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A finite element analysis of the impact of split pole shoes on magnetic liquid sealing performance

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Abstract

Though split pole shoe can solve the problems of increased cost and decreased efficiency caused by replacing pole shoes in the test, assembling and use of split sealing devices, it fails to overcome the issue of sealing in the gap between split pole shoe's junction surface and shaft. In this paper, a split magnetic liquid sealing structure is designed, combining magnetic liquid sealing and split pole shoe's plane sealing. In our study, we have adopted three methods for split sealing and use theory and simulation to ascertain the sealing performance of the split magnetic liquid sealing structure designed by us. The results indicate that magnetic sealant bonded split pole shoes show better sealing performance as compared to those bonded by ordinary sealant, and that the structural optimisation results can meet the requirement for sealing performance. The simulation results coincide with theoretical results, which proves the correctness of this research.

Keywords: Split magnetic liquid sealing, split pole shoe, magnetic sealant, sealing performance, finite element analysis

Split magnetic liquid sealing technology is a new sealing technique of our laboratory, with such merits as compatible with magnetic liquid, zero leakage, long service life, high reliability, no pollution, self recovery ability, simple structure and so on [1, 2]. Based on these, pole shoe is designed as a split structure to solve the problems of increased cost and decreased efficiency caused by replacing pole shoe in the test, assembling and use of sealing device. However, this also causes the problem of sealing between the gap of split shoe's junction surface and the axial clearance. This paper uses theoretical and simulation methods to ascertain the solution for sealing of split magnetic liquid sealing structures, which combine magnetic liquid sealing and split pole shoe's plane sealing. The study is of high practical and economic value.

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The concept of split sealing was proposed by American scholar Kosatka as early as in 1951, who invented a split sealing structure for oil seal of the rear main bearing of internal combustion engines to prevent oil from escaping from the engine crankshaft and to reduce installation and dismantling cost [3]. In 1963, Washburn designed a cable sealing device, especially for control cables that pass through firewall or bulkhead seal, aiming to avoid flamethrough and resultant fires. This design is for astronautic use, enabling replacement of wire or cable system modules at a lower cost without dismantling the intact sealing element [4]. In 2000, to solve the contact plane seal of two semicircle cylinder walls of split cylinder, Pow invented a dentate structure, which achieved better positioning and radial sealing [5]. Huitao made a theoretical study and simulation of the shell's plane seal in the case wherein pole shoe is not split in a split seal, but did not investigate its pressure-resistance under split pole shoe [6, 7]. Decai [8, 9] went into the rotary seal theory of magnetic liquid under large gap, used magnetic liquid in reciprocating seal and designed and improved the seal structure [10]. Nevertheless, it is rarely seen that split pole shoe is combined with rotary seal of magnetic liquid. Thus, based on previous researches, this paper adopts three split pole shoe methods and studies the seal of split pole shoe from theory and simulation.

1 Theoretical analysis of split pole shoe seal

In this paper, three methods are used to seal split pole shoe; the first two methods use ordinary and magnetic sealant to bond split pole shoe, whereas the third method still uses magnetic sealant but further makes an improvement to the structure of split pole shoe. The resultant sealing pressure resistance of split pole shoe is studied theoretically. Traditional magnetic liquid seal structure often uses non-split pole shoe made of 2Cr13 with good magnetic permeability. Consequent to good magnetic permeability, very small reluctance exists at pole shoe and can usually be ignored. However, regarding the proposed split pole shoe structure, due to ordinary or magnetic sealant applied on joint surface of two sections of pole shoe, the relative magnetic permeability of its sealant is far less than that of 2Cr13, and thus the reluctance is larger at pole shoe and cannot be ignored.

1.1 Equivalent magnetic circuit of three sealing methods of split pole shoe

Figures 1 and 2 show the radial and axial section diagrams of split magnetic liquid seal structure combining magnetic liquid rotary seal with split pole shoe's plane seal. Figure 3 is the axial section diagram of optimised seal structure based on Figures 1 and 2.

Fig. 1 Radial section diagram of seal structure.

