ISSN (Print) 1226-1750
ISSN (Online) 2233-6656
Journal of Magnetics 26(2), 229-237 (2021) https://doi.org/10.4283/JMAG.2021.26.2.229

Structural Optimization of Reciprocating Seal with Magnetic Fluid Based on Orthogonal Test Design

Xiaolong Yang[1]*, Gang Liu[1,2], You Li[1], and Shanghan Gao[1]

[1]*School of Mechanical and Transportation Engineering, Guangxi University of Science and Technology, Liuzhou 545006, China*
[2]*Guangxi Earthmoving Machinery Collaborative Innovation Center, Liuzhou 545006, China*

(Received 25 March 2021, Received in final form 21 June 2021, Accepted 29 June 2021)

In order to improve the pressure capability of reciprocating sealing structure with magnetic fluid, the $L_{16}(4^5)$ orthogonal test design and the numerical simulation with the finite element method. were combined to optimize the sealing structure. In the process of orthogonal test design, five factors, four levels and the corresponding orthogonal table were selected. The magnetic field distribution of each orthogonal test was calculated and analyzed by finite element method. The results of orthogonal test were statistically analyzed by using range analysis and variance analysis and it shows that the simulation result of pressure capability of the optimal scheme is the best result in the test simulation analysis. The results showed that the pressure capability of the optimal scheme is about 0.91 MPa higher than that of the initial reciprocating seal with magnetic fluid.

Keywords : magnetic fluid, reciprocating seal, orthogonal test design, numerical simulation

1. Introduction

The hydraulic cylinder of construction machinery is a kind of hydraulic actuator which transforms hydraulic energy into mechanical energy and makes linear reciprocating motion or swing motion [1]. The leakage of hydraulic oil is a key factor affecting the working efficiency and working life of hydraulic cylinder. Therefore, it is of great significance to solve the leakage problem of hydraulic cylinder for improving the working lifetime and efficiency of hydraulic cylinder. With the improvement of hydraulic cylinder technology in construction machinery, the traditional sealing materials and sealing technology can not meet the requirements of high-performance sealing. Magnetic fluid seal has good tightness, long lifetime, no wear, high reliability, high performance and high adaptability, which can meet the sealing requirements of most equipment [2-4]. S. Mijak [5] concluded that magnetic fluid affects the pressure capability of reciprocating seal because of the deformation of the magnetic fluid, and magnetic fluid which is consumed during the operation of the reciprocating shaft. In order to increase the critical pressure value of the hydraulic cylinder seal of construction machinery, Yang *et al.* optimized the existing structure of reciprocating seal with magnetic fluid for hydraulic cylinder [6], so as to improve the pressure capability of reciprocating sealing structure with magnetic fluid for hydraulic cylinder , reduce the leakage of the magnetic fluid and the vibration caused by the impact. Marcin Szczech *et al.* [7] studied the effect of radial clearance on the magnetic field distribution and Saurabh Parmar[8] studied the effect of magnetic pole series on the pressure capability of magnetic fluid seal through experiments. Saurabh Parmar [9] analyzed and calculated different pole tooth shapes to improve the pressure capability of the sealing device. The researches on improving the pressure capability of reciprocating seal structure with magnetic fluid through single factor are limited, Single-factor optimization only optimizes one factor. This method can only be applied to make it clear that there is no interaction between the factors. Once there is an interaction between various factors, using this method is often to draw inaccurate conclusions. But the method of multi-factor analysis to improve the pressure capability of the sealing structure has not been reported.

Effects of the number of magnetic sources, the height of sealing clearance, the length of pole teeth, the ratio of internal and external diameter difference to thickness of permanent magnet, and the ratio of pole shoe height to shaft radius on the reciprocating seals are studied in this

*Corresponding author: Tel: +86-18307721513
Fax: +18307721513, e-mail: 09116324@bjtu.edu.cn

paper [10]. The sensitive change range is selected and four levels are determined. Through the orthogonal test design, the pressure value of reciprocating seal structure with magnetic fluid has been greatly improved.

2. Theory of Magnetic Fluid Reciprocating Seal

In general, Bernoulli equation of motion of magnetic fluid can be expressed by the following formula (1) [11]

$$p+\frac{1}{2}\rho \upsilon^2+\rho_m gh-\int_0^B MdH=\Phi(t) \quad (1)$$

Where p is the overall internal pressure of magnetic fluid; h, ρ_m, υ and M are the height, density, velocity and magnetization of the magnetic fluid from the horizontal reference plane; g is the acceleration of gravity; μ_0 is the vacuum permeability; H is the external magnetic field strength; $\Phi(t)$ is a constant.

The magnetic fluid loss occurs when the piston rod is reciprocating. The calculation formula of the magnetic fluid consumption in the plane clearance is as follows (2) [12]:

$$\mathrm{Q}=0.66\mathrm{D}\,\nu_0\left(\frac{\eta \nu_0}{\sigma}\right)^{\frac{2}{3}} \quad (2)$$

Where Q is the consumption of magnetic fluid; D is the diameter; η is the dynamic viscosity of magnetic fluid; ν_0 is the motion speed of reciprocating shaft; σ is the surface tension of magnetic fluid.

