Analysis of Performance Effect Factors of Three-Stage Electro-Hydraulic Servo Valve

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***Abstract*— A new modeling software, AMEsim is put forward in this paper to develop a nonlinear model for a higher performance three stage electro-hydraulic servo valve. The simulation results and experimental results on existing valve are consistent, which proves that the developed model is right. The analysis of the model shows that pilot valve bandwidth mainly affects the bandwidth of three-stage electro-hydraulic servo valve and is responsible for overshoot. The analysis also indicates that pilot valve resolution affects the resolution of three-stage electro-hydraulic servo valve and pilot valve rated flow affects the bandwidth and overshoot. The result further reveal that the position transducer affects the bandwidth and overshoot, servo controller affects the bandwidth and stability, the spool diameter and mass affect the bandwidth and hydraulic natural frequency, flow force on spool affects the bandwidth, overlap distance of restriction edge affects the dead zone size of mid-position and resolution of mid-position, coulomb friction force between spool and sleeve affects the resolution and radial clearance affects leakage flow and resolution. The analytical results are very useful because the methods can be applied to other similar systems.**

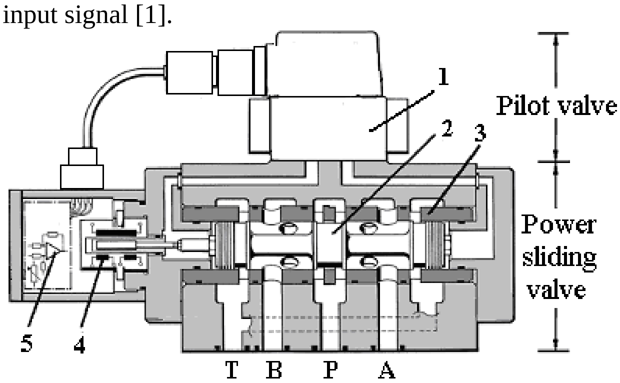
***Index Terms*—Amesim, three-stage electro-hydraulic servo valve, modeling and simulation, test, bandwidth, pilot valve, position transducer, servo controller, overshoot, dead zone, resolution**

I. INTRODUCTION

Three-stage electro-hydraulic servo valve is a complex and integrated mechanism comprising electricity, hydraulic and electronics components. Its application is in higher performance equipments, such as vibration test bench, multi-degree of freedom motion simulator, load simulator etc. Higher performance demands are placed on three-stage electro-hydraulic servo valve, therefore, it is necessary to study the performance of the valve. This paper studies the construction and principle of three-stage electro-hydraulic servo valve and builds its non-linear model using AMEsim modeling software. The simulation results based on parameters of existing valve are almost consistent with the experimental test results, which proves that the model is right. The analysis results of the model show what affect the performance of three-stage electro-hydraulic servo valve.

II. CONSTRUCTION AND PRINCIPLE

The main components of the three-stage electro-hydraulic servo valve as shown in Fig. 1 are pilot valve, power sliding valve, position transducer and servo controller. Its block diagram is shown in Fig. 2. The position transducer, which is excited via an oscillator, measures the position of the spool of power sliding valve. This signal then is demodulated and fed back to compare with the input signal. The servo controller drives the pilot valve until the error between input signal and feedback signal is zero. Thus, the position of the spool is proportional to the input signal and output flow is proportional to both the position of the spool and the input signal [1].



1-The pilot valve; 2-The spool of power sliding valve; 3-The sleeve of power sliding valve; 4-The position transducer; 5-The servo controller

Figure 1. A schematic view of three-stage electro-hydraulic servo valve

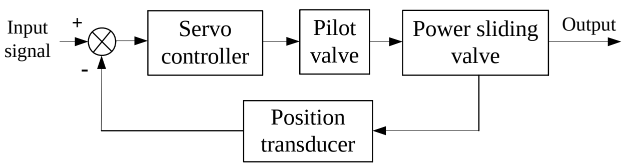


Figure 2. The principle block diagram of three-stage electro-hydraulic servo valve