In Figures 2 and 3, the magnetic loop consists of permanent magnet, pole shoe, magnetic liquid and shaft. Permanent magnet, as the magnetic source of the entire magnetic loop, provides magnetic flux to restrain magnetic liquid in the gap between pole shoe and half-shell, and magnetic liquid can resist pressure difference from both sides under the action of magnetic field force, so as to achieve sealing [11]. As the pole shoe is split, the junction surface of the two sections is bonded by ordinary or magnetic sealant, and therefore its relative

Fig. 2 Axial sectional drawing of seal structure.

magnetic permeability is far less than that of pole shoe material, equivalent to a magnetic shielded ring with the same thickness as pole shoe. See equivalent magnetic circuit in Figures 4 and 5. In Figure 4, R_m is reluctance of permanent magnet, R_{j1} and R_{j2} are reluctance of split pole shoe, and R_{g1} , R_{g2} , R_{gn} , $R_{g1'}$, $R_{g2'}$ and $R_{gn'}$ are reluctance of magnetic liquid at each pole teeth of seal gap, and F_c is magnetomotive force. In Figure 5, R_{j1} , R_{j2} , R_{j3} and R_{j4} represent the reluctance at split pole shoe, and R_{g1} , R_{g2} , R_{g3} and R_{g4} represent the total reluctance at each pole shoe seal gap, where the number of reluctance depends on the number of pole teeth of main shaft, and reluctance are connected in parallel. The magnetic permeability of permanent magnet is μ_m , B_r is remanence, H_c is coercivity, l_m is magnet thickness, and $R_m = \frac{l_m}{\mu_m S_m} = \frac{l_m H_c}{B_r S_m}$.

Fig. 3 Axial section diagram of optimised seal structure.

1.2 Theoretical calculation of sealing performance of split pole shoe

Theoretical research is the basis of experimental study. Without support of theory, all study is meaningless. This section studies the pressure resistance theory of split pole shoe and provides the foundation for follow-up sections, to ensure research correctness and significance.

An approximate calculation is made on the pressure resistance of static seal of magnetic sealant under the action of magnetic field; the formula is [12, 13]

$$\Delta p_m = \mu_0 M_s \sum_{i=1}^N (H_{\max}^i - H_{\min}^i) = M_s \sum_{i=1}^N (B_{\max}^i - B_{\min}^i) \quad (1.1)$$

Fig. 4 Equivalent magnetic circuit diagram of split pole shoe before structural optimisation.

Fig. 5 Equivalent magnetic circuit diagram of split pole boot structure after optimisation.

in which Δp_m is the theoretical pressure resistance of magnetic sealant under action of magnetic field, μ_i and M are magnetic permeability of vacuum and saturation magnetisation of magnetic sealant, $H_{\max}^i$ and $H_{\min}^i$ are the maximum and minimum magnetic field intensity of seal gap between pole shoe in the i^{th} pole teeth and half-shell of magnetic liquid plane structure, $B_{\max}^i$ and $B_{\min}^i$ are the maximum and minimum magnetic flux density of seal gap between pole shoe in the i^{th} pole teeth and half-shell of magnetic liquid plane structure, and N is the total seal series. From Eq. (1), if total magnetic flux density difference is known, we can get the pressure resistance difference of magnetic liquid plane seal.

According to Kirchhoff's First Law,

$$\sum_i \phi_i = 0 \quad (1.2)$$

i.e., the magnetic flux of each magnetic circuit section in magnetic loop sums up to zero.

$$\sum_i U_{mi} = \sum_k F_{mk} \quad (1.3)$$

in which U_{mi} is the magnetic pressure drop of magnetic field in this section of magnetic circuit, and F_{mk} is the magnetomotive force of magnetic circuit; when $U_{mi} = H_i l_i$, its positive direction is the same as magnetic field direction, and when $F_{mk} = I_k N_k$, its positive direction is the same as current direction.

According to Ohm's Law for magnetic circuit,

$$\phi_m = \frac{NI}{l/\mu_c s} \quad (1.4)$$

in which l is the perimeter of pole shoe in wall, $\mu_c = \mu_0 \times \mu_r$ is magnetic permeability of pole shoe material, μ_r is relative magnetic permeability and s is the area of pole shoe in wall.

