Research on Non-contact Electromagnetic Loading Device for Water-lubricated Bearing

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Abstract. In order to deeply study the characteristics of water-lubricated bearing under load condition, a non-contact electromagnetic loading device is designed to solve the problems of friction, vibration and noise in the traditional contact loading methods such as hydraulic cylinder and weight, etc. The device consists of loading plate, E magnets, coil, programmable dc power supply, first of all, is derived by Maxwell's three laws of the theoretical equation of electromagnetic force, and then, application of Solidworks, Ansoft Maxwell 18.2 software modeling and simulation of electromagnetic loading device structure, the final will be the electromagnetic simulation, comparing the theoretical results, the results show that the simulation and the theoretical value is less than 11.4%, validate the rationality and accuracy of the device.

1. Introduction

The water-lubricated bearing with water as a lubricant can effectively avoid the defects of big pollution and high loss of oil-lubricated bearing, so it is widely used in hydraulic machinery. In recent years, the problem of global resources has become more and more prominent, and the research of water lubricated bearing has become a hot issue. In order to study the characteristics of water-lubricated bearing, it is necessary to simulate its load under real working conditions, so the design of loading device is particularly important.

At present, most water-lubricated bearings use contact loading. For example, Kunsheng Lao, et al. Introduced a test bed for vertical radial loading of bearing by means of vertical loading of hydraulic cylinder. The method combining Ansys Workbench simulation and test was applied to reduce vibration and noise of water-lubricated bearing [1]. Xin Liu, et al. a test bed of loading device with fixed pulley horizontal drag mechanism was designed for high speed water lubricated dynamic pressure spiral groove-bearing [2]. Guofeng Yang etc. set up a test bed for mechanical loading, and transformed the rotary motion conveyed by the motor into the linear motion of the screw nut through ball screw, and analyzed the friction characteristics of water-lubricated rubber bearing under different condition [3]. Wojciech Litwin studied the water-lubricated bearing of three-layer composite material, and provided the bearing with load by generating pressure for water supply to the hydraulic cylinder, and measured the pressure distribution through eight sensors on the bearing housing [4]. Wu Ouyang, et al. studied the characteristics of water-lubricated bearing by using the test bed of hydraulic cylinder...
loading mode. The pressure sensor was installed on the end face of the test bearing [5]. Guangwu Zhou introduced a test bed for loading by means of hydraulic loading. Static loading and dynamic loading were realized through linear electrohydraulic servo actuator and all-digital hydraulic servo coordinated loading control system [6]. Bo Qiu etc. designed a test bed loaded by the hydraulic loading system, and realized constant bearing loading and sinusoidal loading by adjusting the electrohydraulic servo valve by the upper computer [7]. Xiaoyan Y designed a test bed that used mechanical loading to realize radial loading by rotating the four disks on the bearing [8].

To sum up, traditional contact loading, such as hydraulic loading, fixed pulley loading, and other loading methods still have problems such as vibration, heat, noise, friction and wear, which have a great impact on the test results. In recent years, some scholars have also studied other loading methods of bearings. For example, Qian Jia etc. designed and manufactured an octupole electromagnetic loading device [9]. Ronghua Qiu etc. introduced the electromagnetic loading test bed and realized radial loading of the motorized spindle by designing u-shaped electromagnets [10]. Xiaoliang Kang etc. used u-shaped electromagnets to load the spindle and analyzed tangential and radial forces [11]. Based on the analysis of the existing technology and the specific test and application of the water-lubricated bearing, a non-contact electromagnetic loading device is designed in this paper, which can solve the problems caused by the traditional contact loading device.

2. Structure and Principle of Electromagnetic Loading Device

2.1. Structure Design of Electromagnetic Loading Device

For the load test requirements of ten-groove water-lubricated concave alloy bearing, the structure of the designed electromagnetic loading device is shown in figure 1. The electromagnetic loading device is mainly composed of a dc e-type electromagnet and a loading disk. The force sensor is installed directly under the electromagnet and fixed on the support. The e-type magnet is distributed on the left and right sides of the loading plate and is 90° to each other. The air gap between the electromagnet and the loading plate is 2mm. DC electromagnet is an E-type magnet consisting of a coil and an iron core with an iron core consisting of pure iron. Compared with the U type magnet, the loading area of the E type magnet is larger and the loading force is larger. The conducting coil is a enameled copper wire wound around an iron core inside an E-type magnet.