When the magnetic fluid is flowing at a certain speed, the mathematical model of the pressure resistance of the reciprocating shaft dynamic seal can be studied. Under the condition that the velocity of the magnetic liquid is slow enough, the laminar flow equation of the magnetic liquid on the free surface can approximate the Stokes equation and the consumption of the magnetic liquid can be approximated. The magnetic liquid film in the sealing clearance moves from the beginning to the stable position, as shown in the dotted line in Fig. 1.

After derivation, the total sealing pressure capability of the reciprocating seal with magnetic fluid is expressed as [13]

$$p_h-p_0=[H(x_C)-H(x_B)]\mu_0 M_S + 6\eta\nu\left\{\frac{1}{\mathrm{h}_\mathrm{C}^2}x_C-\frac{1}{[0.66h_C(\frac{\eta\nu}{\sigma})^{\frac{2}{3}}]^2}x_B\right\} \quad (3)$$

Where p_h is the pressure on the high pressure side; p_0 is the pressure on the low pressure side or atmospheric side; x_C is the coordinate of point C, x_B is the coordinate of point B; $H(x_C)$ is the magnetic field strength of the point x_C; $H(x_B)$ is the magnetic field strength of the point x_B; μ_0 is the permeability in the air; M_S is the saturation magnetization of the magnetic fluid; η is the dynamic viscosity of the magnetic fluid; υ is the motion speed of the reciprocating shaft; h_c is the thickness of magnetic fluid film corresponding to point C, and σ is the surface tension of magnetic fluid.

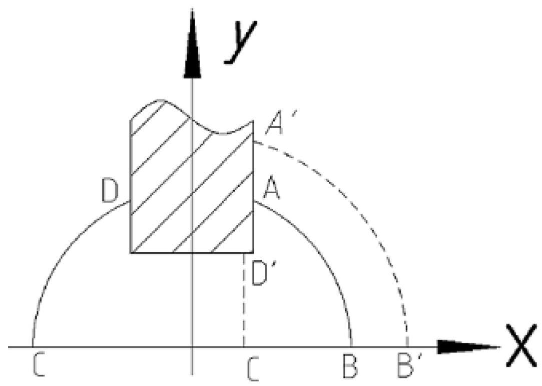


Fig. 1. Model of reciprocating seal with magnetic fluid.

By simulating the magnetic field, the magnetic induction intensity distribution in the sealing gap is obtained, It can complete the acquisition of $H(x_C)$ and $H(x_B)$ of each pole tooth. Assuming that the amount of magnetic fluid injected is sufficient, the movement speed υ of the reciprocating axis moves at a low speed and magnetorheological fluid is selected. In this formula, η is determined; σ, h_c, x_c and x_c are related to the pole tooth parameters and the sealing gap. Finally, the pressure difference of the reciprocating magnetic fluid seal structure can be calculated by calculating the pressure difference on both sides of each pole tooth and summing it up.

3. Structure Design of Reciprocating Seal with Magnetic Fluid

The 2D plane symmetry model of the designed reciprocating sealing structure with magnetic fluid is shown in Fig. 2. 2D plane symmetry model is a plane figure drawn in two dimensions with a symmetrical structure. Through magnetic circuit design, the reciprocating sealing structure parameters of magnetic fluid is shown in Table 1.

According to the geometric parameters of reciprocating seal with magnetic fluid shown in Table 1, the model as shown in Fig. 3(a) is established in ANSYS.

In this model, A1 are the magnetic axis and pole shoe, A2 and A3 are permanent magnets, A4 is air. The magnetic axis and pole shoe are made of 45 steel, and the permanent magnet material is NdFeB, the remanence B_r =

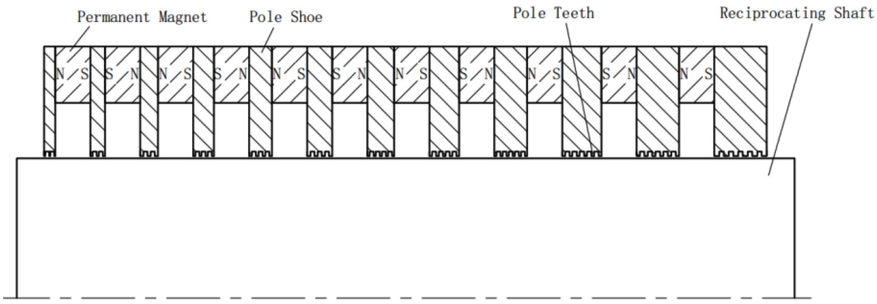


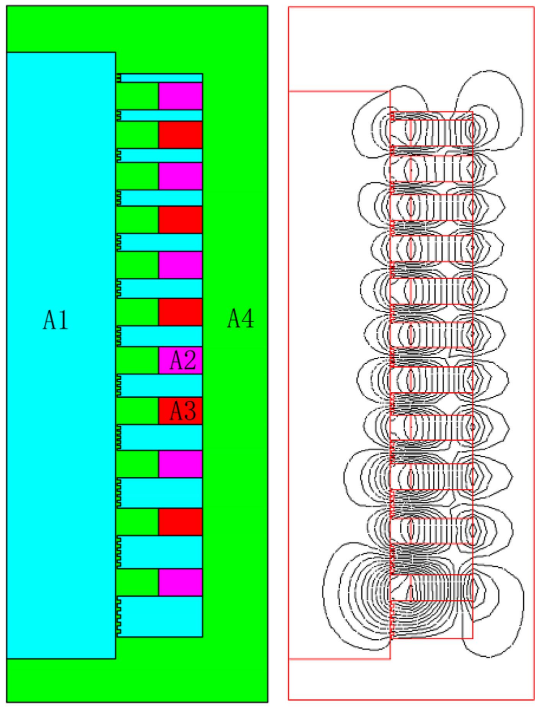
Fig. 2. Two dimensional plane symmetry model of reciprocating sealing structure with magnetic fluid.

