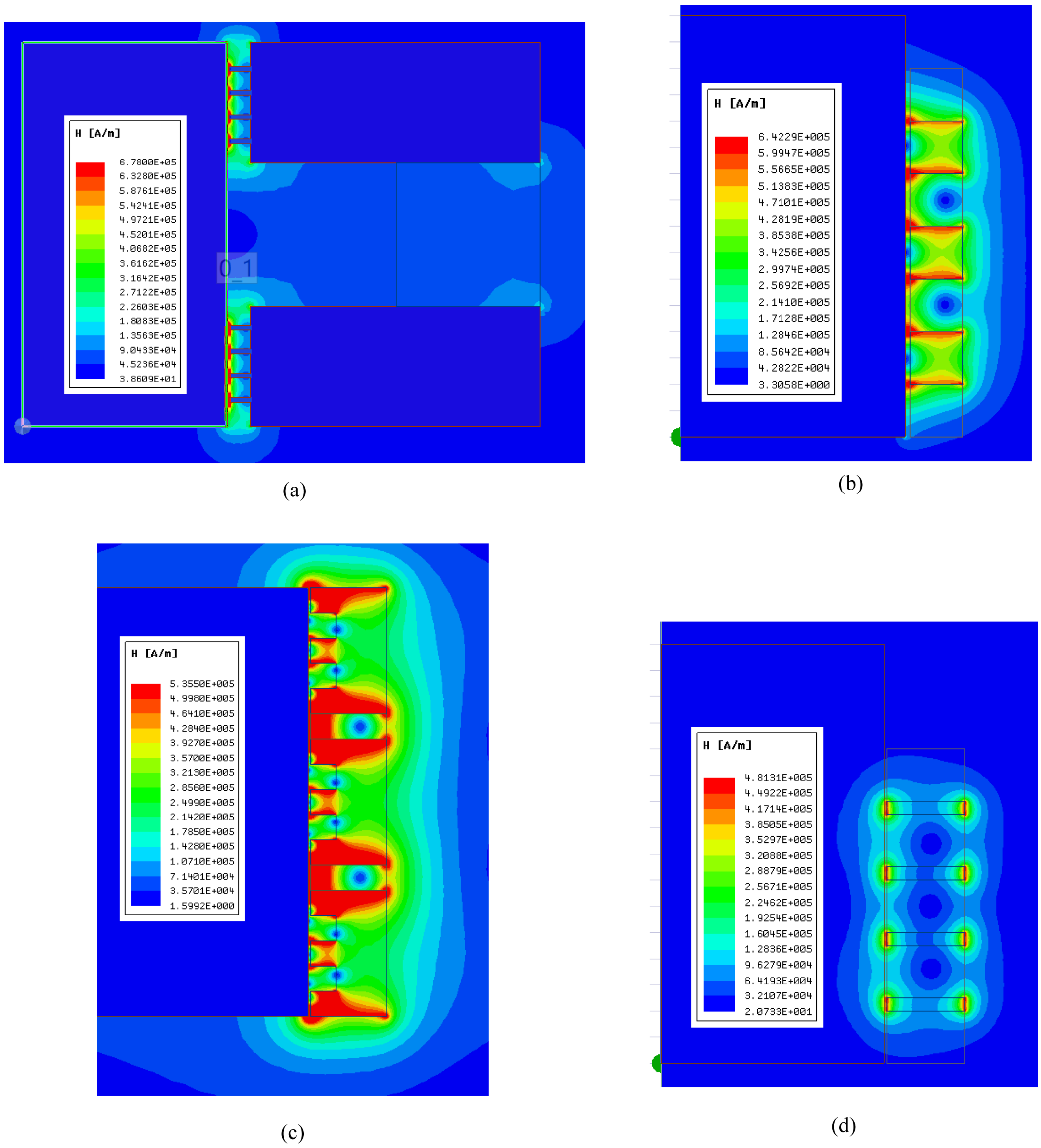
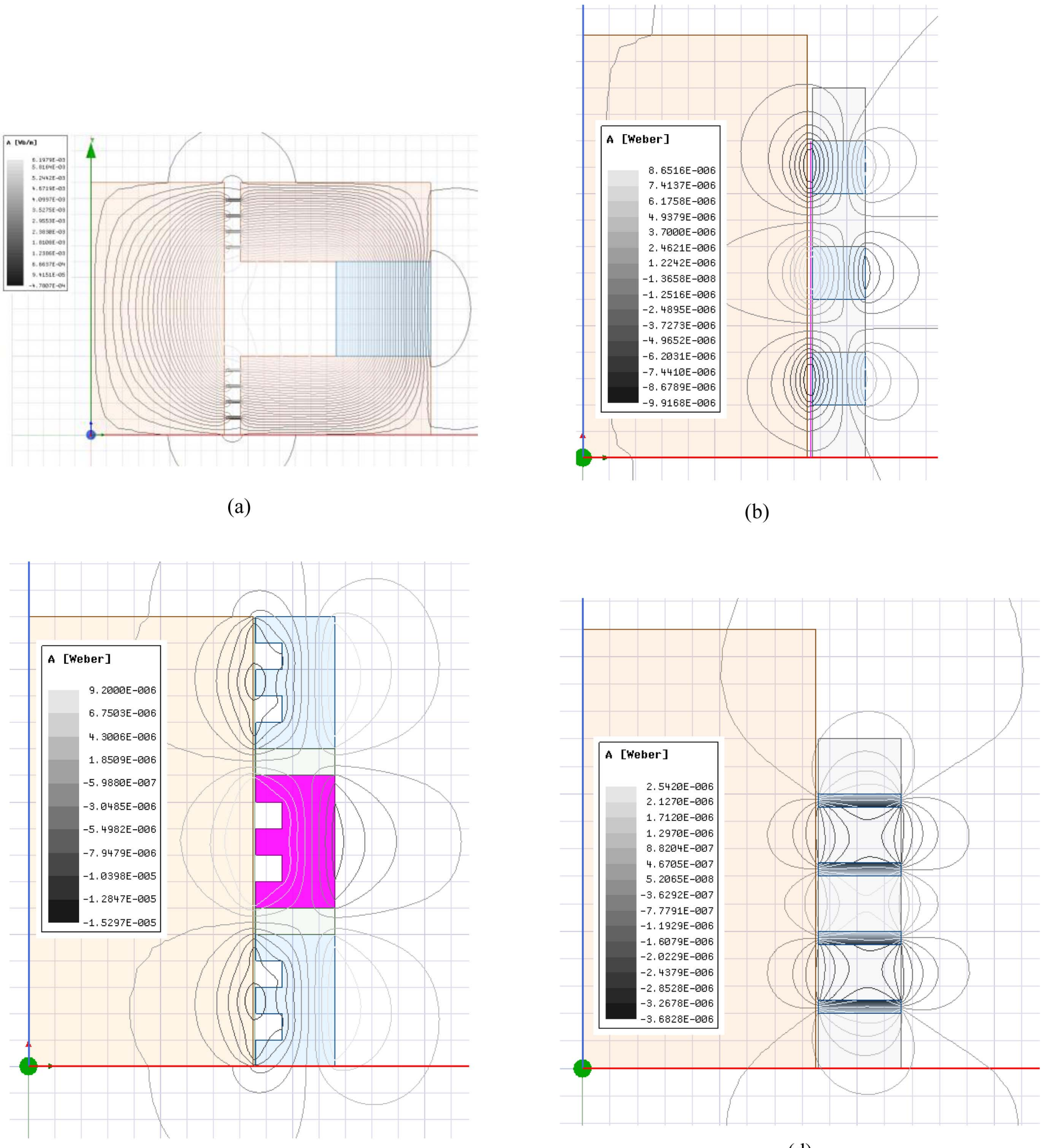