Manuscript received March 16, 2009; revised April 20, 2009; accepted May 15, 2009.
This project is supported by the Ministry of Science and Technology of the People's Republic of China. (No. 2006BAF01B12-03).

doi:10.4304/jcp.4.12.1216-1222

III. MODELING, SIMULATION AND EXPERIMENTAL TEST

A. Introduction of AMESim

AMESim is a modeling, simulation and analysis software for hydraulic and mechanical systems [2,3]. It has recently, developed a unified platform of modeling and simulation in multidisciplinary field, and it can be used in mechanism, hydromechanics, pneumatic, heat, electricity and magnetism. It has rich module libraries, which can be extended according to demands. Modules are used in accordance with the actual physical system to build simulation model without having to deduce the complex mathematical model. In order to reduce simulation time and improve the accuracy of simulation, its intelligent solver can automatically select the best integration algorithm from the seventeen algorithms according to the mathematical features of the model. AMESim provides complete analytical tools to analyze and optimize system, such as linear analysis, modal analysis, spectrum analysis and model simplification tools etc [4].

B. Modeling

The design of the three-stage electro-hydraulic servo valve model includes four parts; namely, pilot valve, power sliding valve, position transducer and servo controller.

The pilot valve is shown in Fig. 3, its model is from hydraulic module and control library of AMEsim, static and dynamic characteristics of the pilot valve are both considered in the model.

Factors considered in the modeling of power sliding valve, are the diameter of spool, the mass of spool, the viscous damping force of spool, the coulomb friction force between spool and sleeve, the stroke of spool, the flow force on spool, the radial clearance and the restriction edge overlap between spool and sleeve [5]. The model of the power sliding valve is from hydraulic component design module and machinery module libraries of AMEsim. In the model of power sliding valve, as shown in Fig. 4, module 3, 4, 6, 7, 10 and 11 are used to consider the diameter of spool, the flow force on spool, the radial clearance and the restriction edge overlap between spool and sleeve; module 5 as the mass of spool, the coulomb friction force of spool, the stroke of spool and the viscous damping force of spool; module 1, 2, 8 and 9 as the spool drive area and the volume of control chamber, module 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26 as the hydraulic flow path. Module 12, 13 are zero force source modules.

The model of position transducer is shown in Fig. 5, it is from control module library of AMEsim. It's characteristic is a first order lag, with k as the gain and τ as the time constant.

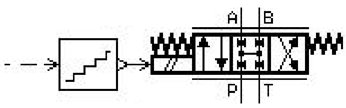
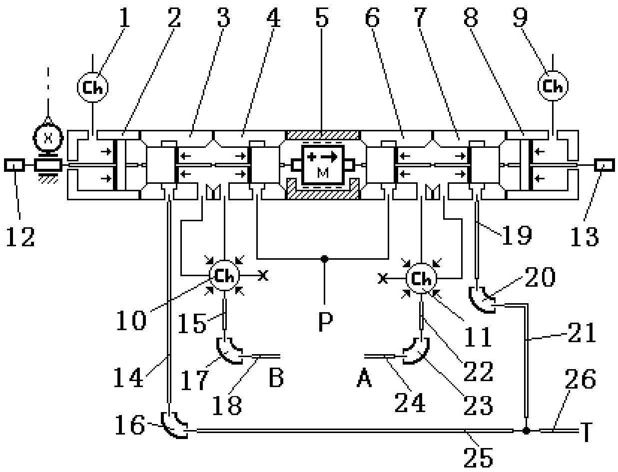


Figure 3. The model of the pilot valve



1,9-Hydraulic chamber; 2,8-Piston; 3,4,6,7-Spool-sleeve; 5-Mass with friction and ideal end stops; 10,11-Hydraulic volume with pressure dynamic; 12,13-zero force source; 14,15,18,19,21,22,24,25,26-Hydraulic pipe; 16,17,20,23-Hydraulic bend pipe

Figure 4. The model of the power sliding valve

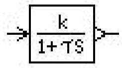


Figure 5. The model of position transducer

The model of servo controller, as shown in Fig. 6, is a classical PID controller; it is from control module library of AMEsim.