Let R be reluctance of magnetic circuit.

$$R = \frac{l}{\mu_c s} \quad (1.5)$$

Simplify magnetic force line around pole tooth as arcs. Let reluctance of middle vertical part be R_1 . S_1 is the area of a single pole tooth. It can be inferred from the reluctance Formula (5) that

$$R_1 = \frac{l_g}{\mu_0 S_1} \quad (1.6)$$

Fig. 6 Magnetic force line model.

In Figure 6, let the reluctance of arc-shaped magnetic force line on both sides be R_2 . L is the length of pole shoe; then we can get

$$dR_2 = \frac{\pi r}{\mu_c dr L} \quad (1.7)$$

Let $t = \int \frac{1}{dR_2}$; then

$$t = \int \frac{1}{dR_2} = \frac{\mu_c L}{\pi} \int \frac{1}{r} dr \quad (1.8)$$

Since R_1 and R_2 are connected in parallel,

$$R_{g1} = \frac{1}{1/R_1 + t} \quad (1.9)$$

As shown in Figure 4, several reluctance connected in parallel have the same structure and size; therefore, their values are equal, i.e., $R_{g1} = R_{g2} = \dots = R_{gn} = R'_{g1} = R'_{g2} = \dots = R'_{gn}$; then

$$R_g = \frac{R_{g1}}{2n} \quad (1.10)$$

and

$$R_j = \frac{l_j}{\mu_j s_j} \quad (1.11)$$

in which R_j is the reluctance of junction surface of split pole shoe, l_j is the thickness of split pole shoe, μ_j is the magnetic permeability of sealant, and s_j is the area of junction surface.

The magnetic flux in magnetic circuit is given by

$$\phi_m = \frac{F_c}{R_m + R_g + R_j} \quad (1.12)$$

Suppose the magnetic flux value ϕ_{pt} is equals in each pole tooth, then we can work out

$$\phi_{pt} = \frac{\phi_m}{2n} \quad (1.13)$$

so that the magnetic flux density B_{pt} at each pole tooth is

$$B_{pt} = \frac{\phi_{pt}}{S_1} \quad (1.14)$$

Substituting Eqs (6)–(14) into Eq. (1), we can ascertain the theoretical pressure resistance at plane seal of split structural magnetic sealant under the action of magnetic field force.

2 Simulation study

See the finite element model in Figures 2 and 3. The properties of material at junction surface change with the material used to bond split pole shoe. The material properties of pole shoe, shaft and pole tooth are defined as 2Cr13, with its B-H curve displayed in Figure 7. Permanent magnet is made of Nd₂Fe₁₄B, with magnetic permeability 1.05 and coercivity 930,000 A/m. On the other hand, magnetic liquid has a very low magnetic permeability, which is almost the same as air, with magnetic permeability 1. Hence, the relative magnetic permeability of magnetic liquid is set as 1, ordinary sealant as 1 due to its being non-magnetic conductive material, and magnetic sealant as 4 because of its magnetic permeability. From the perspectives of the axial section diagram, the weakest seal part between junction surface gap of split pole shoe and shaft gap is simulated, and the simulation results and analysis are as below.

Fig. 7 The magnetisation curve of 2Cr13.

2.1 Simulation study of split pole shoe bonded by ordinary sealant

Ordinary sealant is the most direct way to bond split pole shoe. An analysis on magnetic field number at sealant gap between pole shoe and shaft is made, and the gradient difference of magnetic field intensity in this seal gap is simulated. Substituting into Eq. (1), the maximum simulated pressure resistant property can be obtained.

The distribution of magnetic field lines when ordinary sealant is used to bond the split pole shoes.

In Figure 8, the magnetic field lines distribute in a very thin manner. Beside pole tooth, there are also some closed magnetic field line loops on top of magnet, which indicates a severe magnetic flux leakage. Particularly,

Fig. 8 The distribution of magnetic field lines when ordinary sealant is used to bond the split pole shoes.

there is no magnetic field distribution at pole tooth which is farther from magnet. This suggests that when split pole shoes are bonded by ordinary sealant, the thin sealant is not magnetically permeable, only equivalent to a magnetically shielded ring that is perpendicular to magnetic field direction and is as thick as pole shoe width. Thereby, the magnetic field intensity at the junction gap between sealant and pole tooth is reduced to a large extent.

