Research on Electromagnetic Force Performance of High Speed on-off Valve

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ABSTRACT

Taking a high speed on-off valve as an example, the effects of air gap, shell thickness, armature length, guide sleeve type and armature radius on the electromagnetic force performance are studied. The results show that the air gap is negatively related to the electromagnetic force, the shell thickness, armature length and armature radius are positively related to the electromagnetic force, and the effect of pure copper guide sleeve and non-guide sleeve on the electromagnetic force is basically the same. The electromagnetic force can be increased by the guide sleeve with magnetic separation ring. The influence order of parameters on electromagnetic force is: air gap > armature radius increment > armature length increment > shell thickness increment.

KEYWORDS

High Speed on-off Valve, Electromagnetic Force Performance.

INTRODUCTION

High speed on-off valve is a common electro-hydraulic conversion element, which is often used in various electro-hydraulic control systems to control flow or pressure[1,2]. Under the control of high frequency PWM signal, in a certain signal range, the valve core can be kept at a certain position, which can adjust and control
the pressure of the system. Because it can realize the function similar to proportional solenoid valve, and the price is low, so the research of high speed on-off valve is gradually developing to the direction of high-frequency signal. The main principle of valve core suspension is to balance the comprehensive effect of each force in a certain position range, change the duty cycle of high frequency PWM signal, and change the magnitude of electromagnetic force. When the valve core is in different position, because of the different flow area, the hydrodynamic force is also different. When the forces in a certain position are balanced with each other, the valve core can be suspended. However, because the gradient of hydrodynamic force and electromagnetic force do not match in the range of travel, the suspension range of high speed on-off valve under high-frequency PWM signal is very limited. In order to solve this problem, it is very important to study the electromagnetic force performance of high speed on-off valve in the range of travel. In this paper, the electromagnetic force of high speed on-off valve is taken as the index to study the influence of different parameters on the performance of electromagnetic force, so as to provide theoretical reference for improving the gradient range of electromagnetic force of high speed on-off valve.

**STRUCTURE AND PRINCIPLE OF HIGH SPEED ON-OFF VALVE**

In this paper, a ball valve type high speed on-off valve is taken as the research object, and its mechanical structure is shown in Figure 1:

![Figure 1. High speed on-off valve structure diagram.](image)

The calculation formula of electromagnetic force is as follows:

\[ R_e = \frac{Ni}{\varphi} \quad (1) \]
\[ R_t = R_z + R_{b1} + R_{b2} \]  \hspace{1cm} (2)

\[ R_{b1} = \frac{\delta}{(\mu_0 S)} \]  \hspace{1cm} (3)

\[ R_{b2} = \ln\left(\frac{r_2}{r_1}\right) / (2\pi L\mu_0) \]  \hspace{1cm} (4)

\[ F = (\varphi_j)^2 / (2\mu_0 S) \]  \hspace{1cm} (5)

\( R_t \) is the total magnetoresistance, \( N \) is the number of turns, \( i \) is the current, \( \varphi_j \) is the air gap flux, \( R_z \) is equivalent magnetoresistance of soft magnetic material, \( R_{b1} \) is the working air gap magnetoresistance, \( S \) is the pole area, \( R_{b2} \) is the nonworking air gap magnetoresistance, \( \delta \) is the air gap width, \( r_2, r_1, L \) is the outer and inner radius and length of the nonworking air gap, \( \mu_0 \) is the vacuum permeability, \( F \) is the electromagnetic force.

**ESTABLISHING ANSOFT SIMULATION MODEL**

In order to explore the influence of parameters on the performance of electromagnetic force, it is necessary to establish a simulation model to solve the electromagnetic force. Because of Ansoft Maxwell’s high precision and rich results, it is widely used\(^6\). The simulation model of high speed on-off valve based on Ansoft Maxwell software in this section is shown in Figure 2, and the solution area is not shown:

![Figure 2. Electromagnetic simulation model of high speed on-off valve.](image-url)
The simulation model of high speed on-off valve is built in two-dimensional static magnetic field, and the boundary is set as the Ballon boundary condition. The solution domain is set to vacuum, the excitation is set to 300 ampere turns, and the coil material is set to copper, because the rear valve body and the skeleton are plastic products, the structure is ignored when drawing the model, and the chamfering and other structures are ignored. The armature front valve body and other magnetic conducting materials are set as electrical pure iron. Add the properties of electrical pure iron to Ansoft material library.

STUDY ON THE PERFORMANCE OF ELECTROMAGNETIC FORCE

There are many structural parameters of high speed on-off valve, and the electromagnetic force is closely related to the magnetic circuit.