Fig. 7. (Color online) Contour plot of magnetic flux density (a) classical structure of magnetic fluid seal, (b) Magnetic fluid seal using axially-magnetized ring magnets, (c) Magnetic fluid seal using axially-magnetized slotted ring magnets, (d) Magnetic fluid seal using radially-magnetized ring magnets.

pole pieces and nonmagnetic rings, the magnetic lines generated by the permanent magnets were concentrated in the seal gap, which could greatly reduce magnetic field leakage and increase the magnetic field gradient and improve the seal capacity.

4.3. Data processing

According to the simulation and calculation, we acquired the magnetic field strength curve of all kinds of magnetic fluid seals, which was shown in Fig. 8. Based on the aforementioned formula and the relevant knowledge of magnetic fluid seals, in order to meet the saturation of the magnetic fluid, we discovered that the magnetic field strength in the working gap, where the magnetic fluid existed, should be greater than 200 kA/m. In this case, the difference of the axial magnetic field strength determined the maximal seal capacity. Then, we utilized formula (2) to treat the simulation results. The results were shown in Fig. 9 and Table 1. From Fig. 9, it was obvious that the magnetic field strength curves created in the seal gap of these two kinds of new structures of magnetic fluid seals using ring magnets were both similar to the classic magnetic fluid seal, which had a significant magnetic field strength gradient. The sealing seal capacity was calculated and analyzed as follows. Since the main working area of the magnetic fluid seal was the middle



(a) (b) (c) (d)

Fig. 8. (Color online) Distribution map of magnetic lines (a) classical structure of magnetic fluid seal, (b) Magnetic fluid seal using axially-magnetized ring magnets, (c) Magnetic fluid seal using axially-magnetized slotted ring magnets, (d) Magnetic fluid seal using radially-magnetized ring magnets.

