

Modeling and Simulation of a Hydraulic Reducing Valve Driven by Giant Magnetostrictive Actuator based on Matlab and AMESim

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Abstract. A hydraulic directly operated reducing valve driven by Giant Magnetostrictive Actuator(GMA), which is used in a vehicle, is designed in this paper. The mathematical models of GMA and reducing valve are established. And then use of Matlab and AMESim analyzed the influence of theirs structure parameters on the step response characteristic. The results show that the stiffness of the reducing valve's and GMA's spring have some influence on adjustment time of step response. The sectional diameter of the controlled chamber not only affects the adjustment time, but also affects the output pressure of the reducing valve.

Introduction

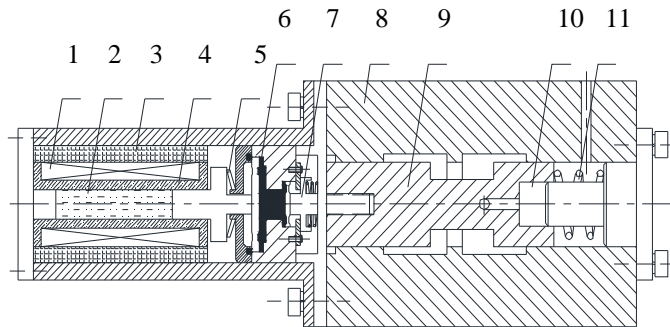
Hydraulic systems are often used in a vehicle. Each branch of the hydraulics pressure is different. Some branch of the hydraulics pressure falls below the system pressure. So a reducing valve is required. In order to improve the stability of the hydraulic system, a faster response, more adaptive electro-hydraulic reducing valve needs developing, to meet increasing stringent requirements of the hydraulic system for the modern vehicle.

Since the birth of Giant Magnetostrictive Material(GMM), Giant Magnetostrictive Actuator(GMA) of which core material is GMM is widely used in the hydraulic control valve, to improve the overall performance of the hydraulic system. Many scholars have done a lot of research on it. Scholars from Sweden developed a fuel injection valve using GMM and applied for a patent.^[1] Mel Goodfriend and other people from America designed a high-frequency proportional valve using GMM.^[2] Takahairo Urai and other people from Japan developed a directly driven servo valve using GMM.^[3] In China, Scholars from Zhejiang University early designed and experimentally studied a kind of flapper-nozzle pneumatic pressure valve driven by GMA.^[4] Yanbin Liu and other people carried out an experimental research on the flow characteristic of the flow valve driven by GMA.^[5] Zhaoshu Yang and other people designed a servo valve driven by GMA, and it approached a bandwidth higher than 100 Hz; the load flow rate reached 30 L/min under a system pressure of 21MPa.^[6] These scholars have researched about the hydraulic control valve driven by GMA, But haven't designed a reducing valve using GMA, so application of new functional materials-GMM in the reducing valve driven by GMA, has important theoretical and practical significance in precise control of pressure and rapid response.

Many scholars in China have carried out the simulation analysis of the electro-hydraulic reducing valve within Matlab or AMESim environment.^[7,8,9,10] A single software was only used to simulate the hydraulic pressure valve in these paper. In this paper, Matlab and AMESim are jointly used to simulate the reducing valve driven by GMA. And analyzed the influence of theirs structure parameters on the step response.

The structure and working principle of the Reducing Valve Driven by GMA

The structure of the directly operated reducing valve driven by GMA is shown in Fig. 1.



- 1- Control coil 2-GMM rod 3- Permanent magnet 4- Bobbin 5- Spring 6- Hydraulic oil
7- Output rod 8-Body 9-Spool 10- Controlled chamber 11- Return spring

Fig. 1. The structure of the Reducing Valve Driven by GMA

The reducing valve consists of GMA, hydraulic amplification mechanism and the directly operated reducing valve. The controller inputs a step signal to GMA, and then GMM rod outputs displacement and force. The displacement is enlarged after hydraulic amplification mechanism. The output rod pushes the spool movement. On the other hand, the oil flows into the inlet port and out from the outlet port. And some of this oil flow through the throttling orifice into controlled chamber. With the valve opening is reduced, the damping and pressure drops increase at valve port, and then the output pressure reduces. When the force acting on the spool reaches a balance, the output pressure holds constant.

The Dynamic Math Model of the Reducing Valve Driven by GMA

The Dynamic Math Model of the GMA. When the current $i(t)$ flows through the control coil, the magnetic circuit equation is

$$\Phi = \frac{N \cdot i(t) + x_1 / d_{33}}{R_m} \quad (1)$$

In Eq. 1, Φ is exciting flux; N is turns per coil; x_1 is displacement of the GMM; d_{33} is Piezomagnetic constant; R_m is magnetic reluctance.