Influence of Shell Thickness on Electromagnetic Force

Select the outer edge of the shell as the object, take the thickness increase as the positive direction, achieve the purpose of changing the thickness of the shell. In the simulation, the variation range of shell thickness increment is 0 ~ 5 mm, and the step size is 0.5 mm. The air gap changes from 0 mm in steps of 0.1mm to 1.3mm. Figure 3 and Figure 4 are obtained by processing the simulation data.

![Figure 3. F - δ diagram of different shell thickness.](image)
When the air gap width increases, the electromagnetic force decreases rapidly, and the change of the thickness increment of the shell has little effect on the $F - \delta$ curve.

According to formula (2), the magnetic resistance of the magnetic circuit can be divided into three parts. Because the magnetoresistance coefficient of air is very large, $R_{b}$ accounts for a large proportion of the total magnetoresistance. Increasing $\delta$, air gap magnetoresistance $R_{b}$ rises, and the ampere turns remain the same, so the air gap flux decreases, and the electromagnetic force drops rapidly. The change of the thickness of the shell will cause the change of the equivalent magnetoresistance $R_{e}$ of the soft magnetic material. The increase of the thickness will increase the cross-sectional area of the magnetic circuit, decrease the magnetoresistance, increase the magnetic flux and increase the electromagnetic force.

The effect of increasing the thickness of the shell to improve the electromagnetic force is not significant. The thickness of the shell is designed too thick, which will cause material waste, so the thickness of the shell does not need to be designed too thick.

The Influence of Armature Length on Electromagnetic Force

In the simulation, the change range of the length increment of the armature is -5 ~ 5mm, the step size is 2mm. Figure 5 is obtained by processing simulation data.
Increasing the armature length $\Delta c$ in the air gap range will increase the electromagnetic force. It can be seen from figure 5 that when the air gap is 0 and 1.3mm, the electromagnetic force increases by 25.8691N and 0.4871N respectively when $\Delta c$ increases from -5 to 5mm.

The increase of $\Delta c$ will increase the magnetoresistance of the armature, but the relative area of the gasket and the armature will increase gradually, and the area of the flux line passing through the magnetic conducting material in the nonworking air gap will increase, which will reduce the magnetoresistance of the rear end of the armature. Because the permeability of air is much lower than that of soft magnetic materials, the proportion of nonworking air gap magnetoresistance in total magnetoresistance is also large, although the increase of $\Delta c$ will cause $R_1$ increases, but also causes $R_{o2}$ reduced, $R_c$ increases less than $R_{o2}$ reduction, total $R$ decreases, the electromagnetic force increases.

the air magnetoresistance is the main part of the total magnetoresistance. When the air gap is large, With the rapid increase of $R_{o1}$, the total magnetoresistance will also rise rapidly. Therefore, when the air gap is large, the influence caused by the change of $\Delta c$ is small and the increase of electromagnetic force is low. The length of the armature can be increased to improve the electromagnetic force, but at the same time, the dynamic performance of the solenoid valve will be reduced.

**Influence of Armature Radius on Electromagnetic Force**

In the composition of the magnetic circuit, the armature is a very important ring. The radius of the armature changes from -2.5mm to 0mm with a positive direction of radius increase and a step of 0.5mm. Figure 6 is obtained.
According to Figure 6, with the increase of radius, the electromagnetic force increases gradually. When $\Delta R$ increases between -2mm and 0mm, the electromagnetic force basically increases linearly.

Increasing $\Delta R$ will increase the cross-sectional area of the armature, and then the area of the pole shoe relative to it. The magnetoresistance of the armature is inversely proportional to its cross-sectional area, so the increase of $\Delta R$ will reduce the magnetoresistance. After passing through the back end of the armature, the magnetic force line will pass through the nonworking air gap and enter the gasket. When $\Delta R$ is increased, the length of the air gap that needs to pass through will be reduced, and the nonworking air gap magnetoresistance will also be reduced. Therefore, under the joint influence of the two aspects, the electromagnetic force will increase with the increase of $\Delta R$. The increase of armature radius will lead to the increase of mass and decrease of dynamic performance of solenoid valve.

**Influence of Guide Sleeve on Electromagnetic Force**

Most of the solenoid valves are non-guide sleeve type. With the deepening of research, researchers try to improve the electromagnetic force performance of high speed on-off valve by adding guide sleeve structure. The two ends of the guide sleeve structure are magnetic conducting materials, the middle section is magnetic isolation materials, usually pure copper, which mainly depends on pure copper to improve the distribution of magnetic force lines. In order to explore the influence on the electromagnetic force performance when the guide sleeve material is all copper, this
paper adds a kind of all copper guide sleeve on the basis of no guide sleeve and magnetic ring type guide sleeve to explore the effect of three guide sleeve structures on the electromagnetic force, as shown in Figure 7. The electromagnetic force performance curves of different guide sleeve structures at 300 ampere turns are shown in Figure 8.

