Motion State Analysis and Seal Ability Study on the Magnetic Fluid Seal of Reciprocating Shaft

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Abstract: The authors have studied the motion mechanism of the magnetic fluid in a reciprocating seal gap, on the basis of which the authors obtain an anti-pressure formula of the reciprocating shaft magnetic fluid seal from general Navier-Stokes equation. In order to verify the correctness of the anti-pressure formula, the authors have calculated the magnetic field distribution of seal structure and have gotten the maximum still anti-pressure. Finally, the authors have verified the influence of speed and stroke on the seal anti-pressure.

Key words: magnetic fluid; reciprocating seal; anti-pressure

The study of magnetic fluid reciprocating seal has been attractive to researchers and engineers since 1980's[1, 2], but so far, many problems in practice as well as theory have not yet been solved. For example, the theoretical formula for calculating the anti-pressure of the reciprocating seal, the influence of the related parameters on the anti-pressure of reciprocating seal and how to improve the seal life and so on, are not well understood. In this paper, the anti-pressure formula of the magnetic fluid reciprocating seal and the influence of shaft reciprocating motion on the anti-pressure are studied both theoretically and experimentally.

1 The Study on the Mechanism of the Magnetic Fluid Motion in the Reciprocating Seal

The study of the state of the magnetic fluid motion in the seal is the key problem for modeling a reliable mathematical model to obtain the correct anti-pressure. Based on this, a new structure of the seal can be designed. But, up to now only a few papers on this problem can be found in the literature. Experiment and investigation on microscope were carried out by the authors. The mechanism of the magnetic fluid motion in the seal is revealed.

The experiment rig sketch is shown in Fig. 1. In Fig. 1, 1, 2, 3, 4, 5 and 6 are the serial numbers of the seal teeth respectively. In addition, the magnetic fluid seal structure in Fig. 1 is a typical traditional structure[3-6], which includes the magnetic fluid, a permanent magnet, two pole pieces and a magnetically permeable shaft. The magnetic structure, implemented by the stationary pole pieces and shaft, concentrates the magnetic flux in the radial gap under each pole. When the magnetic
fluid is applied to the radial gap, it assumes the shape of a "liquid O-ring" and produces a hermetic seal.

Fig. 1 The experiment rig for studying the magnetic fluid motion

Many experiments were carried out by the authors\[7\], and the results obtained are similar in this paper. Only two of them are introduced in details.

1. 1. The case of lower reciprocating speed

Under the microscope magnifying 100 times, the magnetic fluid film on the left of the fourth tooth is observed. The photographs are taken as shown in Fig. 2.

1. 2. The case of higher reciprocating speed

Under the microscope magnifying 100 times, the state of the magnetic fluid film on the left of the fourth tooth is observed. The photographs are shown in Fig. 3.

Fig. 2 The form of magnetic fluid film in the seal gap with the shaft motion at low speed
(a) The shaft is motionless; (b) The shaft moves toward right; (c) The shaft moves toward left;

Fig. 3 The variation of the magnetic fluid film state with the shaft moving at high speed
(a) The shaft is motionless; (b) The shaft moves toward right; (c) The shaft moves toward left;

In Fig. 2 and Fig. 3, the black part of each photograph is the magnetic fluid. The shaft is below the fluid. These photographs describe state variations of the magnetic fluid film and contact points variations between the magnetic fluid film and the tooth with the reciprocating shaft moving in different directions and at different speeds.

1. 3. Conclusions of the experiments mentioned above

(1) The contact point of the magnetic fluid film with the tooth and also the contact point of the film with the reciprocating shaft vary with the reciprocating speed of the shaft.

(2) The deformation of the magnetic fluid film varies with the reciprocating speed of the shaft.

(3) The final position of the magnetic fluid film is not related to the displacement of the reciprocating shaft.

(4) The thickness of the magnetic fluid adhering to the shaft is very thin as compared to the height of the seal gap, and the quantity of the fluid adhering to the shaft then may be neglected in the motion analysis.

1. 4. The theoretical analysis of experimental results

As the speed of the reciprocating shaft
increases, the traction force in the shaft’s linear motion increases, and the relationship can be expressed as

\[ \tau = \eta \frac{v}{h} \]  

(1)

where \( \tau \) may represent the traction force; \( \eta \) is the magnetic fluid viscosity; \( v \) is the reciprocating shaft speed and \( h \) is the thickness of magnetic fluid film in the seal gap. It may be seen that when the shaft speed increases, the fluid seal may break out. The seal deformation changes the value of magnetic field intensity on its free surfaces, which leads to the dependence of anti-pressure upon the shaft motion direction.