Table 1. The Result of the Fea.

Structure	ΔH /A/m	Axial length h/mm	stage	p (when L_g=0.1 mm)/MPa	p/h (MPa/mm)	p (when L_g=0.3 mm)/MPa
Classic structure	1303	16	8	0.431	0.027	0.138
Axially magnetized ring magnet	750	14	4	0.186	0.013	0.119
Radially magnetized ring magnet	762	10	4	0.121	0.012	0.074
Axially magnetized slotted ring magnet	677	17	16	0.359	0.021	0.238

area, the simulation data in Table 1 were arranged after the removal of the singular value on the both sides, and the name was simplified according to their respective characteristics.

4.4. Analysis and discussion

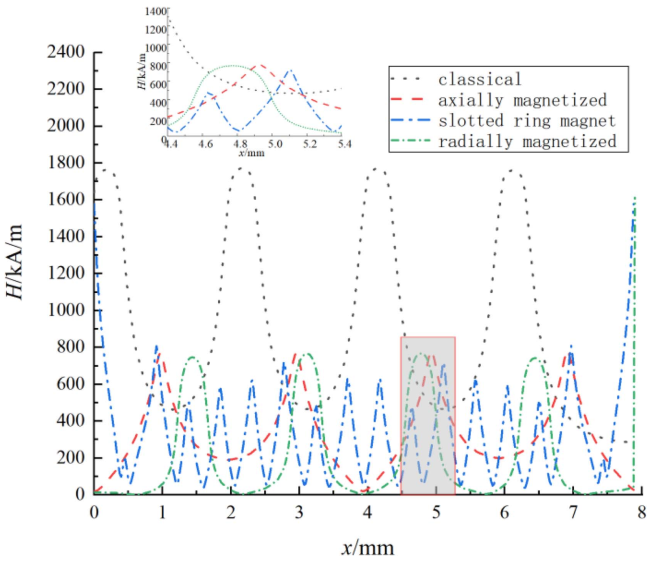


Fig. 9. (Color online) The comparison with magnetic field in seal gap.

According to the simulation and calculation based on the classic structure of the magnetic fluid seal, the magnetic fluid seal using axially-magnetized ring magnets, the magnetic fluid seal using axially-magnetized ring magnets with magnetoconductive pole pieces and the magnetic fluid seal using radially-magnetized ring magnets, we obtained the following discoveries:

It is not difficult to see from Table 1 and Fig. 7 that both the magnetic fluid seal using axially-magnetized slotted ring magnets and the magnetic fluid seal using radially-magnetized ring magnets could generate a certain magnetic field gradient in the seal gap. Therefore, we could discover from formula (2) that the two new structures had a certain seal capacity. The seal capacity of the classic structure of the magnetic fluid seal and magnetic fluid seal using axially-magnetized slotted ring magnets was greater than the other two structures.

Although the classic structure of the magnetic fluid seal could have a great seal capacity under the condition of small seal gaps, as the sealing gap became larger, the seal capacity decreased more significantly than the other three structures. It can be concluded that the magnetic fluid seal using ring magnets performed better under the condition of large gaps.

It was evident that the classic structure of the magnetic fluid seal exhibited the largest maximal magnetic field strength (H_{max}) in the seal gap and the largest magnetic field strength difference (H_{max}-H_{min}), the reason of which might be that multiple adjacent ring magnets set on the shaft induced magnetic field leakage.

According to the magnetic field distribution of the magnetic fluid seal using axially-magnetized ring magnets and the magnetic fluid seal using axially-magnetized ring magnets with magnetoconductive pole pieces in Fig. 7(b, c), Fig. 8(b, c) and Fig. 9(b, c), we could macroscopically justify the tip effect theory and the formula of permanent magnets in Reference [23] and Equation (3). The seal gap near the edge and the angle of the ring magnet had a large magnetic field strength. The magnetic field strength of the seal gap near the edge and the angle of the ring magnet was quite small. Thereby, we obtained the magnetic field strength difference in the seal gap of the axial direction, which could provide the seal capacity.

Compared with the magnetic fluid seal using axially-magnetized ring magnets and the magnetic fluid seal using radially-magnetized ring magnets, the magnetic fluid seal using axially-magnetized slotted ring magnets could take full advantage of the tip effect of the magnets, which could create more seal stages and greater seal capacity in the same space. We used p/h to express the utilization rate of the seal space. By comparing these three kind of new magnetic fluid seals, it was evident that the axially-magnetized slotted ring magnet was the best.

For magnetic fluid seals, we could improve the seal capacity by adding the amount of ring magnets and pole pieces, whereas meeting the actual working status is more important.