![Figure 7. Three types of high speed on-off valve.](image)

(a) Magnetic ring type  (b) Pure copper type  (3) Without guide sleeve

![Figure 8. Influence of guide sleeve type on electromagnetic force performance.](image)

The influence of pure copper guide sleeve and no guide sleeve on the electromagnetic force is basically the same, the two curves are coincident, and the guide sleeve with magnetic separation ring can increase the electromagnetic force in the small air gap width.

By looking up the list of Ansoft material library, it is found that the relative permeability of pure copper is about 1, which is basically the same as that of vacuum, so when the guide sleeve material is set to all copper, its effect is the same as that of no guide sleeve, so the two curves coincide. Because the magnetic permeability of the magnetic separation ring and its upper and lower materials is very different, which plays the role of changing the magnetic line path, so the electromagnetic force can be increased. When the air gap is 0 mm, compared with the other two structure valves,
the electromagnetic force is increased by 14.87N. When the air gap width of the three structures is large, the magnitude of the electromagnetic force is basically the same. Therefore, we can improve the electromagnetic force of the solenoid valve by designing the guide sleeve with a magnetic separation ring, so as to increase the gradient of the electromagnetic force.

THE INFLUENCE ORDER OF PARAMETERS ON ELECTROMAGNETIC FORCE

Different parameters will have different effects on the electromagnetic force. In order to improve the electromagnetic force according to the demand, it is not only more purposeful to select some parameters with significant effect for subsequent improvement, but also can reduce the number of trial production. Therefore, it is necessary to obtain the order when the parameters affect the response. Usually, the coefficient $r$ can be used to evaluate the correlation between variables and output. The closer the absolute value of $r$ is to 1, the greater the influence is. When $r < 0$, response $y$ is negatively correlated with parameter $x$, when $r > 0$, response $y$ is positively correlated with parameter $x$.

$$
r = \frac{n \sum x_i y_i - (\sum x_i)(\sum y_i)}{\sqrt{n \sum x_i^2 - (\sum x_i)^2} \sqrt{n \sum y_i^2 - (\sum y_i)^2}}$$

$n$ is the number of sample points, $x_i$ is the size of a parameter at point $i$, $y_i$ is the size of the point $i$ response. The parameters are shown in Table I, and the order of influence of five parameters on electromagnetic force is analyzed.

| Parameter name                      | Range    | Step |
|------------------------------------|----------|------|
| Air gap/mm                         | [0, 1.2] | 0.6  |
| Shell thickness increment/mm       | [0, 4]   | 2    |
| Length increment of armature/mm    | [-4, 4]  | 4    |
| Radius increment of armature/mm    | [-2, 0]  | 1    |
Four parameters, each of which takes three values, generate a total of 81 sample points to analyze the influence of parameters on the electromagnetic force. The results of electromagnetic force are obtained by simulation in Ansoft, and the results of influence degree of parameters on electromagnetic force are displayed by $r$-parameter table, as shown in Table II.

| Parameter name                | $r$  |
|-------------------------------|------|
| Air gap                       | -0.631 |
| Shell thickness increment     | 0.004 |
| Length increment of armature  | 0.099 |
| Radius increment of armature  | 0.408 |

According to table II, except for air gap, when other parameters increase in a positive direction, the electromagnetic force will increase. The order of influence of parameters on electromagnetic force is: air gap > armature radius increment > armature length increment > shell thickness increment. The influence of air gap on the electromagnetic force is the greatest. The purpose of changing the electromagnetic force can be achieved through the reasonable design of air gap range, while the thickness of the shell basically does not affect the electromagnetic force. The influence of armature radius is greater than that of armature length, so when designing armature, more consideration can be given to the design of radius.

**CONCLUSION**

In this paper, the influence of some structural parameters on the electromagnetic force performance is studied, and the order of the influence of parameters on the electromagnetic force is obtained by coefficient $r$, and the following conclusions are obtained:

1) When the thickness increment of the shell increases, the electromagnetic force can be increased, but the effect is not obvious. The length of the armature changes the magnitude of the electromagnetic force by influencing the magnetoresistance. The electromagnetic force increases with the increase of the length of the armature. The electromagnetic force performance of the high speed on-off valve without guide sleeve is basically the same as that of the pure copper guide sleeve, and the guide sleeve with magnetic separation ring can increase the electromagnetic force. The
armature radius can change the magnitude of the electromagnetic force by influencing the magnetoresistance. When the radius is increased, the electromagnetic force can be increased.

(2) The influence order of four parameters on electromagnetic force is: air gap > armature radius increment > armature length increment > shell thickness increment.

ACKNOWLEDGEMENTS

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