2. The Distribution of the Magnetic Field and the Maximum Static Anti-Pressure Ability of the Seal

The distribution of the magnetic field of the reciprocating seal pieces shown in Fig. 4 is analyzed by the finite element method [7, 9].

![Fig. 4](image)

Fig. 4 The distribution of the magnetic field in the seal pieces

The relation between the static anti-pressure capacity and the quantity of the magnetic fluid is also analyzed. The related curves are shown in Fig. 5.

![Fig. 5](image)

Fig. 5 The theoretical and experimental curves of static anti-pressure

3. The Theoretical Analysis of the Anti-Pressure of the Seal

The mathematical model for studying the magnetic fluid reciprocating seal is shown in Fig. 6. The magnetic fluid film in the seal gap moves along with the movement of the shaft and stops at a definite shaft speed. In Fig. 6 AB and CD represent the magnetic fluid film in the seal gap before the shaft moves. A'B' and C'D' represent the magnetic fluid film in the seal gap after the shaft moves.

![Fig. 6](image)

Fig. 6 The mathematic model for analysis of the magnetic fluid reciprocating seal

In order to establish the anti-pressure formula, assumptions are made as follows [1, 10]:

1. Because the radius of the shaft is large enough as compared with the height of the seal gap, the motion of the magnetic fluid is described by a plane rectangular Cartesian coordinates instead of a cylindrical polar coordinates.

2. The quantity of the magnetic fluid adhering to the shaft is neglected.

3. No shaft rotation occurs and \( v_z \) is equal to zero.

4. \( v_z \) is equal to zero approximately.

5. The motion of the magnetic fluid is steady.

6. The motion of the magnetic fluid is a laminar flow.

According to the Navier-Stokes equation, one can have

\[
\rho \left( \frac{\partial u_x}{\partial t} + u_x \frac{\partial u_x}{\partial x} + u_y \frac{\partial u_x}{\partial y} + u_z \frac{\partial u_x}{\partial z} \right) =
F_x - \frac{\partial P}{\partial x} + \eta \nabla^2 u_x
\]

\[
\rho \left( \frac{\partial u_y}{\partial t} + u_x \frac{\partial u_y}{\partial x} + u_y \frac{\partial u_y}{\partial y} + u_z \frac{\partial u_y}{\partial z} \right) =
F_y - \frac{\partial P}{\partial y} + \eta \nabla^2 u_y
\]
\[
\rho \left( \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + u \frac{\partial v}{\partial y} + u \frac{\partial v}{\partial z} \right) = \\
F_z - \frac{\partial p}{\partial x} + \eta \nabla^2 u_z
\]
and with the assumptions mentioned above, one can get
\[
0 = F_z - \frac{\partial p}{\partial x} + \eta \frac{\partial^2 u_z}{\partial x^2} \quad (2)
\]
\[
0 = F_y - \frac{\partial p}{\partial y} \quad (3)
\]
\[
0 = F_z - \frac{\partial p}{\partial z} \quad (4)
\]
Also one can have
\[
F_z = M \mu_0 \frac{\partial H}{\partial x} \\
F_y = M \mu_0 \frac{\partial H}{\partial y} \\
F_z = M \mu_0 \frac{\partial H}{\partial z}
\]
\[
\frac{\partial H}{\partial x} = 0 \\
\frac{\partial H}{\partial y} = 0
\]
Finally, one can get
\[
\frac{\partial \nabla}{\partial y} = 0, \frac{\partial \nabla}{\partial z} = 0
\]
\[\square \square \] From this it can be seen that \( p \) and \( h \) are only functions of \( x \), and that Eq. (2) may be simplified as
\[
\mu_0 M h = \frac{\partial p}{\partial x} + \eta \frac{\partial^2 u_z}{\partial x^2} dx = 0 \quad (5)
\]
From the magnetic curve shown in Fig. 7, one can get
\[
0 \leq H \leq H_s, M = x_n H \\
H \geq H_s, M = M_s
\]