Table 1. Geometric parameters of sealing structure.

Parameters	Sizes
Pole teeth on pole shoes (number)	3/4/5/6
Inner radius of pole shoe (mm)	25.1
Outer radius of pole shoe (mm)	45
Axial width of polar teeth (mm)	0.2/0.4/0.5/0.6/0.9
Groove depth (mm)	0.6/0.7/0.8/0.9
Lengths of permanent magnet (mm)	6.3/7.6/8.8/10.1
Sealing clearance (mm)	0.1/0.2/0.3/0.4
Groove width (mm)	0.7/0.8
Axis radius (mm)	25

1.05 T, the coercivity $H_c = 1.35\times10^6$ A/m, the magnetic fluid is selected as the MRF, its saturation magnetization is 3.07×10^5 A/m. In ANSYS, the grid is selected intelligently and the accuracy of the grid is set to 1. The grid makes the accuracy value reach the highest so that the magnetic field results of the sealing gap can be calculated well. The pole teeth must be very precise.So the grid is divided into quadrilaterals. After the mesh is divided, the boundary conditions of the magnetic field lines parallel to the physical model are further loaded. After waiting for the completion of all the previous work, it is necessary to conduct a static analysis of the magnetic field to check whether the results of the static analysis have converged. If the result is convergent, the result of static analysis is correct. The magnetic induction intensity and magnetic field intensity on the path can be calculated at this time.

It can be seen from Fig. 3(b) that the magnetic line of force of air is the thinnest, which is caused by magnetic flux leakage. The magnetic lines of force in the pole teeth part are the densest, and the force lines of the sealing clearance between the pole teeth and the shaft under the middle pole shoe are more dense than those of the pole shoes on both sides. The reason is that the middle pole shoe is affected by two permanent magnets, while the pole shoe on the both sides is only affected by a single permanent magnet. The magnetic line of force at the pole teeth part of the pole shoe is relatively concentrated, and most of the lines pass through the pole tooth, which can increase the magnetic gathering ability of the pole shoe, increase the gradient difference of the magnetic field, ensure that the magnetic fluid works under a large magnetic field gradient difference, resist the differential pressure on both sides of the sealing device, and finally achieve a good sealing effect.



(a) (b)

Fig. 3. (Color online) Structure diagram (a) of magnetic fluid reciprocating seal with incremental type of teeth width pole shoe and magnetic line distribution diagram (b).

4. Orthogonal Test Design of Reciprocating Sealing Structure with Magnetic Fluid

4.1. Orthogonal test design of reciprocating sealing structure with magnetic fluid

Orthogonal test design is a method of scientifically arranging and analyzing multi-factor tests by using orthogonal table [14]. The main steps of orthogonal test are as follows:

4.1.1. Define the purpose of the test and determine the test index

The purpose of this orthogonal test is to solve the problem of insufficient pressure capability of reciprocating sealing structure with magnetic fluid for the hydraulic cylinder of construction machinery, and to find the optimal structure size of the device. The quantitative index of this test refers to the pressure value of reciprocating sealing structure with magnetic fluid.

4.1.2. Select the factors and determine the level

According to the experience [6], five factors that affect the pressure capability of the reciprocating seal with magnetic fluid are selected: the number of magnetic sources, the height of sealing clearance, the length of pole teeth, the ratio of internal and external diameter difference to thickness of permanent magnet, and the ratio of pole shoe height to shaft radius.

In this experiment, the five parameters are taken as the research factors, and four levels are selected, as shown in Table 2.

4.1.3. Select the orthogonal table and design the header

Since this article is an orthogonal experiment analysis through simulation, this article does not introduce empty columns as error columns. According to the number of factors and levels to select the appropriate orthogonal table. There are five factors and four levels in this orthogonal test, and the orthogonal table meeting the requirements is the table $L_{16}(4^5)$.

The head design is because it is difficult to change the level number of factor A, so the number of magnetic sources is put in the first column, the ratio of pole shoe height to shaft radius is placed in the last column, and the sealing clearance height, the length of pole teeth, and the ratio of internal and external diameter difference to thickness of permanent magnet are placed in the second, third and fourth columns. The test scheme is shown in Table 3.

Table 3. $L_{16}(4^5)$ orthogonal table.

Test number	A	B	C	D	E
1	1	1	1	1	1
2	1	2	2	2	2
3	1	3	3	3	3
4	1	4	4	4	4
5	2	1	2	3	4
6	2	2	1	4	3
7	2	3	4	1	2
8	2	4	3	2	1
9	3	1	3	4	2
10	3	2	4	3	1
11	3	3	1	2	4
12	3	4	2	1	3
13	4	1	4	2	3
14	4	2	3	1	4
15	4	3	2	4	1
16	4	4	1	3	2

4.1.4. Clear the test scheme, carry out the test, and get the results

According to the orthogonal table and the head design, each test scheme is determined, carry out the test, and the results of the test index form of the structure pressure resistance value are obtained.