Combining the models of pilot valve, power sliding valve, position transducer, and servo controller, coupled with control signal, oil tank, restrictive valve and hydraulic fluid property module, we get the complete simulation model of three-stage electro-hydraulic servo valve, as shown in Fig. 7 [6].

Figure 6. The model of servo controller

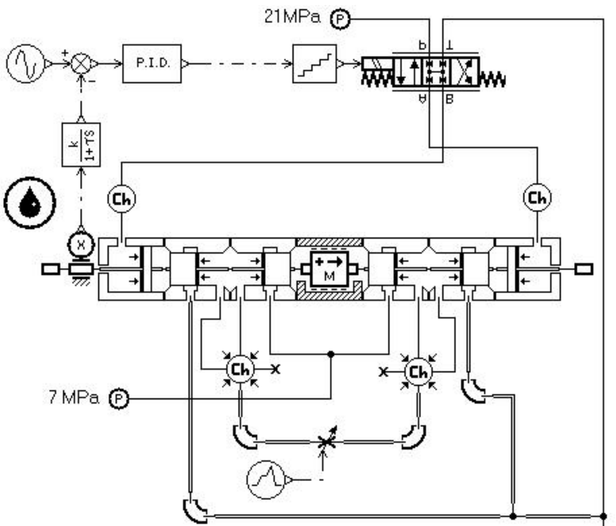


Figure 7. The model of three-stage electro-hydraulic servo valve

C. Simulation and Experimental Test

Based on existing three-stage electro-hydraulic servo valve, we set the parameters of the model, where several parameter values will be introduced. The oil pressure of the pilot valve is 21 MPa; the diameter of spool is 0.022 m; the oil pressure of power sliding valve is 7 MPa. PID controller parameter values are adjusted to optimize performance of three-stage electro-hydraulic servo valve in the process of simulation. A variety of diagrams, such as zero load flow diagram and Bode diagram, are obtained from the simulation. From zero load flow diagram; overlap distance, flow gain and rated flow are obtained; from Bode diagram, bandwidth of amplitude response and phase response are obtained.

Fig. 10 shows the experimental test of three-stage electro-hydraulic servo valve. Fig. 8 is the zero load flow diagrams, which shows simulation curve and test curve. Fig. 9 is the Bode diagram, which also shows simulation curve and test curve. Obviously, the simulation results and the test results are almost consistent, so the model, as shown in Fig. 7, is right.