![Fig. 7](#) The magnetic curve of magnetic fluid

Then from Eq. (5) one can get
\[
p = \frac{1}{2} H^2 \mu_0 x_n + \eta \frac{\partial^2 u_z}{\partial y^2} + C
\]
(\( 0 \leq H \leq H_s \))
\[
p = \mu_0 M s H + \frac{\eta}{h^2} \frac{\partial^2 u_z}{\partial y^2} x + C
\]
(\( H \geq H_s \))
Assuming that \( \square U_s = Ay^2 + By + C \) and that the boundary conditions are
\[
y = 0, U_s = V \\
y = h(x), U_s = 0
\]
one can get
\[
p = \frac{1}{2} H^2 \mu_0 x_n + \eta \frac{6V}{h^2(x)} x + C \quad (8)
\]
\[
p = \mu_0 M s H + \eta \frac{6V}{h^2(x)} + C \quad (9)
\]
For simplicity, only the case \( H \geq H_s \) is discussed.

The pressure inside CD is
\[
p_{\perp} = H (x c) \mu_0 M s \quad (10)
\]
\[\square \square \] The pressure inside AB is
\[
p_{\perp} = H (x n) \mu_0 M s + \eta \frac{6V}{h^2(x_n)} x_n + C \quad (11)
\]
\[\square \square \] Neglecting the surface tension and the stress jump caused by the normal component of magnetization, one can get from Eqs. (10) and (11),
\[
p_{\perp} - p_{\perp} = [H (x c) - H (x n)] \mu_0 M s + \eta \frac{6V}{h^2(x c)} x_c - \eta \frac{6V}{h^2(x_n)} x_n
\]
where
\[
h(x_n) = 0.66 h(x_c) \left( \frac{\eta V}{\sigma} \right)^{2/3} \quad (13)
\]
\[
h(x_c) = h_c
\]
and \( h_c \) represents the gap height.

Substituting Eq. (13) into Eq. (12), one can obtain
\[
p_{\perp} - p_{\perp} = [H (x c) - H (x n)] \mu_0 M s + \eta \frac{6V}{h^2(x c)} x_c - \eta \frac{6V}{h^2(x_n)} x_n
\]
and with the assumptions mentioned above, one can get
\[
p_{\perp} - p_{\perp} = \frac{1}{h^2(x_c)} \left[ \frac{1}{0.66 h(x_c) \left( \frac{\eta V}{\sigma} \right)^{2/3}} \right]^{2/3} \quad (14)
\]
\[\square \square \] From Eq. (14), the influence of the reciprocating motion on the magnetic fluid seal is quantitatively and qualitatively described.

In the above equations, the meaning of the letters is as follows:
\[
\rho \text{— density of the magnetic fluid;}
\]
\[
u, u_x, u_y, u_z \text{— motion velocities of the magnetic fluid in the } x, y, z \text{ directions;}
\]
\[
F_x, F_y, F_z \text{— body forces in the } x, y, z \text{ directions;}
\]
\[
p \text{— pressure of the magnetic fluid;}
\]
\( p_h \) — the pressure inside \( C'D' \);
\( p_l \) — the pressure inside \( A'B' \);
\( p_s \) — the pressure inside \( C'D' \) neglecting the surface tension and the stress jump;
\( p_v \) — the pressure inside \( A'B' \) neglecting;
\( \eta \) — viscosity of the magnetic fluid;
\( M \) — magnetization;
\( H \) — magnetic field intensity;
\( x_m \) — magnetic permeability of the magnetic fluid;
\( H_c \) — thickness of the magnetic fluid film;
\( M_s \) — saturation magnetization of the magnetic fluid;
\( V \) — velocity of the reciprocating shaft;
\( \sigma \) — surface tension coefficient of the magnetic fluid.

4. Experiment on Anti-Pressure of the Seal

In order to verify the influence of the reciprocating motion parameters on the anti-pressure of the seal and the correctness of the anti-pressure formula, a magnetic fluid anti-pressure experiment rig for a reciprocating seal is set up. The rig is shown in Fig. 8. The mechanism of the magnetic field motion and the static anti-pressure of the seal have been analyzed in Sections 1-3.

The experiment rig is composed of two parts: the first part is the main part of the experiment rig (see Fig8(a)), while the second part is the driving part (see Fig8(b)). The main part is composed of linear bearings, the seal chamber, pole pieces, and so on. It is worth mentioning that the authors choose the linear bearings as the support in order to make the seal gap uniform.