4.2. Finite element analysis of magnetic field based on orthogonal test design

Put them in the same group according to the factors that are difficult to change the number of levels, so the test schemes with the same number of magnetic sources are put into the same group. In ANSYS finite element software, according to 16 groups of orthogonal table tests, the model is established, and the curve of clearance flux density is analyzed. The curves of magnetic induction strength are shown in Fig. 4(a), (b), (c) and (d).

Table 2. Test factors and levels.

Level	(A) the numbers of magnetic sources/number	(B) the heights of sealing clearance/mm	(C) the lengths of pole teeth/mm	(D) the ratios of internal and external diameter difference to thickness of permanent magnet	(E) the ratios of pole shoe height to shaft radius
1	8	0.1	0.6	1.0	0.6
2	9	0.2	0.7	1.2	0.8
3	10	0.3	0.8	1.4	1.0
4	11	0.4	0.9	1.6	1.2

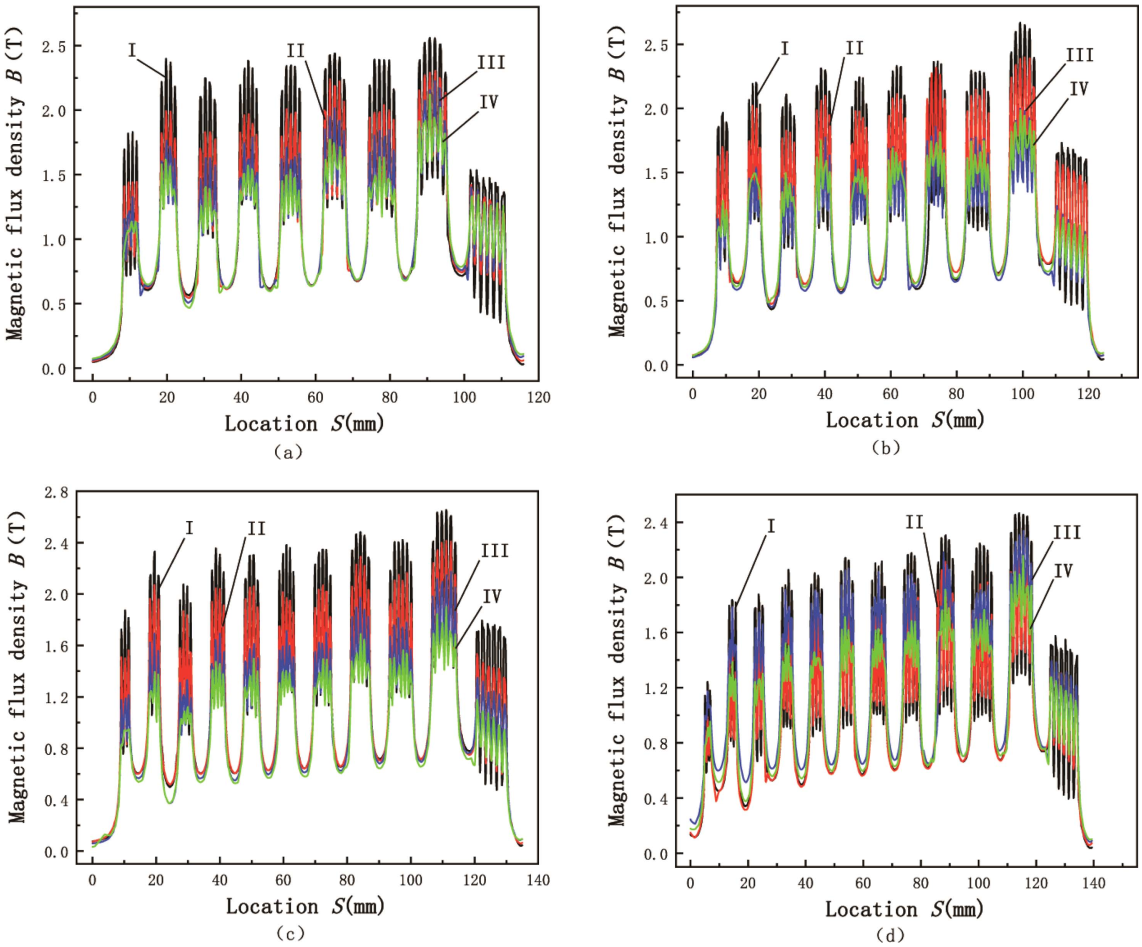


Fig. 4. (Color online) Magnetic field distribution of 16 groups of tests. (a) the curve of magnetic induction strength with Test No. 1-4; (b) the curve of magnetic induction strength with Test No. 5-8; (c) The curve of magnetic induction strength with Test No. 9-12; (d) the curve of magnetic induction strength with test No. 13-16.