Dynamic equation of GMM is

$$k \frac{\Phi}{d_{33}} = m_e \frac{d^2 x_1}{dt^2} + B \frac{dx_1}{dt} + K_1 x_1 + F_1 \quad (2)$$

In Eq. 2, k is eddy current constant; m_e is equivalent mass for GMM; B is damping coefficient for GMM; K_1 is stiffness coefficient for GMM; F_1 is the hydraulic force acting on the output rod.

In this paper a hydraulic amplification mechanism is used, and the compressibility of oil is negligible, so the equation about the displacement and force of input and output is

$$\frac{F_2}{F_1} = \frac{x_1}{x_2} = \frac{1}{n} \quad (3)$$

In Eq. 3, F_2 is the hydraulic force amplified acting on output piston; x_2 is the displacement of output piston; x_1 is the displacement of input piston; n is the amplification.

Dynamic equation of hydraulic amplification mechanism is

$$F_2 = m_2 \frac{d^2x}{dt^2} + B_0 \frac{dx}{dt} + K_0x \quad (4)$$

In Eq. 4, m_2 is output equivalent mass; B_0 is the friction damper between output piston and cylinder wall; K_0 is the stiffness of return spring.

The Math Model of the Reducing Valve. The spool force balance equation is

$$F_2 - P_1A_1 = M \frac{d^2x}{dt^2} + B_v \frac{dx}{dt} + K_s(x + x_0) \quad (5)$$

In Eq. 5, P_1 is the pressure in the controlled chamber; A_1 is the area of the middle piston; M is the mass of the spool; B_v is the viscous damping coefficient; K_s is the stiffness of the spring; x_0 is the pre-compression of the spring.

The flow equations at the outlet port is

$$Q_1 = C_d Wx \sqrt{\frac{2(P_s - P_0)}{\rho}} \quad (6)$$

In Eq. 6, C_d is the flow coefficient; W is the Area Gradient; P_s is the input pressure; ρ is the density of hydraulic oil.

The orifice flow equation is

$$Q_2 = C'_d A_x \sqrt{\frac{2(P_0 - P_1)}{\rho}} \quad (7)$$

In Eq. 7, C'_d is the flow coefficient for the orifice, A_x is the area of the orifice; P_0 is the output pressure.

The continuity flow equation is

$$Q_1 - Q_2 = \frac{V}{E} \frac{dP_0}{dt} - A_1 \frac{dx}{dt} \quad (8)$$

In Eq. 8, V is the volume of the controlled chamber; E is the bulk modulus.

The Co-Simulation Model of the Reducing Valve Driven by GMA

The Matlab Model. Matlab is mainly used to solve the mathematical simulation model of GMA. Program is divided into four portions: Signal Input, The module of GMA, The module of hydraulic amplification mechanism, And AMESim Interface Modules. The block diagram of the Matlab model is shown in Fig. 2.

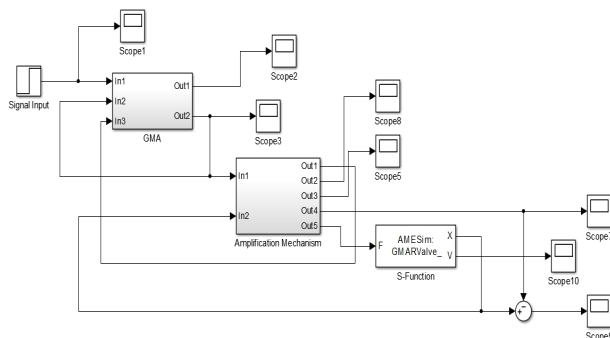


Fig. 2. The block diagram of GMA

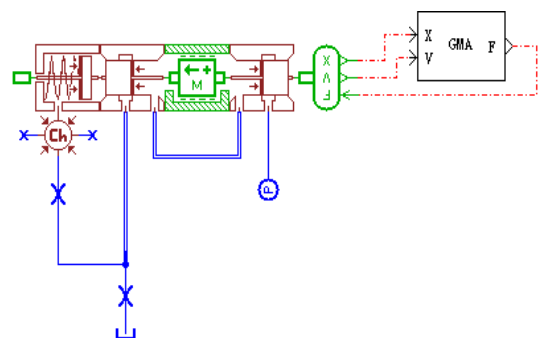


Fig. 3. The AMESim Model

The AMESim Model. A simulation model of its work process is established using the library of hydraulic component design in AMESim. It also needs to pay attention to the parameter in Matlab interface module. The simulation model of the whole system using AMESim is shown in Fig. 3.

The Simulation Results of Engagement Process

This paper researched that the impact of the stiffness of the reducing valve’s and GMA’s spring, the sectional diameter of the controlled chamber on the step response. In this paper, the flow coefficient and the density of hydraulic oil are not affected by the temperature. So the flow coefficient is constant, and the density of hydraulic oil is $860kg/m^3$. The system pressure is $2.8MPa$.

