Design and performance analysis of hydraulic switching valve driven by magnetic shape memory alloy

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Abstract
In this paper, the hydraulic switching valve is designed and its dynamic performance is investigated through proposing a fast response actuator with magnetic shape memory alloy (MSMA) to drive the valve. MSMA actuator with spring return is designed and a double-layered coil is constructed to achieve compactness of electromagnetic case. The dynamic characteristics of the MSMA actuator are analyzed and the step response characteristics is tested. Hydraulic switching valve with MSMA actuator is designed with poppet type. Pressure and velocity field in the flow channel under different valve opening and different inlet and outlet pressure differences are analyzed in COMSOL Multiphysics software. The dynamics of the valve poppet during opening and closing process is modeled mathematically, and simulation analysis are conducted in AMESim software to analyze the response of valve under step and square wave signals. The step response of output flow rate and pressure-flow characteristic under different operating conditions are obtained through experiment. The results show that the MSMA based valve can achieve fast response with opening time of 5 ms at the pressure difference of 1 MPa, providing a theoretical support for the development of hydraulic switching valve with high performance actuator driven by MSMA.

Keywords
Magnetic shape memory alloy, hydraulic valve, actuator, flow rate, pressure drop

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Introduction
Valve is a very important control component in the fluid power transmission system. Response is one of the most important characteristic parameters of hydraulic valve. With the increasing demand for hydraulic control systems by specific applications, especially with the development of digital hydraulics in recent years, high speed switching valve is attracting more and more interests from industrial applications. Electromagnet used to play an irreplaceable role in driving the valve switching actions conventionally, but disadvantages such as heat generation and low energy efficiency exist unfavorably at the same time. In recent years, with the emergence of new smart materials, various smart materials based sensors and actuators have become a very attractive research focus. Accordingly, efforts on employing smart materials into valve actuation devices in hydraulic systems have been taken extensively by the scholars from all over the world to pursue better dynamic performance of the valve.

Commonly, smart materials including piezoelectrics (PZT) and giant magnetostrictive material (GMM) are concerned most frequently. PZT has the advantages of fast response, large output force and low power
consumption, can be used to fabricate many kinds of actuators for hydraulic valve.\textsuperscript{1} However, since the strain of piezoelectric material is relatively small, it is impossible to directly drive the hydraulic valve spool. So it is necessary to use multi-layered stacking or displacement amplification mechanism to achieve the proper displacement for spool.\textsuperscript{4} In the case for the two-stage servo valve, the actuator of pilot stage can use the piezoelectric material to replace the traditional torque motor so as to miniaturize the whole pilot valve.\textsuperscript{5,6} Taking the advantages of light weight, simple structure, low power consumption, it has been widely used in robotic drives and other micro actuator related fields.\textsuperscript{7} At present, GMM materials in hydraulics are mainly used to develop high response actuators to replace torque motors of traditional force feedback servo valves. Because of fast response, high precision and large output force, its application in servo valve can enhance the dynamic performance effectively.\textsuperscript{8} In contrast with the conventional way by proposing the novel spool, the main body of the existing valve is not required to change while the performance is improved.\textsuperscript{9} Besides, magnetorheological fluid is also active in the research field of smart hydraulic valves. By controlling the current applied to the excitation coil of such valve, the pressure difference across the valve can be adjusted freely. The valve with such smart fluid can be made into a variety of valves with different structures to meet the corresponding requirements.\textsuperscript{10,11}

However, the biggest challenge to those applications is inadequate deformation of the materials. Magnetic shape memory alloy (MSMA) is characterized by rapid response comparable to them and large strain attributed to traditional temperature controlled shape memory alloy. Studies show that its maximum strain can reach 10\%, very suitable for driving directional valve.\textsuperscript{12} MSMA combines the fast response of PZT and GMM with the large strain of shape memory alloy.\textsuperscript{13} It has wide prospect applied in actuator because it is caused by the shape change of itself, rather than the result of the displacement of the armature component in the electromagnetic drive mechanism.