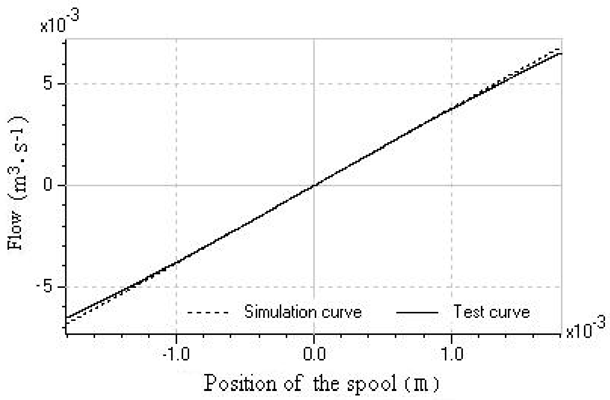


Figure 8. The zero load flow diagram

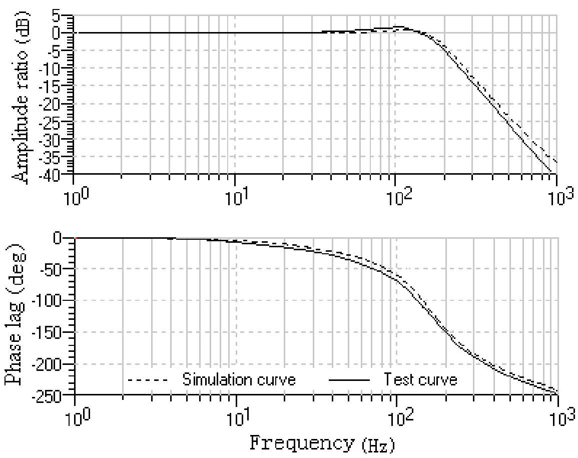


Figure 9. The Bode diagram

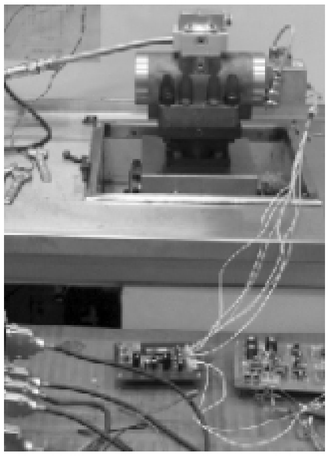


Figure 10. The experimental test

IV. Simulation Analysis

The complete model of three-stage electro-hydraulic servo valve is built and the model is proved right, so it can be used to analyze how all kinds of factors affect the performances of three-stage electro-hydraulic servo valve.

A. Analysis of Pilot Valve Bandwidth

For the model, as shown in Fig. 7, assuming that other parameters do not change, we only change the parameter values of pilot valve bandwidth, the simulation results show that the change of pilot valve bandwidth parameter values will affect the bandwidth of three-stage electro-hydraulic servo valve, and overshoot etc.

For example, the bandwidth of amplitude response of the pilot valve is changed from 140 Hz to 87 Hz, the simulation result is shown in Fig. 11, comparing simulation curve in Fig. 9 with Fig. 11, it shows that the bandwidth of amplitude response of three-stage electro-hydraulic servo valve changes from 200 Hz to 151 Hz, meaning that bandwidth of amplitude response reduces while the overshoot increases.

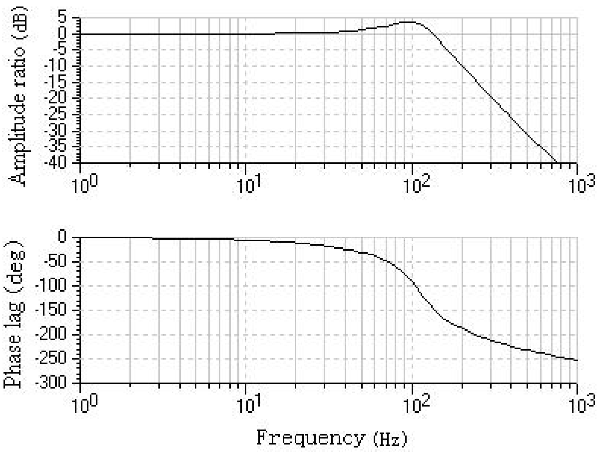


Figure 11. The Bode diagram

B. Analysis of Pilot Valve Resolution

For the model, as shown in Fig. 7, assuming that other parameters do not change, we only change the parameter of pilot valve resolution, the simulation results show that this will affect the resolution of three-stage electro-hydraulic servo valve.

For example, when the resolution of pilot valve is 0.1%, the resolution diagram of three-stage electro-hydraulic servo valve is Fig. 12; when the resolution of pilot valve is 0.2%, the resolution diagram of three-stage electro-hydraulic servo valve is Fig. 13. Comparing Fig. 12 with Fig. 13, it shows that Δx_1 is smaller than Δx_2; that means, the smaller the pilot valve resolution, the smaller the resolution value of three-stage electro-hydraulic servo valve.

C. Analysis of Pilot Valve Rated Flow

For the model, as shown in Fig. 7, assuming that other parameters do not change, we only change the parameter of pilot valve rated flow, the simulation results show that this will affect the bandwidth, overshoot etc.

For example, with large changes in the pilot valve rated flow, the Bode diagram from the simulation result is shown in Fig. 14. Comparing simulation curve in Fig. 9 with Fig. 14, the bandwidth and overshoot increase.