The impact of the stiffness of the reducing valve’s spring. The stiffness of the springs are 15N/mm, 25N/mm, 35N/mm and 45N/mm; the sectional diameter of the controlled chamber is 11mm; the stiffness of GMA’s spring is 60 N/mm. These data input the module of the parameter initialization. Run the simulation, drawing the curve as shown in Fig. 4. In the curve, the horizontal axis represents the time-t, of which unit is second-s; the vertical axis represents the pressure, of which unit is bar. From Fig. 5 to Fig. 6, the coordinate axes have the same meaning as with Fig. 4, not repeat them.

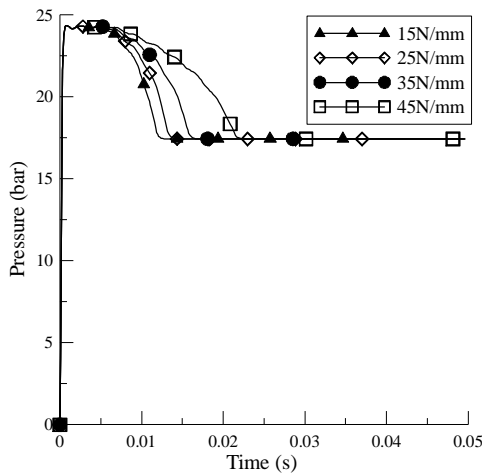


Fig. 4. The impact of the stiffness

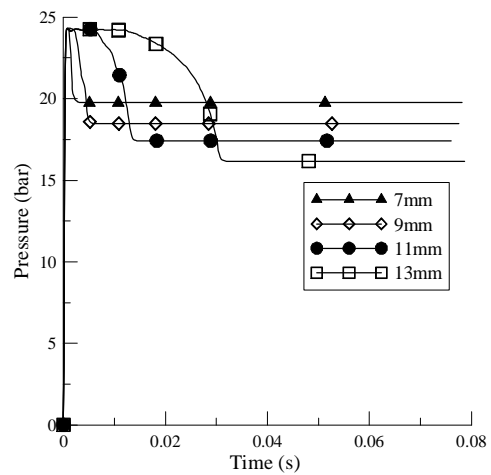


Fig. 5. The impact of the sectional diameter

Fig. 4 shows that with the increase of the stiffness of the valve’s spring, the step response of adjustment time increases, and the output pressure is steady.

The impact of the sectional diameter of the controlled chamber. The sectional diameter are 7mm, 9mm, 11mm and 13mm. The stiffness of the spring is 15N/mm; the stiffness of GMA’s spring is 60 N/mm. Run the simulation, drawing the curve as shown in Fig. 5.

Fig. 5 shows that with the increase of the sectional diameter of the controlled chamber, the step response of adjustment time increases, and the output pressure drops.

The impact of the stiffness of GMA’s spring. The stiffness of GMA’s spring are 60N/mm, 120N/mm and 240N/mm; the stiffness of the spring is 15N/mm, the sectional diameter of the controlled chamber is 11mm. Run the simulation, drawing the curve as shown in Fig. 6.

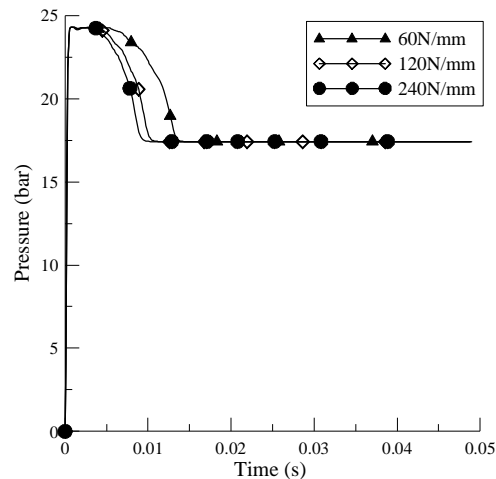


Fig. 6. The impact of the stiffness of GMA's spring

Fig. 6 shows that with the increase of the stiffness of GMA's spring, the step response of adjustment time drops, and the output pressure is still steady.

Conclusions

A mathematical model of the reducing valve driven is established. Then use of Matlab and AMESim analyzed the influence of its structure parameters. The results show:

The stiffness of the reducing valve's and GMA's spring have some influence on adjustment time of step response. The sectional diameter of the controlled chamber not only affects the adjustment time, but also affects the output pressure of the reducing valve. So reasonable optimization of the stiffness of the reducing valve's and GMA's spring, the sectional diameter of the controlled chamber, can obviously improve the dynamic characteristics of the reducing valve driven by GMA.

Through simulation analysis of the reducing valve driven by GMA in this paper, it has instruction significance to optimize the structure for the next work. Simulation results show using GMA can significantly improve the response time of the reducing valve and output the stable pressure.

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