Modeling and simulation of flow field in giant magnetostrictive pump

Yapeng Zhao\(^a\), Shiyong Ren\(^a\), Quanguo Lu\(^b\)

\(^a\)The 713th Research Institute of China Shipbuilding Industry Corporation, Zhengzhou, China  
\(^b\)Institute of Micro/Nano Actuation and Control, Nanchang Institute of Technology, Nanchang, China

Abstract. Recent years, there has been significant research in the design and analysis of giant magnetostrictive pump. In this paper, the flow field model of giant magnetostrictive pump was established and the relationship between pressure loss and working frequency of piston was studied by numerical simulation method. Then, the influence of different pump chamber height on pressure loss in giant magnetostrictive pump was studied by means of flow field simulation. Finally, the fluid pressure and velocity vector distribution in giant magnetostrictive pump chamber were simulated.

1. Introduction
The hydraulic pump which converts mechanical energy into hydraulic energy is the power source and core components of hydraulic system. Traditional hydraulic pumps require the use of internal combustion engine or electromotor to provide power. However, the traditional pumps are always heavy and huge, and their energy loss is always very huge in energy transmission process. Compared with other smart materials, the rare earth giant magnetostrictive material has the features of large strain, big output force and fast response et al[1]. It provides the possibility to change Hydraulic pump drive mode. Using Terfenol-D material to drive the fluid directly, the complexity of energy transduction is reduced. Recent years, there has been significant research activity in the development of hydraulic pump driven by Terfenol-D material. A magnetostrictive stack based hybrid pump was developed by Gerver et al[3]. This design used Terfenol-D as the driving element and employed stroke amplification to obtain high flow rates. The pump achieved a flow rate of 15 ml/s with a power input of 41 W. CSA Engineering reported the development of several hybrid actuators, including a magnetostrictive hydraulic actuator with power output exceeding 100 W[4]. The maximum no-load flow rate was 25.2 ml/s and the maximum developed pressure was 11.7 MPa.

Inertial loads, fluid viscosity and compressibility combine with loss mechanisms inherent in the active material limit the effective bandwidth of the driving pump and the total pump output power[6]. Care must be taken in the design and analysis of giant magnetostrictive pump to match the mechanical impedance characteristics of the Terfenol-D material to the fluid transmission so that maximum efficiency of operation is obtained. In this paper, we have carried out the design, modeling and simulation of the flow field in giant magnetostrictive pump to find some laws in the design method.
2. Flow field model of giant magnetostictive pump
As shown in Figure 1, the giant magnetostictive pump has several main components: Terfenol-D rod, piston, pump body, pump chamber, inlet tube, outlet tube and check valve. The piston is driven by a Terfenol-D rod to compress the liquid in the pump chamber. The diameter of the giant magnetostictive pump chamber is also the diameter of the piston \( d_p \). The height of the pump chamber is \( h_{ch} \). The diameter of inlet tube and outlet tube both are \( d_t \) and the distance from the center axis of pump chamber to outlet tube or inlet tube is \( R \).

\[ Q = \Delta l \frac{\pi d_p^2}{4} f \]  

(1)

Where, \( f \) is the working frequency of piston.

For the liquid in the pump chamber, \( \rho \) is a constant, \( v_r \), \( v_\theta \) and \( v_z \) are their velocity components in the \( r \), \( \theta \) and \( z \) directions respectively. By the law of conservation of mass, simplifying the continuity equation of fluid mechanics, we can get its expression in cylindrical coordinate system as follows:

\[ \frac{v_r}{r} + \frac{\partial v_r}{\partial r} = 0 \]  

(2)

By the law of conservation of momentum, the momentum equation of hydrodynamics is transformed into the cylindrical coordinate system, and the expression of steady state incompressible flow can be obtained[7].

\[ \rho v_r \frac{\partial v_r}{\partial r} = -\frac{\partial P_{ch}}{\partial r} + \mu \frac{\partial^2 v_r}{\partial x^2} \]  

(3)

Where \( \rho \) is the density of the liquid, \( \mu \) is the dynamic viscosity of the liquid, \( P_{ch} \) is the pressure of the liquid in pump chamber.