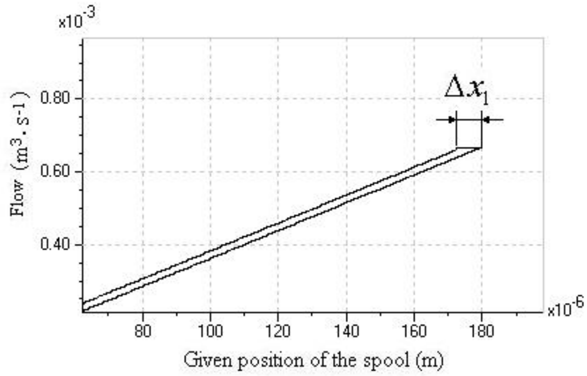


Figure 12. The resolution diagram

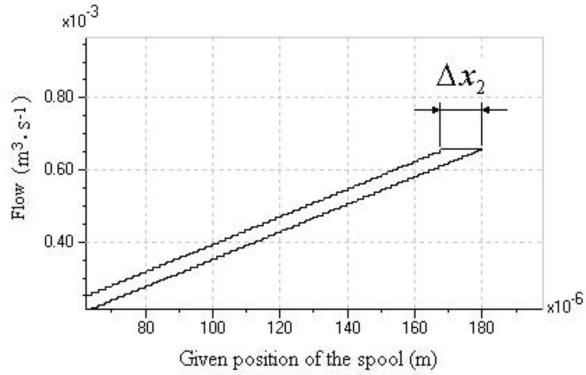


Figure 13. The resolution diagram

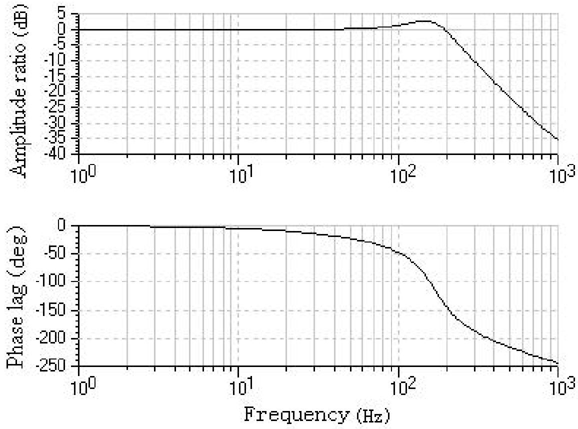


Figure 14. The Bode diagram

D. Analysis of the Position Transducer

For the model, as shown in Fig. 7, assuming that other parameter do not change, we only change the parameter of the position transducer, the simulation results show that this will affect the bandwidth, overshoot etc.

For example, the turning point in frequency of position transducer changes smaller, namely, the time constant τ changes larger, from the simulation we have the Bode diagram, as shown in Fig. 15. Comparing simulation curve in Fig. 9 with Fig. 15, the bandwidth reduces and overshoot increases.

E. Analysis of the Servo Controller

For the model, as shown in Fig. 7, assuming that other parameters do not change, we only change the parameter of the servo controller. The simulation results show that this will affect the bandwidth, stability etc.

For PID controller, it will become a P controller when we change its parameters properly [7]. When the servo controller is a P controller, by simulation we have the Bode diagram, as shown in Fig. 16. Comparing Fig. 16 with simulation curve in Fig. 9 with PD controller, the bandwidth of amplitude response of three-stage electro-hydraulic servo valve changes from 200 Hz to 145 Hz. The bandwidth of phase response changes from 140 Hz to 100 Hz. The result indicates that control strategy can affect the bandwidth.