In the existing research, efforts are mainly taken on the attempt for sensors, actuators, and linear motors based on the magnetic shape memory effect, as well as energy recovery devices, strain sensors, and dampers based on the inverse magnetron shape memory effect.\textsuperscript{14-16} Moreover, since MSMA is a type of relatively new material, its constitutive equations and numerical simulation for deformation mechanism are under investigation by many scholars to pave the way for potential applications.\textsuperscript{17,18} However, the application of MSMA in hydraulic systems is mainly focused on the feasibility analysis of structure design, the applicability of different mathematical models and control strategies for different types of valves to improve the numerical simulation.\textsuperscript{19-21} Although valve is designed, analysis on the flow field and dynamic characteristics is carried out by simulation, fabrication of the MSMA valve prototype and the flow characteristics still need further demonstration. It is well known that hydraulic system is intrinsically weak in energy efficiency. With the increasing demand for energy saving implementation, energy efficient systems integrated with high speed switching valve are playing a more and more important role in future.\textsuperscript{22,23} Thus, valves with smart materials and structures are quite worthy of further investigation. However, study the application of MSMA based actuator into hydraulic valve is not conducted systematically in the existing work.

This paper mainly presents a compact hydraulic poppet valve driven by magnetic shape memory alloy to achieve high speed switching. The rest content is arranged as follows. Section 2 introduces the principle of MSMA based actuator and the design of electromagnetic coils. The characteristics of the actuator excited by different input signals are analyzed by simulation. In section 3, hydraulic switching valve is designed in detail and flowing characteristics are analyzed by simulation taking the influence of different factors into consideration. In section 4, the mathematical modeling of dynamic simulation is established in AMESim software. The step response and square wave input response characteristics of the valve are simulated and analyzed. In section 5, the performance test platform of the hydraulic switching valve is built, and the step response and pressure-flow rate characteristics of the valve are verified. Finally, a work summary of this paper is presented in section 6.

**Design of actuator based on MSMA**

**Switching principle**

Fast switching between on and off status is the basic need of the hydraulic switching valve. The rapid reciprocating motion of the spool makes the oil flow on and off at high speed through the opening. Therefore, the return scheme has to be considered in the design of high-speed switching valve actuator. According to the material characteristics, the spring recovery is proposed to make sure the valve spool returns to its original position firmly.\textsuperscript{24} As shown in Figure 1, Both the MSMA and the spring are in an initial state when they are not subject to a magnetic field. When a magnetic field perpendicular to the long axis of the MSMA is applied, MSMA stretches and the spring is compressed. The spring can be adjusted to provide a certain preload. If the magnetic field strength is reduced or even the magnetic field is completely removed, the spring in compression can provide a restoring force along the z-axis and squeeze the MSMA piece to its original shape. By
applying and canceling the magnetic field alternatively, the reciprocating regulation of material deformation can be realized. As an actuator, it drives the valve spool to perform the high speed switching motion.

**Electromagnetic field**

For a hydraulic valve, compactness is regarded as important feature all the way. So the ratio of magnetic flux density to volume should be emphasized when designing the actuator. In order to pursue high density and uniformity of magnetic field across the MSMA specimen, three types of coil winding layouts are analyzed by numerical simulation carried out in COMSOL Multiphysics software. The three-dimensional models are created as shown in Figure 2. According to design and calculation results in terms of electromagnetic circuit, the number of coil turns is 220, 224, and 220, respectively, and the input current through the wire is 0–6 A. Given the electromagnetic characteristics of the solenoid, simulation results of magnetic field strength around the air gap corresponding to the three coils are obtained as shown in Figure 3.