Distribution of magnetic flux density B in the seal gap between split pole shoes and shaft bonded by ordinary sealant is exported, as shown in Figure 9.

Fig. 9 Distribution of B in the seal gap between pole shoes and shaft using ordinary sealant to bond split pole shoes.

In Figure 9, only at two pole teeth close to magnet is the magnetic flux density higher and the corresponding magnetic field gradient difference larger. The situation is just opposite in other positions, i.e., weaker magnetic flux density and smaller magnetic field gradient difference. After exporting B distribution point value in seal gap, we calculate the sum of all magnetic field gradient differences as 3.45 T, and substitute into Eq. (1) to ascertain the theoretical pressure resistance in seal gap between pole shoe and shaft when using ordinary sealant to bond split pole shoe, which comes out to be 0.6 atmospheric pressure.

2.2 Numerical analysis of magnetic field when using magnetic sealant to bond split pole shoes

In order to solve the seal problem of split pole shoe, magnetic sealant that owns not only magnetism but also air tightness of sealant, is adopted to bond split pole shoe. This extends the application field of magnetic sealant. The distribution of magnetic field lines using magnetic sealant to bind split pole shoes is shown in Figure 10.

Fig. 10 The distribution of magnetic field lines using magnetic sealant to bond the split pole shoes.

Comparing Figures 8 and 10, it is discovered that in Figure 10, the distribution of magnetic field lines is denser, with less closed loops of magnetic field lines appearing on top of magnet. This indicates a decrease of magnetic flux leakage. Especially, the distribution of magnetic field also exists at pole tooth farther from magnet, which indicates that when magnetic sealant is used to bond split pole shoes, the magnetic permeability of the thin magnetic sealant layer is higher than that of air. Compared to nonmagnetic, ordinary sealant, magnetic sealant enhances the magnetic field intensity of junction gap between sealant and pole tooth to a large extent.

Distribution of magnetic flux density B in the seal gap between split pole shoes and shaft in the case when magnetic sealant is used to bond the split pole shoes is exported, as shown in Figure 11.

Fig. 11 Distribution of B in the seal gap between split pole shoes and shaft in the case when magnetic sealant is used to bond the split pole shoes.

Comparing Figures 9 and 11, it is discovered that in Figure 11, the magnetic flux density is increased

significantly. Not only is the magnetic flux density close to magnet pole tooth higher, with larger magnetic field gradient difference, but also the magnetic flux density in other positions is somewhat increased. After exporting B distribution point values in seal gap, we work out the sum of all magnetic field gradient difference as 7.88 T, substitute into Eq. (1) and calculate the theoretical pressure resistance in seal gap between pole shoes and main shaft using magnetic sealant to bond split pole shoe, which comes out to be 1.5 atmospheric pressure.

2.3 Analysis on magnetic field value of optimised split pole shoe structure

To further enhance the magnetic field intensity in seal gap between junction surface of split pole shoe and pole tooth, magnetic sealant is used to bond split pole shoes. In case the number of pole shoes remains unchanged, the thickness of split pole shoe is reduced and two cylinder magnets are added. Under this situation, the distribution of magnetic field values is studied and the pressure resistance of seal gap is worked out.

The distribution of magnetic force lines in seal gap between junction surface of split pole shoes and pole tooth is shown in Figure 12.

Fig. 12 The distribution of magnetic field lines of the split pole shoes for the optimised structure.

Comparing Figures 10 and 12, it is observed that in Figure 12, the distribution of magnetic force lines becomes denser. Due to reduced thickness of split pole shoes, magnetic field distribution exits at every pole tooth farther from magnet. On satisfaction of the condition of same number of pole teeth, and when compared to original two-sectional split pole shoe, this suggests that the use of magnetic sealant reduced pole shoe thickness and that the increase of cylinder magnets can largely enhance the magnetic field intensity in seal gap between sealant and pole tooth.

Distribution of magnetic flux density B in the seal gap between split pole shoes and shaft for split shoes with optimised structure is exported, as shown in Figure 13.