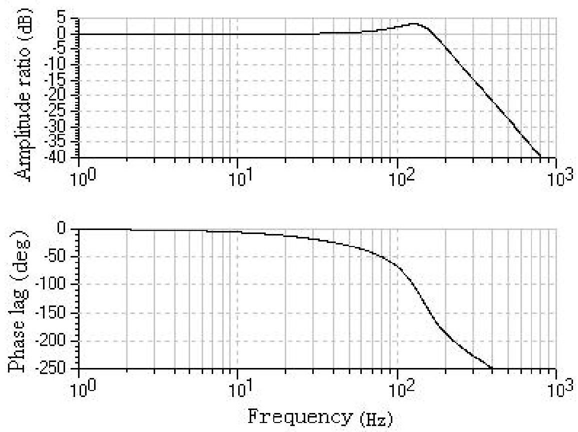


Figure 15. The Bode diagram

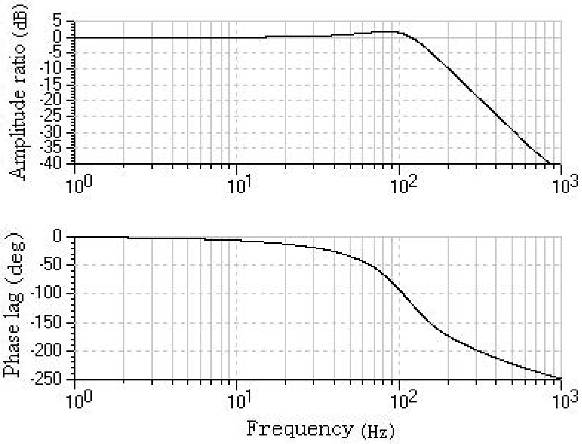


Figure 16. The Bode diagram

F. Analysis of Spool Diameter and Mass

Spool diameter may be different for different rated flow. The mass of spool is different because of different spool diameter. The mass of large diameter spool is usually larger than the mass of small diameter spool. For the model, as shown in Fig. 7, assuming that other parameters do not change, we only change the diameter of the spool, the simulation results show that the change of spool diameter will affect the bandwidth, hydraulic natural frequency etc.

For example, the diameter of spool is changed from 0.022m to 0.030m, the simulation result is shown in Fig. 17, comparing simulation curve in Fig. 9 with Fig. 17, it shows that the bandwidth of amplitude response of three-stage electro-hydraulic servo valve changes from 200 Hz to 99 Hz, meaning that bandwidth of amplitude response reduces.

G. Analysis of the Flow Force on Spool

The flows through the spool ports induce non-linear forces on the spool, which may have some effect on the performance of the three-stage electro-hydraulic servo valve. For the model, as shown in Fig. 7, assuming that other parameters do not change, the flow force on spool is not taken into account. The simulation results show that this will affect bandwidth.

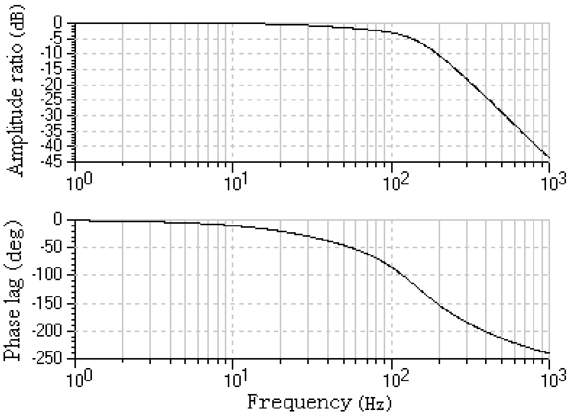


Figure 17. The Bode diagram

For example, the flow force on spool is not taken into account, The Bode diagram, as shown in Fig. 18, is from the simulation result. Comparing simulation curve in Fig. 9 with Fig. 18, it shows a slight change in the bandwidth of amplitude response and phase response.

H. Analysis of Overlap Distance of Restriction Edge

When spool is at the mid-position, the overlap distance of restriction edge of spool and sleeve will affect the performance of three-stage electro-hydraulic servo valve. For the model, as shown in Fig. 7, assuming that other parameters do not change, we only change the overlap distance of restriction edge of spool and sleeve, the simulation results show that this will affect the dead zone size of mid-position, resolution of mid-position etc.