From Fig. 4(a), (b), (c) and (d), it can be seen that with the increase of the number of magnetic sources, the total flux density will increase, and the magnetic energy provided will also increase due to the increase in the number of magnetic sources. In addition, in each curve of magnetic induction strength, with the increase of the test numbers, the magnetic induction strength decreases. The main reason is that the sealing clearance of factor B increases gradually.

According to the curve of magnetic induction strength shown in Fig. 4(a), (b), (c) and (d) and the theoretical formula of reciprocating sealing with magnetic fluid pressure resistance, the sealing pressure resistance value X_i corresponding to test No. 1 to test No. 16 is calculated.

In order to study the effect of different factors of the same magnetic source clearance on the sealing pressure resistance value X_i, the serial numbers with the same number of magnetic sources are put together for research, as shown in Fig. 5(a), (b), (c) and (d). From Fig. 5(a), (b), (c) and (d), with the increase of the number of magnetic sources, the pressure capability of the sealing structure will also be improved under the condition of the same sealing clearance height. This is due to the increase of the number of magnetic sources, the magnetic energy of the sealing structure is also increased. When the number of magnetic sources is the same, the increase of sealing clearance height will make the pressure resistance value of reciprocating seal with magnetic fluid structure decrease. This is because the same number of magnetic sources provides the same magnetic energy, the height of the sealing clearance increases, the magnetic resistance of the magnetic circuit increases, and the magnetic energy consumption of the sealing clearance increases, which leads to the decrease of the final structural pressure resistance value.

The pressure resistance values of 16 groups of orthogonal test schemes are filled in the index column of orthogonal test indexes. The test results are shown in

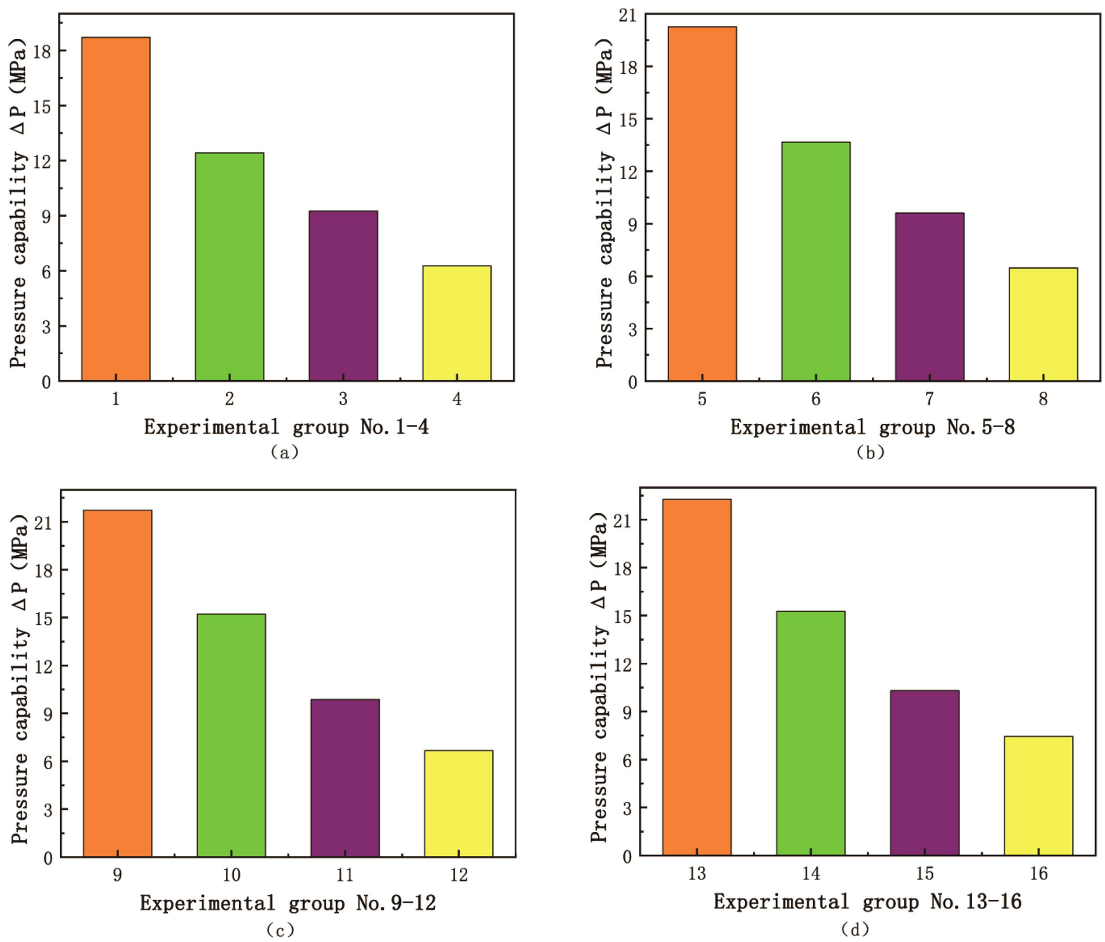


Fig. 5. (Color online) Pressure resistance values of 16 groups of tests, (a) the pressure resistance values of Test No. 1-4; (b) the pressure resistance values of Test No. 5-8; (c) the pressure resistance values of Test No. 9-12; (d) the pressure resistance values of Test No. 13-16.

Table 4. Index results of orthogonal test.