![Figure 1. Structure drawing of electromagnetic loading device](image)

2.2. Principle of Electromagnetic Loading

According to figure 2, direct current is applied to the coil. Since the permeability of the air is far less than that of the loading plate, the electromagnetic force $F_{\text{left}}$ and $F_{\text{right}}$ will be generated on the interface between the loading plate and the air gap, and the direction of the electromagnetic force is perpendicular to the boundary. When the load plate is equal to the air gap of the magnets on both sides, the resultant electromagnetic force of the device $F = (F_{\text{left}}^2 + F_{\text{right}}^2)^{1/2}$, and the direction is vertically downward.

When the water-lubricated bearing is rotating, vortices will be formed on the surface of the loading plate, and then lorentz forces $f_1$ and $f_2$ will be formed. The load-carrying force of water-lubricated bearing is simulated by maxwell electromagnetic force and lorentz force.
As shown in figure 2, maxwell electromagnetic force is a result of the permeability of different on both sides of the interface materials. On the basis of the conditions, to produce a larger electromagnetic force, loading plate should choose high permeability and permeability performance good material. Through analysis and comparison, choose silicon steel as the material of loading plate.

![Figure 2. Electromagnetic force analysis diagram](image)

3. Theoretical Calculation of Electromagnetic Loading Force

For the actual needs of load simulation of water-lubricated bearing, the e-type electromagnetic loading device as shown in figure 1 is designed. Design parameter of electromagnetic loading force: 2200N. Static magnetic field and static electromagnetic force are used as the object of analysis and calculation. Electromagnetic loading is a symmetrical structure. Therefore, the left part of the model is now carried out mathematical analysis, and its section size is shown in figure3.

![Figure 3. Section of electromagnetic loading device](image)

Under ideal conditions, simplified equivalent magnetic circuit diagram is drawn for the section diagram, as shown in figure4. The magnetic circuit forms a closed circuit, which is known by the formulas of magnetic permeability and reluctance. The reluctance of each part is shown in equations (1) ~ (5).

![Figure 4. Equivalent magnetic circuit diagram of electromagnetic loading device](image)

It can be seen from figure 4 that the magnetic circuit forms a closed loop. According to the formulas of magnetic permeability and magnetic resistance, the magnetic resistance of each part

\[ R_{\omega 1} = R_{\omega 2} = \frac{b}{2 \mu_s A_1} = \frac{b}{2 \mu_s A_2} \]  

(1)

\[ \frac{1}{R_{\delta_i}} = \frac{1}{R_{\delta_j}} = G_{\delta_i} = G_{\delta_j} = \mu_0 \frac{S_1}{\delta} = \mu_0 \frac{S_2}{\delta} \]  

(2)

\[ \frac{1}{R_{\delta_i}} = G_{\delta_i} = \mu_0 \frac{S_1}{\delta} \]  

(3)
In the formula:
\[ R_{m_1} = R_{m_4} = \frac{l_1}{\mu_o A_3} = \frac{l_2}{\mu_o A_4} \]  \hspace{1cm} (4)
\[ R_{m_3} = \frac{l_3}{\mu_o A_5} \]  \hspace{1cm} (5)

In the formula:
\[ R_{m_1}, R_{m_2} \] -- the magnetic resistance of the loading plate, H\(^{-1}\); \[ R_{m_3}, R_{m_4}, R_{m_5} \] -- the reluctance of an electromagnet, H\(^{-1}\); \[ G_{\delta_1}, G_{\delta_2}, G_{\delta_3} \] -- the permeability of the air gap, H; \[ b \] -- the length of the loading disk, mm; \[ \delta \] -- the size of the air gap, mm; \[ l_1, l_2, l_3 \] -- the path of the magnets on both sides of the e-type magnet, mm; \[ \mu_o, \mu_s \] -- the vacuum permeability, H/m; \[ A_1, A_2 \] -- the cross-sectional area of the axis, mm\(^2\); \[ A_3, A_4, A_5 \] -- the cross-sectional area of three iron cores of an electromagnet, mm\(^2\); \[ S_1, S_2, S_3 \] -- the area of an iron core projected by an axis through an air gap, mm\(^2\).