For example, the overlap distance of restriction edge of spool and sleeve changes larger, from the simulation we have the zero load flow diagram, as shown in Fig. 19, comparing simulation curve in Fig. 8 with Fig. 19, it shows that the dead zone size of mid-position becomes larger.

The overlap distance of restriction edge of spool and sleeve changes smaller to negative value, we have the zero load flow diagram, as shown in Fig. 20, comparing Fig. 20 with simulation curve in Fig. 8 and Fig. 19, it shows that there is no dead zone. The flow gain of mid-position is larger than other position in Fig. 20.

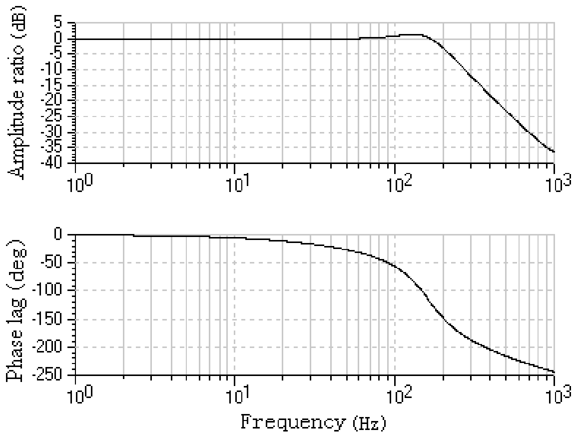


Figure 18. The Bode diagram

Figure 19. The zero load flow diagram

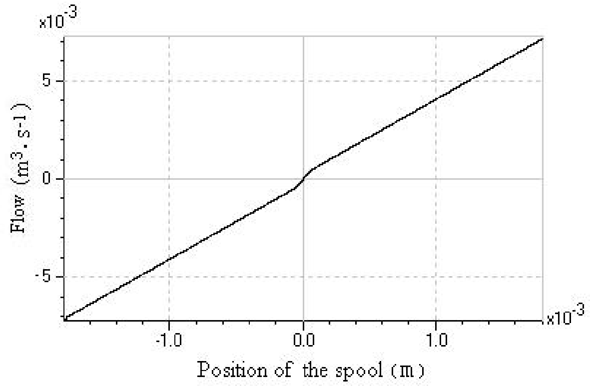


Figure 20. The zero load flow diagram

I. Analysis of Coulomb Friction Force

When spool moves in sleeve, there is coulomb friction force on spool, the direction of force is opposite to direction of spool moving, and so the performance of three-stage electro-hydraulic servo valve will be affected. For the model, as shown in Fig. 7, assuming that other parameters do not change, we only change the coulomb friction force value of spool; the simulation results show that this will affect the resolution [8].

Fig. 21 and Fig. 22 are the resolution diagrams for different coulomb friction force values. The friction value corresponding to Fig. 21 is smaller than the friction value corresponds to Fig. 22. Comparing Fig. 21 with Fig. 22, it shows that Δx_1 is smaller than Δx_2 ; meaning that the smaller the friction force, the smaller the resolution value.