By the law of conservation of mass, the velocity distribution of the liquid in the radial direction should be

\[ v_r = \frac{C_1 z (h_{ch}-z)}{r_p} \]  

(4)

Where \( C_1 \) is the speed coefficient, \( r_p \) is radius of piston.

Integrate \( z \) above this equation,

\[ \int_0^{h_{ch}} v_r = \int_0^{h_{ch}} \frac{C_1 z (h_{ch}-z)}{r_p} = \frac{Q}{2\pi r_p} \]  

(5)

Where \( Q \) denotes the average flow in the height direction of pump chamber.

Solve the above formula, you can get
\[ C_1 = \frac{3Q}{\pi h_{ch}^2} \]  

(6)

Substituting equations (4) and (6) into equation (3), the radial pressure gradient of the liquid in pump chamber can be obtained.

\[ \frac{\partial p_{ch}}{\partial r} = \frac{9\rho Q^2}{\pi^2 h_{ch}^2 r^2} Z^2 (h_{ch} - z)^2 - \frac{6Q\mu}{\pi h_{ch}^2 r} \]  

(7)

Integrate the above equation, you can get the pressure loss in pump chamber,

\[ \Delta p_{ch} = \frac{6Q\mu}{\pi h_{ch}^2} \ln \left(\frac{d_p}{d_t}\right) + \frac{Q}{60} \left(\frac{6Q}{\pi h_{ch} d_p}\right) \left[\left(\frac{d_p}{d_t}\right)^2 - 1\right] \]  

(8)

Where \(d_p\) denotes the pump chamber diameter, \(d_t\) denotes the inlet tube diameter.

The first term in equation (8) represents the pressure loss due to the viscosity of the liquid; the second term indicates the pressure loss due to the change in the radial flow area when the flow of liquid pass from pump chamber to outlet tube.

Similarly, the pump chamber is simplified, considering only its two-dimensional state, ignoring the radial area of the change, the fluid flow path as a rectangular path, you can get its two-dimensional model.

In [8], the flow expression of the slit flow is given:

\[ q = \frac{b h^3 \Delta p}{12 \mu l} \]  

(9)

Where \(l = d_p - d_t\), \(b=12.5\).

Besides, \(q\) is the flow rate per unit length and its expression can be obtained by \(Q\)

\[ q = \frac{Q}{\pi \left(\frac{d_p + d_t}{2}\right)} \]  

(10)

Combine Equation (9) and Equation (10), the equation of pump chamber pressure loss is as the following,

\[ \Delta p_{ch} = \frac{480\mu}{25 \pi h_{ch}^2} \left(\frac{d_p - d_t}{d_p + d_t}\right) \]  

(11)

Substitute equation (1) into equations (11), the expression of pressure loss in the two-dimensional space is obtained when the pump chamber is discharged,

\[ \Delta p_{ch} = \frac{12\mu d_p^3 \Delta t}{25 h_{ch}^2} \left(\frac{d_p - d_t}{d_p + d_t}\right) \]  

(12)

Substitute equation (1) into equations (8), the expression of pressure loss in the three-dimensional space is obtained when the pump chamber is discharged,

\[ \Delta p_{ch} = \frac{3d_p^3 \mu f \Delta t}{2 h_{ch}^2} \ln \left(\frac{d_p}{d_t}\right) + \frac{3d_p^3 f^2 \Delta t^2}{80 h_{ch}^2} \left(\frac{d_p}{d_t}\right)^2 - 1 \]  

(13)

From the equations (12) and (13), we can get the relationship between pressure loss in pump chamber and working frequency of the piston under two-dimensional and three-dimensional conditions. The structure parameters of giant magnetostrictive pump designed in this paper are as follows: \(d_p=50\) mm; \(d_t=4\) mm; \(h_{ch}=0.5\) mm; \(\Delta t=0.1\) mm; Parameters of the selected hydraulic oil are as follows: \(\rho=850\) kg/m3; \(\nu=6.8 \times 10^{-5}\) m2/s; \(\mu=0.0578\) Pa.s.
Figure 2. Relationship between the pump chamber pressure loss and the working frequency