It can be seen from Figure 3 that the flux density at the core area of air gap section is around 0.65 T (Tesla), 0.4 T and 0.4 T respectively. From the perspective of size of the whole electromagnet, the volume of the actuator integrated with these electromagnets accounts for $2.16 \times 10^{-4} \text{m}^3$, $2.22 \times 10^{-4} \text{m}^3$, and $1.08 \times 10^{-4} \text{m}^3$ respectively. For a hydraulic valve, compactness is regarded as important all the way. So the ratio of magnetic flux density to volume should be emphasized when designing the actuator. From this aspect, the different architectures turn out with 3009, 1802, and 3704 T/m³ respectively. Obviously, electromagnet of type III represents the highest magnetic flux density and volume ratio. Therefore, it would be better to select for the electromagnet architecture of the MSMA actuator. On the other hand, when winding the copper wire of this type coil, the lower part of the structure has to drill a hole to output MSMA displacement, as shown in Figure 2(c). In practice, it will greatly increase the difficulty in winding, and this is a limitation to some extent. To avoid the shortage, and considering that both the magnetic flux density and volume ratio of the type I and III are greater than 3000 T/m³, the coil structure is finally determined with a combination of the advantages of the two structures. As shown in Figure 4(a), it is a double layered structure with separate upper and lower parts to facilitate the manufacture and installation. In each half, the outer shell made of electrician pure iron is added on the basis of structure type I. The structure guides the magnetic lines effectively and shields the magnetic field to reduce the interference of the internal magnetic field to the outside. The number of turns of the coil is finally taken as $240 \times 2$, and the maximum input current is 4 A. The simulation result for the magnetic field distribution of this structure is shown in Figure 4(b). The magnetic flux density at the air gap is increased to about 0.6 T and flux density is uniformly distributed, perfectly satisfying the requirements of the MSMA actuator.

**Dynamic response analysis**

In order to verify the performance of the MSMA actuator designed based on the structure proposed above, prototype is built to test. In the experiment, the
electromagnet of the actuator is applied with a step current signal of different amplitude and measurement for dynamic output response performance is conducted using the eddy current displacement sensor. The response in forward direction is mainly concerned in the experiment to investigate the fast switching actuation. The spring stiffness is 9.36 N/mm and the initial pre-pressure of spring is 0 N. Figures 5 to 7 show the experimental results of dynamic response performance of the MSMA actuator under different current amplitudes. The current signal is generated by the program-controlled power supply used in the experiment, and the current data is real-timely collected and read into computer.

It can be seen that the maximum displacement which the actuator increases with the magnitude of the

**Figure 3.** Simulation results of electromagnetic field analysis: (a) type I, (b) type II, and (c) type III.

**Figure 4.** Electromagnetic characteristics of final architecture: (a) architecture in final design and (b) magnetic field at cross section.

**Figure 5.** Step response performance of actuator at 2 A current.

**Figure 6.** Step response performance of actuator at 3 A current.

**Figure 7.** Step response performance of actuator at 5 A current.
controlled current. The displacement is large enough to drive the valve spool and the opening can be regulated by applying different current across the coil. When the input current amplitude is 2 A and 3 A, the displacement response of the actuator has a small overshoot because there is no perforce acting on the MSMA sample at the initial stage. When the current amplitude increases to 5 A, there is no overshoot between the input signal and the output displacement because the response of the current generator begins to degrade when large current output is required. Moreover, a certain time delay exists between displacement output and signal input and the hysteresis time is about 20 ms, mainly resulting from the dynamic characteristic of power supply, spring and material deformation. The response time of the actuator is approximately 15 ms under the condition of 2 A current input and decreases with larger current, as the larger current induces larger spring compression and thereby more resistance acting on the actuator.

Design of hydraulic switching valve

Working principle

For the purpose of simple structure and effective avoidance of internal leakage, the poppet valve was chosen as the structure of the MSMA high speed switching valve. The taper angle of the valve body is made on the valve body to prevent the hydraulic pressure induced by flow dynamics when it is closed. The inlet and outlet have the same diameter. The hole diameter of valve seat and poppet diameter are determined with reference to the conventional valve. The valve opening formed by poppet and seat is shown in Figure 8.

The high-speed switching valve is integrated into a transparent block to observe the flow and poppet motion in the neighborhood of opening, as shown in Figure 9. There is no relative movement between the valve sleeve and the valve body, so the O-ring is used. Since the pushrod to drive the poppet has to reciprocate, the Y-ring is selected. Switching is realized by controlling the elongation of the MSMA. When the actuator coil is energized and produces a magnetic field perpendicular to the long axis of the MSMA, it allows the MSMA to stretch and push the rod forward. Then the poppet begins to move axially and the valve is opened with the inlet A connected to the outlet B. When the coil is deenergized, the magnetic field is removed and the stress in the MSMA disappears. The return spring in the valve body pushes the poppet backwards, and the valve is closed. In the meantime, the spring force also recovers the MSMA to its original shape and get ready for next cycle. It should be mentioned that the MSMA is not included inside the pressurized case because actuator and valve body are separate. It requires a seal on the pushrod to avoid external leakage.