In conclusion, we put forward the design methods of magnetic fluid seal using ring magnets: Regarding the magnetic fluid seal using axially-magnetized ring magnets and the seal using axially-magnetized slotted ring magnets, their ring magnets were installed adjacently on the shaft. In order to obtain larger magnetic field strength difference, the ring magnet thickness should be at least twice thicker than the nonmagnetic ring thickness (i.e. $L_{h1} \geq 2L_{h2}$). Meanwhile, it's also necessary to ensure a sufficient axial width of the rings mentioned above. On the contrary, for the magnetic fluid seal using radially-magnetized ring magnets, the nonmagnetic ring thickness should be at least twice thicker than the ring magnet thickness (i.e. $L_{h2} \geq 2L_{h1}$).

5. Conclusion

By virtue of Maxwell FEA, we obtained the seal capacity of the magnetic fluid seals with different structures. Based on the acquired results, the following conclusions and recommendations are suggested:

In the seal gap, both the magnetic fluid seal using axially-magnetized slotted ring magnets and the magnetic fluid seal using radially-magnetized ring magnets can generate a certain seal capacity.

The magnetic fluid seal using ring magnets performs better under the condition of a large gap.

Compared with the classic magnetic fluid seal, the three types of magnetic fluid seal using ring magnets exhibit the advantages of smaller radial space occupation, wonderful processability, simple installation and high reliability. They can easily solve the existing problems of the classic magnetic fluid seal, such as installation difficulties, vulnerability, poor processability of the classic pole pieces, and poor sealing capacity under large gaps.

For future research directions:1) The aforesaid new structures have to be further verified by experiments. 2) In order to solve the daunting problems of magnetic fluid seals with large gaps, researches in this regard are warranted.

References

[1] Beijing: Science Press. Theory and Application of Magnetic fluid Sealing. D. Li, Beijing (2010) pp 112-113.

[2] Cambridge University Press, Ferrohydrodynamics. Rosensweig R E, Cambridge (1985) pp 38-39.

[3] X. Yang, D. Li, W. Yang, et al. Chinese Journal Journal of Vacuum Science and Technology **32**, 919 (2012).

[4] Szczech, M. Journal of Magnetics **32**, 24 (2019).

[5] Z. Wang, D. Li, Y. Zhang, et al. Tribology Transactions **62** (2019).

[6] Szczech, M. Experimental Studies of Magnetic Fluid Seals and Their Influence on Rolling Bearings[J]. Journal of Magnetics **48**, 25 (2020).

[7] C. Du and H. Lin, Chemical Equipment Technology 71 (2006).

[8] X. Yang and D. Li, Chinese Journal of Vacuum Science and Technology **36**, 258 (2016).

[9] D. Li and W. Yang, Acta Armamentarii **31**, 355 (2010).

[10] Szczech, M. and Horak, W. IEEE Trans. Magn. **53**, 4600601 (2017).

[11] J. Liu, D. Li, and Z. Zhang, Journal of Beijing Jiaotong University **42**, 1 (2021).

[12] van der Wal K, van Ostayen, R. A. J., and Lampaert, S. G. E. Tribol Int. **150**, 106372 (2020).

[13] X. He, D. Li, H. Chinese Journal of Vacuum Science and Technology **34**, 1160 (2014).

[14] Z. Wang, D. Li, and Z. Jing, J. Magn. **22**, 299 (2017).

[15] X. He, Y. Miao, L. Wang, et al. Chinese Journal of Vacuum Science and Technology **39**, 361 (2019).

[16] D. Li and D. Hao, Chinese Journal of Vacuum Science and Technology **38**, 564 (2018).

[17] X. Yang and D. Li, International Journal of Applied Electromagnetics and Mechanics **50** (2016).

[18] Z. Li, S. Li, X. Wang, et al. IEEE Trans. Magn. **57** (2021).

[19] D. Li and D. Hao, Chinese Journal of Vacuum Science and Technology **38**, 564 (2018).

[20] D. Li, H. Xu, X. He, et al. Journal of Magnetism and Magnetic Materials 289 (2004).

[21] M. Yuichi, S. Hiroshi, Y. Hayato, et al. Procedia Manuf. 33 (2015).

[22] E. Luo, College Physics **6**, 20 (1993).

[23] Beihang University Press, Magnetic Fluid Hydrodynamics, C. Chi, et al., Beijing (1993) pp 59-60.

[24] X. Yang, Z. Li, and D. Li, Science China Technological Sciences **56** (2013).

[25] M. Zhao, J. Zou, and J. Hu, J. Magne. Magn. Mater. **303** (2006).

[26] F. Xing and J. Ji, Lubr. Eng. **44**, 87 (2019).