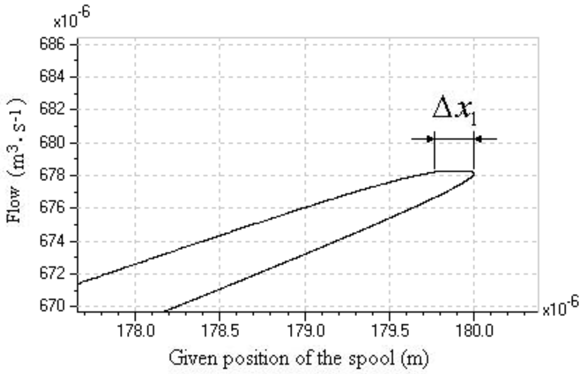


Figure 21. The resolution diagram

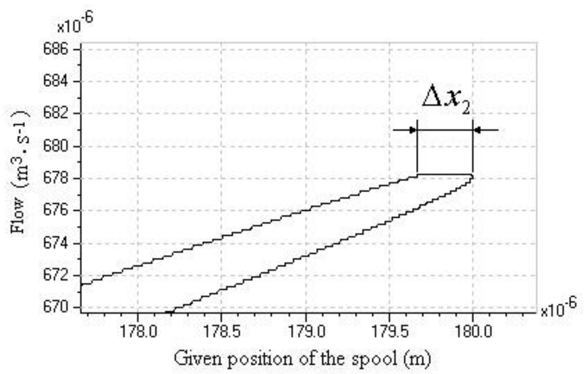


Figure 22. The resolution diagram

J. Analysis of the Radial Clearance

There is radial clearance between spool and sleeve. It will affect the performance of three-stage electro-hydraulic servo valve. For the model, as shown in Fig. 7, assuming that other parameters do not change, we only change the radial clearance value; the simulation results show that this will affect the leakage flow, the resolution, etc.

In Fig. 7, restrictive valve is closed; leakage flow can be obtained. Fig. 23 and Fig. 24 are the leakage flow diagrams for different radial clearance value. The radial clearance value corresponding to Fig. 23 is smaller than the radial clearance value corresponds to Fig. 24. Comparing Fig. 23 with Fig. 24, it shows that the smaller the value of the radial clearance, the smaller the leakage flow.

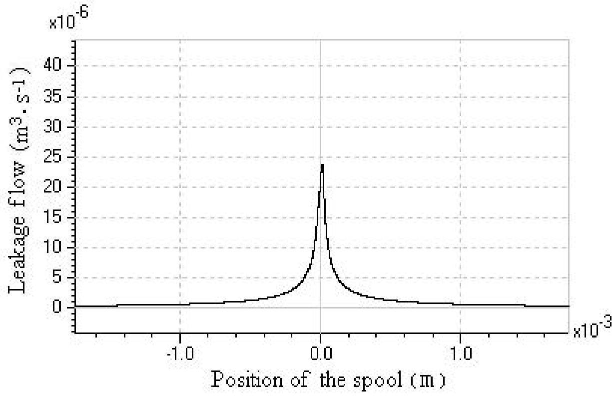


Figure 23. The leakage flow diagram

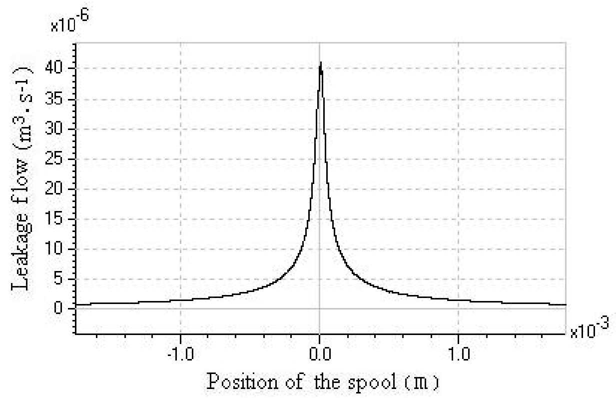


Figure 24. The leakage flow diagram

V. CONCLUSIONS

Modeling and simulation results of Three-Stage Electro-Hydraulic Servo Valve have been presented. The results show that the performances of three-stage electro-hydraulic servo valve are mainly affected by pilot valve bandwidth, pilot valve resolution, pilot valve rated flow, position transducer performance, servo controller performance, the spool diameter and mass, flow force on spool, overlap distance of restriction edge, coulomb friction force and radial clearance between spool and sleeve. We can conclude from the results that all kinds of effect factors must be considered synthetically in developing higher three-stage electro-hydraulic servo valve. The methods of modeling and analysis presented in this paper are very useful as it can be applied to other similar systems.

ACKNOWLEDGMENT

The authors wish to thank Professor H. R. Li for his guidance. This work is supported financially by the Ministry of Science and Technology of the People's Republic of China.

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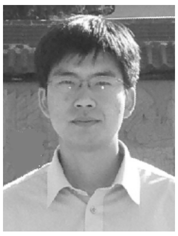

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