Flowing characteristics of valve

In order to analyze the oil flowing characteristics through the flow passage of valve subject to high speed on-off switching, the flow field change produced under several typical working conditions are taken into account. Through the computational fluid dynamics (CFD) simulation of flow dynamics in the MSMA high-speed switching valve, the relationship between valve opening, inlet and outlet pressure difference as well as flow rate response is analyzed. Numerical simulation of flow passage is implemented utilizing fluid drive modules in COMSOL Multiphysics software. Solutions are obtained based on the following basic assumptions and initial conditions.

(1) Hydraulic oil is an incompressible, adiabatic and flowing fluid. No slip between oil and wall.
(2) HM46 hydraulic oil is selected, of which the density is 850 kg/m³, the dynamic viscosity \( \mu \) is 0.017 Pa·s and the saturated vapor pressure is 6–200 Pa at 20°C.

(3) The Reynolds number \( Re \) of the CFD simulation model is 3850, much larger than the critical Reynolds number of the pipeline (\( Re = 2300 \)). The initial flow velocity \( v \) is 5 m/s. Therefore, the flow state of the hydraulic oil in the valve flow passage can be regarded as turbulent flow and the \( k-\varepsilon \) turbulence equation was adopted for analysis.

According to the calculation result, the outlet pressure should be less than 5 MPa so as to achieve reliable switching motion because the pressure produces counterforce on the poppet directly. So the following analysis results are obtained under the designated range of pressure difference.

Influence of different openings. Opening is the key parameter of hydraulic valve because it has close relation with flow rate and pressure drop. Although the switching valve usually operates shifting between on and off mode, its opening still affects the oil flow state and stability. In the simulation, the hydraulic pressure across the valve opening is 0.1 MPa, assuming 5 MPa at the inlet and 4.9 MPa at the outlet. The flow characteristics inside the valve are analyzed under three different valve openings: small, medium and large. In order to display graphically, the flow field is represented by the flow velocity and the pressure distribution in the cross section of the flow passage, as shown in Figures 10 to 12.

As can be seen from Figure 10(a), when the valve opening is small, the pressure distribution is similar on both sides of the opening. Pressure transition only takes place at the valve port. As the valve opening increases, the pressure distribution changes greatly, as shown in Figures 11(a) and 12(a). Pressure transition spreads in the mainstream flow passage due to the change of the flow passage area mainly. Because of throttling effect, the pressure drop across the valve is concentrated at the cracking locations when the valve opening is small. When the valve opening is larger, the pressure drop distributes smoothly and changes gradually.

The inlet and outlet velocity of valve is also influenced by openings, as can be seen from the Figures 10(b), 11(b), and 12(b). The maximum speed appears at the narrow flow passage formed by poppet and hole.
As the valve opening increases, the maximum speed also increases, which are 9.02, 9.49, and 10.1 m/s. Flow speed gradient changes in broader area corresponding to larger opening.

Figure 13 shows the flow rate of the high-speed switching valve obtained by simulation with different valve openings when the inlet and outlet pressures are 5 and 4.9 MPa. The flow rate increases with the valve opening nonlinearly. When the valve opening is less than 0.4 mm, the flow rate increases at a faster pace. When the valve opening is greater than 0.4 mm, the increase of flow rate is obviously slow. When the valve opening is at maximum of 1 mm, the flow rate reaches 2.04 L/min.

Influence of different pressure drop. The flow field characteristics inside the valve are also analyzed operating under different inlet and outlet pressure differences when the valve opening is 0.7 mm. Figures 14 and 15 show the simulation results of pressure and velocity. It can be seen from Figures 14(a) and 15(a) that the pressure field is basically the same distribution under different pressure difference, irrespective of the different pressure at the outlet. On the poppet side of the flow passage, the pressure changes sharply at the opening area and the pressure transition is completed quickly. But on the side near the outlet, the pressure changes more gently. The pressure transition takes place throughout the whole flow passage. It can be seen from Figures 14(b) and 15(b) that the oil flow velocity distribution is basically in the same manner under different
pressure drops, and the maximum velocity appears in the upstream of the main flow passage near the inlet port and away from the inlet. The maximum velocity reaches up to 80 and 34.7 m/s corresponding to the different pressure drop. As the pressure difference between the inlet and outlet is reduced, the maximum flow velocity also decreases. In practice, the pressure drop is even smaller and the steady flow can be guaranteed firmly.