Because \( S_1 = S_2 = A_3 = A_4 = A_5 = S_3 \), and \( \mu_s \) is much greater than \( \mu_0 \), it can be considered that:
\[ \phi = \frac{IL}{\mu_s S_1 + \mu_s (S_2 + S_3)} \]  \hspace{1cm} (6)

According to the magnetic path continuity theorem and Maxwell's electromagnetic attraction formula,, it can be known that:
\[ F_{\text{left}} = \mu_o \left( \frac{NI}{\delta} \right)^2 \frac{S_1(S_2 + S_3)}{S_2 + S_1 + S_3} \]  \hspace{1cm} (7)

Moreover, because the electromagnetic loading device is a left-right symmetrical structure, and the included angle is 90°, the total electromagnetic loading force is:
\[ F = \frac{F_{\text{left}}}{\cos 45^\circ} \]  \hspace{1cm} (8)

In the formula:
\[ \phi \] -- the magnetic flux in the magnetic circuit, equivalent magnetic flux, wb; \[ F_{\text{left}}, F \] -- the electromagnetic force of the left part of the loading device, the whole electromagnetic force, N.

Since the total area of the axis projected on the left core is \( S = 3045 \text{mm}^2 \), the coil is 915 turns and the air gap size is 2mm, the relationship between current and force can be obtained as shown in table 1.

| I/A | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 |
|-----|-----|-----|-----|-----|-----|-----|
| \( F_l/N \) | 61  | 243 | 546 | 970 | 1516| 2184|

4. Finite Element Analysis of Electromagnetic Loading Device

The finite element simulation can simulate the mechanical and nonlinear characteristics of the loading device under the actual situation, and the calculated results are close to the actual results. Ansoft maxwell 18.2 was used for two-dimensional and three-dimensional simulation of the loading device, and then the magnitude of electromagnetic force was solved under different current conditions. According to the actual loading situation, SOLIDWORKS2016 was selected for physical modeling, as shown in figure 5.
Figure 5. Three-dimensional model of electromagnetic loading device
For the material used in the actual loading device, the material is added to the model. Loading plate—silicon steel sheet; Type E magnet—pure iron; Coil—copper. In 2D static magnetic field, the Boundary condition is Vector Potential Boundary. In a 3D static magnetic Field, the selected boundary condition is Zero Tangential H Field; Add excitation source for 2475 ampere turns.
In setting choose subdivision On Selection - Skin the depth -based refinement, the Skin effect layer encryption subdivision. See figure 6.

Figure 6. Loading device 2D mesh generation
In the setting of solution: the maximum number of steps of convergence is set to 10; The percentage error of convergence is set at 1%; Choose solve matrix, and find the matrix parameter terms After last pass; The nonlinear residual is set as 0.00015; Other options are set to default.
After setting, the distribution of magnetic induction line and the vector diagram of magnetic induction intensity are obtained after solving, as shown in figure 7.

Figure 7. Magnetic induction line distribution and magnetic induction intensity vector diagram of loading device
According to figure 7, the working conditions of the loading device are obtained after finite element analysis. The magnitude of electromagnetic force is shown in table 2.

Table 2. Simulated electromagnetic force

| I/A | 0.5 | 1   | 1.5 | 2   | 2.5 | 3   |
|-----|-----|-----|-----|-----|-----|-----|
| F/N | 56  | 222 | 500 | 889 | 1389| 1936|

5. Results and Analysis
Matlab was used to analyze and compare table 1 and table 2, and the figure obtained was shown in figure 8.
As can be seen from figure 8, the maximum error between the theoretical value and the simulation value under static load is 11.4%, and the trend change of the two is basically the same. Because the effect of magnetic flux leakage and the error of theoretical calculation are not considered in the ideal case [10]. Therefore, the above error is acceptable.

6. Conclusion
(1) Design a simulation of water lubricated bearing load of non-contact electromagnetic loading device. Analysis results show that the theoretical value and simulation value of the maximum error is 11.4%, verified the rationality of the design of electromagnetic loading device, and in the water lubricated bearing load test with the test data analysis to verify the exactness of the device.
(2) The simulation results show that the magnetic inductance line is symmetrical to the left and right. The magnetic inductance line runs through the air gap from the end of the e-type magnet. Most of the magnetic inductance line only goes through the lower half of the loading disk, and only a small part goes through the upper half. The closer the magnetic induction intensity is to the electromagnet, the greater it is.

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