As shown in Figure 2, we can see the relationship between the pump chamber pressure loss and the working frequency. It can be seen from the Figure 2, in the ideal state, the pump chamber pressure loss increases with increasing working frequency. With the same working frequency, the pressure loss of three-dimensional model is more than the pressure loss of the two-dimensional model, and the loss gap increases between them when their models are under high frequency. The slope of the three-dimensional model curve changes around 200 Hz, because the effect of the flow area changes on the pressure loss exceeds the effect of liquid viscosity on the pressure loss when the liquid flows radially on the piston surface. At low frequencies, the difference between two-dimensional model and three-dimensional model is the liquid viscosity term. At high frequencies, the difference becomes larger because two-dimensional model does not contain the effect of changes in the radial over-current area. In the actual flow field, the pressure loss in pump chamber increases faster with the increase of the working frequency due to some factors such as the response speed of the reed, the leakage of pump chamber at high frequencies and effect of some cavitation.

3. Influence of pump chamber height on pressure loss

The most important factor affecting the flow field in pump chamber is its height. By studying the influence of different pump chamber height on the pressure loss in the pump chamber, the optimal height parameter is determined. The two-dimensional geometric model of pump chamber was established by FLOTTRAN, and the FLUID141 fluid element was used for meshing. The results are shown in Figure 3.

Figure 3. Geometrical model of pump chamber

The flow of liquid in pump chamber is derived from the reciprocating linear motion of piston. In the simulation analysis, the speed of piston is the excitation load. For the same pump chamber height, with different initial speed of piston to load, the relationship between the pump chamber pressure loss and the piston speed curve is obtained.
Figure 4. Relationship between pump chamber pressure loss and piston speed

Figure 4 shows the relationship between pump chamber pressure loss and working speed of the piston when the pump chamber height $h_{ch}$ were 0.5 mm, 0.6 mm, 0.7 mm,. Figure 4 (a) for the discharge state, Figure 4 (b) for the intake state. It can be seen that the pressure loss in pump chamber increases non-linearly with the decrease of pump chamber height. As is well known, the smaller the pump chamber height, the greater changing rate of pump volume, the more self-priming capacity gets. For the selection of pump chamber height, it is necessary to make a trade-off between the self-priming capacity of pump and the pressure loss in pump chamber. Giant magnetostrictive pump is used to drive the hydraulic system, which requires high output pressure and good self-priming capacity, so a smaller pump chamber height should be selected.

4. Fluid pressure and velocity vector distribution in pump chamber

Figure 5 shows the radial pressure distribution of the top and bottom of the bump whose chamber height is $\bar{v}=0.5$ mm and the initial piston excitation speed is 20 mm/s. As can be seen from Figure 5, the pressure rises sharply at the inlet and outlet tube walls ($x = 13$ mm, $17$ mm, $33$ mm and $37$ mm), because there is a rapid decline in flow velocity when it pass through the interface between the pump chamber and the inlet tube or outlet tube. Because the liquid flows out of pump chamber at a higher speed, there is a greater pressure loss around the center line place ($x = 15$ mm and $35$ mm).
In Figure 6, the direction of the arrow in a certain point is the direction of liquid flow at that point. In the direction of the arrow in the connection between the pump chamber and the inlet or outlet piping, it can be seen that the direction of the pump is reduced to the horizontal, that is, the lateral flow increases. The lateral flow at the pump chamber exit will prevent the liquid from flowing out. That is the reason that when the pump chamber height is reduced, the pressure loss of the pump chamber increases.

5. Conclusion

In this paper, two-dimensional flow field model and three-dimensional flow field model of giant magnetostrictive pump are established. The numerical simulation results show that the pressure loss in pump chamber increases as the piston working frequency increases. The flow field simulation analysis of giant magnetostrictive pump chamber is carried out and it is found that with the decrease of the pump chamber height, the pressure loss in pump chamber increases. For the selection of pump chamber height, it is necessary to make a tradeoff between the self-priming capacity of pump and the pressure loss in pump chamber. Finally, the fluid pressure and velocity vector distribution in giant magnetostrictive pump chamber are simulated. The simulation results also verify the relationship between pump chamber height and pressure loss in pump chamber.

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