Test number	A	B	C	D	E	Pressure resistance value X_i/MPa
1	1	1	1	1	1	18.7127
2	1	2	2	2	2	12.4174
3	1	3	3	3	3	9.2572
4	1	4	4	4	4	6.2723
5	2	1	2	3	4	20.2685
6	2	2	1	4	3	13.6703
7	2	3	4	1	2	9.612
8	2	4	3	2	1	6.4739
9	3	1	3	4	2	21.7419
10	3	2	4	3	1	15.2172
11	3	3	1	2	4	9.8686
12	3	4	2	1	3	6.674
13	4	1	4	2	3	22.2748
14	4	2	3	1	4	15.2763
15	4	3	2	4	1	10.3215
16	4	4	1	3	2	7.4538

Table 4. It can be seen from Table 4 that each test number corresponds to a combined test scheme. The orthogonal test design is only part of the experiment, which can not guarantee that the optimal result of the orthogonal test design can be obtained in the global optimization. Therefore, it is necessary to evaluate the indexes of orthogonal test.

5. Results and Discussion

5.1. Range analysis

Range analysis and variance analysis are usually used to analyze the results of orthogonal test. The advantage of range analysis of orthogonal test design is simple and easy to understand. Range analysis gives accurate quantitative estimation of the significance of factors.

In order to make up for the deficiency of visual analysis, analysis of variance can be used. The range analysis is carried out through the calculation formula,

Table 5. Range analysis of orthogonal test.

Index		A	B	C	D	E
Pressure resistance value X_i/MPa	K1	46.6596	82.9979	49.7054	50.275	50.7253
	K2	50.0247	56.5812	49.6814	51.0347	51.2251
	K3	53.5017	39.0593	52.7493	52.1967	51.8763
	K4	55.3264	26.874	53.3763	52.006	51.6857
	k1	11.6649	20.74948	12.42635	12.56875	12.68133
	k2	12.50618	14.1453	12.42035	12.75868	12.80628
	k3	13.37543	9.764825	13.18733	13.04918	12.96908
	k4	13.8316	6.7185	13.34408	13.0015	12.92143
	Excellent level	4	1	4	3	3
	range R	8.6668	56.1239	3.6949	1.9217	1.151
	Primary and secondary order			BACDE		
	Optimization scheme			$B_1A_4C_4D_3E_3$		

and the range analysis results are shown in Table 5.

The larger the range *R* corresponding to the factor is, the greater the effect of the factor on the pressure resistance value of reciprocating sealing structure with magnetic fluid is. Therefore, the sealing clearance height of factor *B* has the largest impact on the pressure resistance value.

Comparing the *R* values of these five factors, we can know that $R_B > R_A > R_C > R_E > R_D$, so the order of effects of factors on the indexes of orthogonal test is: BACED.

In order to show the result of range analysis more intuitively, the trend chart of each factor and index is drawn. The horizontal number of factors is taken as the abscissa and K_i as the ordinate. The test indexes corresponding to factors A, B, C, D and E are shown in (a), (b), (c), (d) and (e) in Fig. 6.

The larger the excellent level K_i corresponding to the factors is, the greater the effect of the corresponding factors on the pressure resistance value of the sealing structure is.

Through the trend chart, it is very obvious to know the number of excellent level of each factor. The excellent level of factor A is 4, that of factor B is 1, that of factor C is 4, that of factor D is 3, and that of factor E is 3.