Figure 16 shows that the simulation results of the valve flow rate with different inlet and outlet pressure differences when the valve opening is kept at 0.7 mm and inlet pressure 5 MPa. Here, we consider 0.1 MPa pressure drop to demonstrate the working condition of low flowrate and large load. As the pressure difference between the inlet and outlet is reduced, the maximum flow velocity also decreases. In practice, the pressure drop is even smaller and the steady flow can be guaranteed firmly.

Figure 16 shows that the simulation results of the valve flow rate with different inlet and outlet pressure differences when the valve opening is kept at 0.7 mm and inlet pressure 5 MPa. Here, we consider 0.1 MPa pressure drop to demonstrate the working condition of low flowrate and large load. As the pressure difference between the inlet and outlet increases, the flow rate increases nonlinearly like a square root function. When the pressure difference is less than 1 MPa, the rate of flow rate change is faster. When the pressure difference is greater than 1 MPa, the increase rate of flow is relatively slow. When the outlet is connected with oil tank, the flow rate is about 18.17 L/min, corresponding to the pressure relief operation of the hydraulic system.

Influence of different inlet pressure. Actually, the inlet of valve is connected with hydraulic power source and varying with different working conditions of actuators. So the flow field inside the valve is analyzed under the different inlet pressure, when the valve opening is 0.7 mm and pressure difference between inlet and outlet is 0.1 MPa. The flow velocity and pressure change under different conditions are shown in Figures 17 and 18. From Figures 17(a) and 18(a) it can be seen that the pressure distribution appears basically in the similar way with the same valve opening. So when the inlet and outlet pressure difference is constant, different inlet pressures hardly affects the pressure distribution of oil flow in the hydraulic valve. From Figures 17(b) and 18(b) it can be seen that the velocity field also distributes similarly at the same valve opening, and the maximum flow rate is 8.9 m/s. So when the inlet and outlet pressure difference is constant, different inlet pressures has little influence on the flow speed of the hydraulic oil too.

Simulation of switching valve dynamics

Mathematical modeling

Valve opening process. Once the actuator is energized, MSMA material is subject to the effect of the magnetic field and extends pushing the poppet to open the valve. Considering the dynamics of opening process of valve, the force equilibrium equation of the valve poppet is

\[
F_{\text{msma}} - F_{\text{Hp}} - F_{Lp} - F_0 = M \frac{d^2x}{dt^2} + B \frac{dx}{dt} + Kx
\]

where \(F_{Lp}\) is transient flow force, \(F_{\text{msma}}\) is driving force of MSMA, which varies with \(x\) according to the experimental results of testing, \(F_{\text{Hp}}\) is the force caused by pressure difference of inlet and outlet, \(F_0\) is perforce of...
spring, \( x \) is poppet displacement, \( M \) is the total mass of poppet and moving parts, \( K \) is stiffness, \( B \) is viscous damping coefficient.

The transient flow force \( F_{Lp} \) is

\[
F_{Lp} = L_0 C_m \pi D \sin \alpha \sqrt{2 \rho \Delta p} \frac{dx}{dt}
\]

(2)

where \( L_0 \) is flowing length, \( C_m \) is flow coefficient, \( \alpha \) is cone angle, \( D \) is diameter of valve sleeve, \( \rho \) is oil density, \( \Delta p \) is pressure difference.

The flow continuity equation is:

\[
q_{v,1} - q_{v,2} + \frac{\pi}{4} (d^2 - D^2) \dot{x} = \frac{V_1}{\beta} \dot{p}_1
\]

(3)

where \( q_{v,1} \) is inlet flow, \( q_{v,2} \) is outlet flow, \( V_1 \) is chamber volume in oil inlet, \( \beta \) is effective bulk modulus of oil.