Comparing Figures 11 and 13, it is observed that in Figure 13, there are four groups of regular concave-convex lines corresponding to pole tooth under the four sections of pole shoes. The magnetic flux density is increased significantly, and the position where the magnetic flux density is the highest is at the two split pole shoes in the middle. This is because the seal gap between pole teeth corresponding to the split two pole shoes in the middle is affected by the action of two magnets with opposite N-S poles. After exporting B distribution point values in seal gap, we work out the sum of all magnetic field gradient difference as 16.83 T, substitute into Eq. (1) and calculate the theoretical pressure resistance in seal gap between pole shoes and main shaft using magnetic sealant to bond split pole shoe, which comes out to be 3.3 atmospheric pressure.

Fig. 13 Distribution of B in the seal gap between split pole shoes and shaft for the split pole shoes with optimised structure.

3 Results and analysis

Combined with Eqs (1)–(14), we ascertain the magnetic field intensity in the seal gap when pole shoes are split, and then the theoretical pressure resistance ability of split sealing device, as shown in Figure 14. The calculation parameters are shown in Table 1 [14, 15].

Fig. 14 The comparison of the simulation and theoretical results of pressure resistance for the pole shoes in different conditions.

Figure 14 shows the simulation and theoretical results of pressure resistance in seal gap between pole shoes and shaft in conditions of split pole shoe bonded by ordinary sealant, by magnetic sealant and with optimised structure. From a holistic analysis, we ascertain that the simulation pressure resistance in the gap between pole shoes and shaft for different conditions is less than the theoretical value and it is due to that that the theoretical calculation is an ideal situation, ignoring the magnetic field error and leakage flux caused by the outer film of permanent magnet.

From the perspective of solving the seal of split pole shoe, the simulation and theoretical pressure resistance using magnetic sealant are perceptibly better than the results obtained using ordinary sealant. It can be seen

Table 1 The parameter table for calculating magnetic field intensity in the seal gap of split pole shoe structure.

Parameter	Symbol	Value	Unit
PM coercivity	H_c	930,000	A/m
PM remanence	B_r	1.28	T
PM length	L_m	0.008	M
PM sectional length	L_a	0.314	M
PM sectional height	L_b	0.01	M
Pole shoe's initial teeth width	L_t	0.0002	M
Pole shoe's initial groove width	L_s	0.0008	M
Initial gap	l_g	0.0002	M
Saturation magnetisation of magnetic liquid	M_s	400	G
Permeability of vacuum	μ_0	$4\pi \times 10^{-7}$	T·m/A
Relative magnetic permeability of pole shoes	μ_j	100	
Relative magnetic permeability of ordinary sealant	μ_p	1	
Relative magnetic permeability of magnetic sealant	μ_d	4	
Remark	In theoretical calculation, 1/3 of groove width added with 1/2 of teeth width is taken as the upper limit of integral, and 1/2 of teeth width is taken as the lower limit.		

from Eq. (5) that when pole shoes are split, the relative magnetic permeability of the bonding material at the junction surface is perceptibly lower than that of magnetised steel (2Cr13) material, and is equivalent to a layer of magnetic isolated ring; therefore, the reluctance at pole shoe cannot be ignored in the sealing process. However, the relative magnetic permeability of magnetic sealant is evidently higher than ordinary sealant; therefore, the results obtained using magnetic sealant are better than those for ordinary sealant, as shown in Figure 14.

In Figure 14, the variation tendency of the simulation pressure resistance curve is similar to that of the theoretical pressure resistance curve. Meanwhile, the simulation results coincide with the theoretical results, which verifies the correctness of our theoretical research.

4 Conclusions

1. A split magnetic liquid seal structure is designed, combining magnetic liquid's rotary seal and split pole shoe's plane seal.
2. Three methods are used for split seal, and theoretical and simulation research are conducted on seal of split pole shoe. The seal performance obtained by using magnetic sealant to bond split pole shoe and applying it in split sealing device is far better than using ordinary sealant. After the structure is optimised, the seal performance of sealing device is improved significantly, which solves the seal of split pole shoes in split sealing device.

3. The theoretical and simulation results are identical, which verifies the correctness of our theoretical research.

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