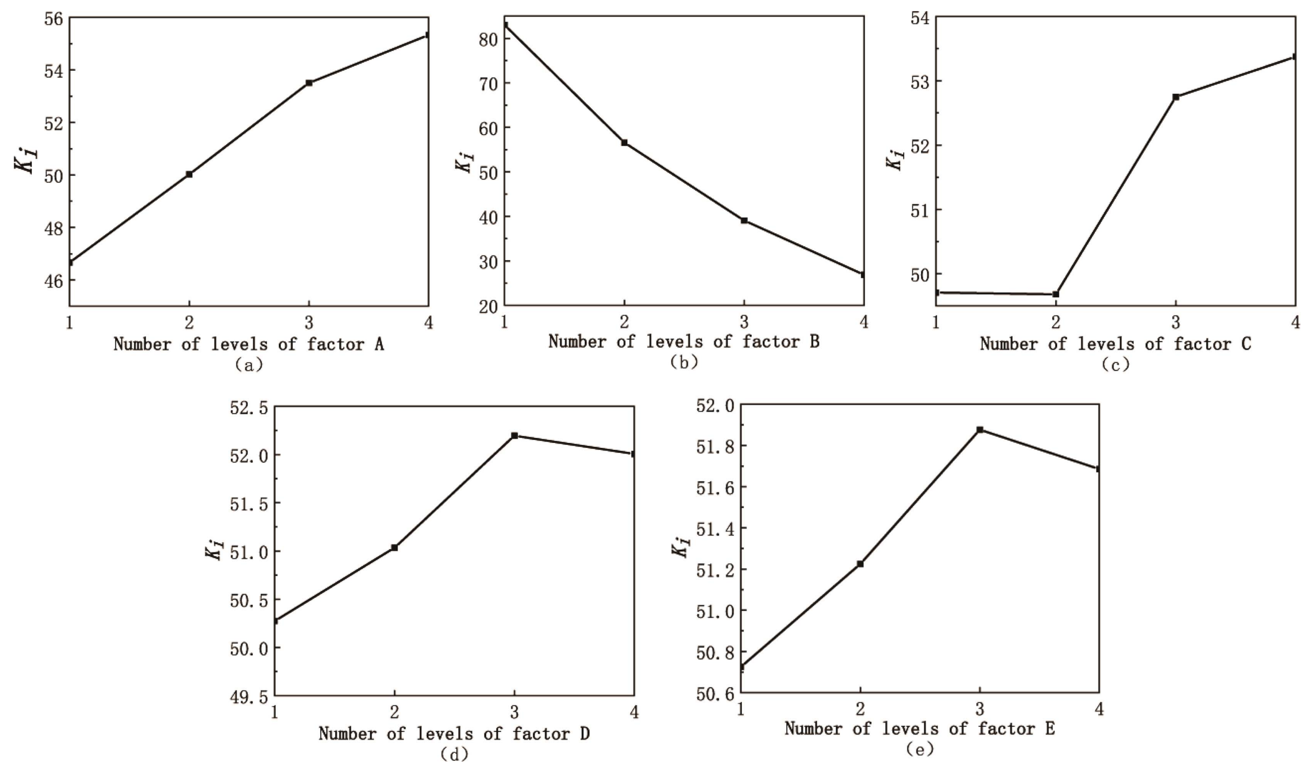


Fig. 6. Trend chart of each factor and index in orthogonal test.

Table 6. Variance analysis of orthogonal test.

Source of difference	Sum of squares of deviations *SS*	Degree of freedom *df*	Mean square *MS*	*F* value	F_α	Significance
factor A	11.04867	3	3.68289	55.77476		High significance
factor B	444.7719	3	148.2573	2245.252	$F_{0.05}(3,3) = 9.2766$	High significance
factor C	2.887427	3	0.962476	14.57601	$F_{0.01}(3,3) = 29.4567$	Significance
factor D	0.599779	3	0.199926	3.027744		
sum	459.5059	15				

Through the primary and secondary order of the effects of factors on the indexes of orthogonal test and the number of excellent levels of each factor, the optimal combination of various factors of the structure of magnetic fluid reciprocating seal can be obtained, i.e. $B_1A_4C_4D_3E_3$.

5.2. Analysis of variance

The advantage of range analysis of orthogonal test design is simple and easy to understand, but range analysis can not give accurate quantitative estimation of the effect of factors. In order to make up for the deficiency of visual analysis, analysis of variance was used. The variance analysis table of orthogonal test of reciprocating sealing structure with magnetic fluid is shown in Table 6.

Through the calculation formula of variance, the sum of square deviation SS, degree of freedom df, mean square *MS* and *F* value of each factor are calculated, The critical value $F_{0.05}(3,3) = 9.2766$, $F_{0.01}(3,3) = 29.4567$ was found by F-test, for a given level of significance $\alpha = 0.05$, factors A and B have a very significant effect on the test results, factor C has a significant impact on the test results, and factors D and E have no significant impact on the test results. This shows that the number of magnetic sources of factor A and the sealing clearance height of factor B have a great effect on the pressure capability of reciprocating sealing structure with magnetic fluid, and the pole teeth length of factor C has a greater effect on the pressure capability of reciprocating seal structure with magnetic fluid, the ratio of internal and external diameter difference to thickness of permanent magnet with D factor and the ratio of pole shoe height to shaft radius of factor E have certain effects on the pressure capability of reciprocating sealing structure with magnetic fluid.

5.3. Effects of structure before and after optimizing on sealing pressure capability

According to the results of orthogonal test design, the optimal combination of reciprocating sealing structure with magnetic fluid is $B_1A_4C_4D_3E_3$. The corresponding specific parameters are as follows: There are 11 magnetic sources, the sealing clearance height is 0.1 mm, the pole tooth length is 0.9 mm, the ratio of internal and external diameter difference to thickness of permanent magnet is 1.4, the ratio of pole shoe height to shaft radius is 1.0. In ANSYS software, the finite element analysis in magnetic field is carried out on the structure before and after optimizing, and the magnetic induction strength curve of the original structure and the optimized structure is obtained, as shown in Fig. 7(a).