The outlet flow rate \( q_{v,2} \) can be expressed as

\[
q_{v,2} = C_m A \sqrt{\frac{2}{\rho} (p_1 - p_2)}
\]

(4)

where \( A \) is flow passage area, which can be written into

\[
A = \pi dx \sin \alpha \left( 1 - \frac{x}{2d_1} \sin 2\alpha \right)
\]

(5)

where \( d_1 \) is diameter of seat hole.

Valve closing process. See Figure 19 for Schematic diagram of spool opening. When the actuator coil is out of power supply, the valve poppet is closed under the effect of compressed return spring. The force equilibrium equation of this process is

\[
F_{Hp} + F_{Lp} + F_0 + Kx - F_{msma2} = -M \frac{d^2x}{dt^2} + B \frac{dx}{dt}
\]

(6)

where \( F_{msma2} \) is restoring force required by MSMA after the magnetic field disappears.
Simulation

Dynamics of switching valve in operation is analyzed in AMESim software environment. Simulation model is established by means of the hydraulic component design function, as shown in Figure 20. In order to simplify the analysis, the hydraulic oil source is taken as a constant pressure supply. The actuator model is also built in the software with the combination of magnetic modules and calculators to formulate the constitutive equation of the material.

The basic parameters of hydraulic components involved in the simulation model of MSMA switching valve are listed in Table 1.

### Simulation

**Step response.** A step current signal with amplitude of 5 A is applied across the actuator coil. The response of the poppet displacement and output flow rate of the hydraulic valve is shown in Figures 21 and 22. It can be seen that the valve poppet has a displacement of 0.156 mm at the steady stage, with the corresponding output flow rate of 8 L/min. The response characteristics of the mechanical system are obtained as follows. The rise time $t_r$ is 1 ms, the peak time $t_p$ is 2 ms, and the settling time $t_s$ is 7.5 ms. It is shown that

![Figure 20. Simulation model of MSMA high speed switching valve.](image)

![Figure 21. Step response of poppet displacement.](image)

![Figure 22. Step response of flow rate output.](image)

### Table 1. Parameter settings of simulation model in Amesim.

| Items                      | Value            | Items                      | Value            |
|----------------------------|------------------|----------------------------|------------------|
| Spring preload             | 6 N              | Seat aperture              | 4 mm             |
| Spring stiffness           | 9 N/mm           | Seat cone angle            | 45°              |
| Poppet mass                | 20 g             | Maximum flow coefficient   | 0.7              |
| Poppet diameter            | 5 mm             | Inlet chamber volume       | 115 mm³          |
| Viscous friction coefficient| 20 N/(m/s)       | Outlet chamber volume      | 168 mm³          |

![Image](image)
the switching valve opening dynamics has a fast response in milliseconds, and the output displacement in steady-state is large enough and the dynamic performance is satisfying.

**Square wave response.** Excited by square wave signals the switching valve can operate in on and off conditions, so its response performance is very important to the valve. The output flow rate of the hydraulic valve at different excitation frequency is shown in Figure 23 through Figure 26. It can be seen from that the period from the starting point of the square wave signal to the moment valve is fully opened is named $T_{on} = 1.68 \text{ ms}$, which also indicates the time since the poppet moves until the opening reaches its limit. Similarly, the period from the removal of the square wave signal to the fully closed state of valve opening is called the closing time $T_{off} = 0.93 \text{ ms}$, which also indicates the time from the poppet closing until the valve port is completely closed. From Figure 23, it takes a certain amount of time for movement to open and close the spool, which has some delay compared to the square wave signal profile.

Moreover, it can be seen that due to the large overshoot of the high-speed switching valve, as the signal frequency decreases, the output flow rate of the valve has an oscillation of a certain time (about 7.5 ms) during the opening period. The flow rate tends to stabilize at $8 \text{ L/min}$ or so when the signal frequency is under $100 \text{ Hz}$. Higher switching frequency requires faster response to achieve flow in steady state and prevent the defect caused by overlapping of opening and closing stage shown in Figure 23.