The driving part uses hydraulic driving, which has many advantages. For example, the reciprocating shaft is stepless speed change; the influence of the speed and stroke on the anti-pressure ability is dependent.

It is necessary to point out that the motion principle of the reciprocating shaft in the previous experiment rig set up by the authors is the same as that of a crank-connecting rod mechanism, so the influence of the stroke and speed on the anti-pressure ability and seal longevity is independent.

4.1 The influence of the reciprocating speed on the seal life at the same stroke

The magnetic fluid used in the experiment is the No. 2 engine oil base, and the reciprocating stroke is 100mm, and 10ml of the magnetic fluid working at 0.11 \( \times 10^3 \) Pa is used in the experiment. The experiment result is shown in Table 1.

<table>
<thead>
<tr>
<th>Speed/(mm·s(^{-1}))</th>
<th>0.03</th>
<th>1.11</th>
<th>2.22</th>
<th>2.94</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seal life/s</td>
<td>3000</td>
<td>90</td>
<td>45</td>
<td>34</td>
<td>25</td>
</tr>
<tr>
<td>Speed/(mm·s(^{-1}))</td>
<td>6.25</td>
<td>8.33</td>
<td>20</td>
<td>25</td>
<td>66.67</td>
</tr>
<tr>
<td>Seal life/s</td>
<td>16</td>
<td>12</td>
<td>5</td>
<td>4</td>
<td>1.5</td>
</tr>
</tbody>
</table>

In Eq. (14), it is known that \( 6\mu V \left[ \frac{1}{H_c} \right]^2 x_m - \left[ 0.66 \frac{H_c}{H_c} \right]^2 x_m \) is a negative number and that with the increase of \( V \), the value of \( p_h - p_v \) becomes small. That is, the anti-pressure of the magnetic fluid decreases and the seal longevity of magnetic fluid decreases too. The experiment results verify the correctness of Eq. (14) from one aspect.
4.2 The influence of the reciprocating stroke on the seal life at the same reciprocating speed

The speed of the reciprocating shaft is 0.42mm/s, and 10mL of the magnetic fluid working at 0.11×10^3Pa is used in the experiment. The experiment result is shown in Table 2.

<table>
<thead>
<tr>
<th>Stroke/mm</th>
<th>100</th>
<th>80</th>
<th>60</th>
<th>40</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seal life/s</td>
<td>240</td>
<td>240</td>
<td>240</td>
<td>240</td>
<td>240</td>
</tr>
</tbody>
</table>

In Table 2, the influence of the stroke on the anti-pressure is not obvious. This is because the quantity of the magnetic fluid carried away from the seal gap relies on the length of the stroke, and the strokes used are matching. Therefore, the seal lives are approximately equal.

Besides, from Eq. (14), it can be seen that the equation does not directly describe the influence of the reciprocating stroke on the anti-pressure ability. In addition, from Section 1, it is known that the position of the magnetic fluid in the seal gap is decided by the reciprocating speed. The position of the magnetic fluid in the seal gap decides the value of anti-pressure, and that is the seal longevity of the magnetic fluid. Therefore, the influence of the stroke on the anti-pressure is not obvious. The experiment results verify the correctness of Eq. (14) from another aspect.

By the way, although many factors can affect the magnetic fluid seal life of the reciprocating shaft, only the influence of the reciprocating speed and stroke on the seal life is studied in this paper.

5 Conclusions

(1) The study on the magnetic fluid anti-pressure formula of the reciprocating seal is of important significance in guiding the practical application.

(2) The deformation of the magnetic fluid film in the seal gap and the reduction of the magnetic fluid quantity caused by the moving of the reciprocating shaft are the major causes of failure of the magnetic fluid seal.

(3) In order to improve the seal life, a newly designed structure must be put forward. The new structure should be able to prevent the deformation of the magnetic fluid film and reduce the loss of the magnetic fluid in the seal gap. The traditional structure cannot meet the practical application.

References


Biographies:

LI Decai Born in 1965, he is a professor at Northern Jiaotong University. He is interested in the preparation, theory and application of magnetic fluid. To date he has published about fifty papers, and has published the monograph The Theory and Application of Magnetic Fluid. He has taken charge of the study of two projects of National Science Foundation of China and has completed more than twenty projects about magnetic fluid.

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