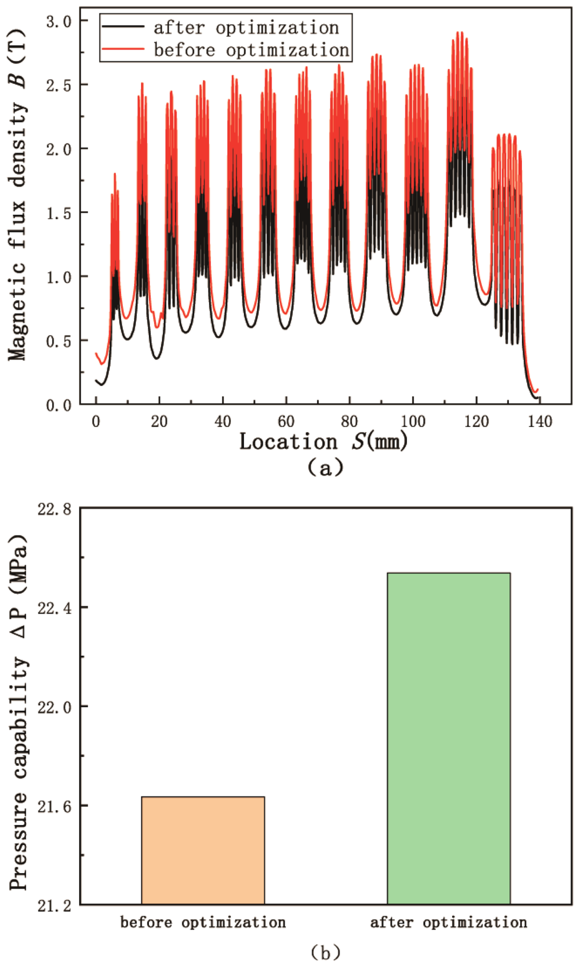


Fig. 7. (Color online) (a) Curve of magnetic induction strength before and after structure optimizing, (b) Pressure value of magnetic fluid seal before and after structure optimizing.

According to the pressure resistance formula of the reciprocating sealing structure with magnetic fluid, the pressure resistance value X_i of the sealing structure is calculated, and the results are shown in Fig. 7(b).

It can be seen from Fig. 7(a) that the difference between the lowest point and the highest point of magnetic induction strength after structure optimizing has been significantly improved. When the number of magnetic sources is 11, the effect of permanent magnet on pole shoe is basically the same; when the height of sealing clearance is 0.1 mm, the magnetic resistance in the magnetic circuit is basically unchanged; When the length of pole teeth increases to 0.9 mm, the gradient difference of magnetic field increases obviously, and the effect of magnetic concentration of pole teeth is improved; When the ratio of internal and external diameter difference to thickness of permanent magnet increases to 1.4, the magnetic energy increases; when the ratio of pole shoe height to shaft radius becomes 1.0, the maximum magnetic energy product can be obtained in the magnetic circuit.

According to Fig. 7(b), the pressure resistance value of the reciprocating sealing structure with magnetic fluid before optimizing is about 21.63 MPa, and after optimizing it is about 22.54 MPa. The optimized results obtained by orthogonal test design, which make the pressure resistance value of the initial sealing structure increase by about 0.91 MPa. The main reason is that the increase of the length of the pole teeth makes the magnetic gathering effect of the pole teeth increase, and the magnetic induction strength difference becomes larger. According to the theory of pressure resistance, the greater the sealing pressure resistance is when the magnetic saturation strength of the magnetic fluid is certain, the difference of magnetic induction strength increases.

6. Conclusion

In order to improve the pressure capability of the reciprocating sealing structure with magnetic fluid, the $L_{16}(4^5)$ orthogonal test design was used to optimize the reciprocating sealing structure, and the pressure resistance value of the reciprocating sealing structure with magnetic fluid was increased by 0.91 MPa. According to the variance analysis of the orthogonal test, it can be clearly shown that the number of magnetic sources and the height of sealing clearance have a very significant impact on the pressure resistance value of the reciprocating sealing structure with magnetic fluid. The length of the pole teeth also has a significant impact on the capability of sealing structure. The ratio of the internal and external diameter difference to the thickness of the permanent magnet and the ratio of the pole shoe height to the shaft radius have a smaller impact on the capability of sealing structure.

Acknowledgements

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. 2020GXNSFAA159042), and the support of the Science and Technology Project of LiuZhou (Grant No. 2017BC20204), and the support of Innovation Project of GuangXi University of Science and Technology Graduate Education (Grant No. GKYC202111).

References

[1] Z. Y. Quan and L. Quan, Renewable & Sustainable Energy Reviews. **35**, 336 (2014).
[2] D. Y. Kim and H. S. Bae, International Journal of Applied Electromagnetics and Mechanics **33**, 857 (2010).
[3] Y. Mitamura, S. Takahashi, K. Kano, E. Okamoto, S. Murabayashi, I. Nishimura, and T. Higuchi, Artif Organs. **33**, 770 (2009).
[4] M. Szczech, Journal of Magnetics **25**, 48 (2020).
[5] S. Mijak, ASLE Transactions **28**, 56 (1985).
[6] X. L. Yang, F. X. Hao, and P. Sun, Journal of Magnetics **25**, 190 (2020).
[7] M. Szczech, Transactions of the Society for Modeling and Simulation International **96**, 403 (2020).
[8] S. Parmar, V. Ramani, R. V. Upadhyay, and K. Parekh, Vacuum. **156**, 325 (2018).
[9] S. Parmar, V. Ramani, R. V. Upadhyay, and K. Parekh, Vacuum. **172**, (2020).
[10] Z. Wang and D. C. Li, International Journal of Applied Electromagnetics and Mechanics **48**,101 (2015).
[11] M. J. Li and R. P. Zhang, Magnetohydrostatics, Science Press, Beijing (2018) pp 41.
[12] D. C. Li, Theory and Application of Magnetic Liquid Seal, Science Press, Beijing (2010) pp. 229.
[13] J. C. Tang and G. C. Gong, Applied Energy **169**, 696 (2016).
[14] Y. Y. Li and C. R. Hu, Experiment design and data processing, Chemical Industry Press, Beijing (2017) pp 153.