**Experiment**

**Experimental setup**

In order to measure the flow rate and pressure characteristics for evaluating the performance of high-speed switching valve, the experimental setup was developed as shown in Figure 27. In the experiment, flow rate output response of the valve is specially tested. The schematic diagram of hydraulic system of the test setup is shown in Figure 27. In the system, the overflow valve 6 regulates the oil pressure at the inlet of valve 7 to be measured, throttle valve 10 is used to generate...
backpressure and act as load. Manual three-way cutoff valve 4 shifts the hydraulic pump and motor unit into idle condition. Pressure gauge 5 and 9 measure the inlet and outlet pressure respectively, while flow meter 8 measures flow rate getting through the valve 7. The whole test platform in site is shown in Figure 28.

**Experimental results**

Firstly, the flow step response characteristics of high-speed switching valve under different inlet and outlet pressure differences are tested. See Figure 28 for Test platform for high-speed switching valve. In the experiment, the outlet is directly connected to the oil tank by regulating the inlet pressure through the overflow valve. Figures 29 and 30 show the flow rate step response with the inlet pressure maintaining 0.65 and 1 MPa respectively. It can be seen that the valve can be quickly opened under the action of a step current with amplitude of 5 A. When the inlet pressure is 0.65 MPa, the opening time is 15 ms, and the flow rate can reach 0.53 L/min. When the inlet pressure is 1 MPa, the opening time is 5 ms, and the flow rate can reach 0.88 L/min. After the valve opening is stabilized, the output flow rate also keeps at a certain level. This response speed is obviously high enough compared with that of the traditional type of valves with armature of electromagnet averaging at tens of milliseconds level. In order to verify the feasibility of the simulation results presented in the previous section, Comparison between simulation and experimental results is made in Figure 30 corresponding to the operating condition of the pre-force of 16.9 N and the pressure difference of 1 MPa between

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**Figure 26.** Dynamic response under 10 Hz square wave excitation.

**Figure 27.** Schematic of hydraulic system and prototype valve to test.

**Figure 28.** Test platform for high-speed switching valve.

**Figure 29.** Step response under pressure difference of 0.65 MPa.

**Figure 29.** Step response under pressure difference of 0.65 MPa.
the inlet and outlet. By comparison, the experimental results are consistent with the simulation data satisfactorily, and the flow rate error in steady state is within 3%. Although it shows that the simulation accurately models the steady state response, it appears to be relatively poor in the dynamics, with a large error in damping ratio. Because damping coefficient of valve poppet is difficult to measure in practice, parameter setting in simulation is referring to the value commonly adopted, which may cause deviation from the physical system.

According to the principle of oil flow through orifice, the flow rate is determined by opening area and pressure drop across the opening. Under different valve openings, the flow characteristics of high speed switching valve were tested with different inlet and outlet pressure differences, as shown in Figure 31. Due to the limitation of the output performance of the hydraulic pump equipped on the experimental setup, the inlet pressure is set to 2.5 MPa in maximum. With the increase of valve opening, the flow rate is getting larger under the same pressure difference. It can be seen that when the pressure difference between the inlet and outlet is small, the flow rate increases rapidly under the given valve opening. The change becomes dramatic when the opening is on the relatively high level. This is influenced by the maximum output flow rate of the test platform to some extent, as it approaches the maximum flow rate of the system. In order to further explore the relationship between flow rate and pressure difference, curve fitting was conducted with square root function. According to the fitted data, relations between the pressure difference $\Delta p$ and the flow rate $q_v$ under different valve opening are obtained. As shown in Figure 31, the goodness of fit $R^2$ are demonstrated all larger than 0.98, in good agreement with the conventional calculation equation for flow rate through valve opening. Moreover, Three-dimensional plot of different valve opening $x$, pressure difference $\Delta p$ and flow rate $q_v$ is depicted in Figure 31 to get a clearer understanding to their interactions. See Figure 32 for Relations of valve opening, pressure difference and flow rate.

Figure 31. Relation between pressure difference and flow rate under different valve opening.

Figure 32. Relations of valve opening, pressure difference and flow rate.
application of such valves. Primarily, the characteristics of such valves are often limited by their actuation power. According to monitoring of the input power supply, the electric power consumed in experiment is about 120 W at the maximum valve opening, approximately equivalent to that of electromagnetic drive.

**Conclusion**

In this paper, taking the magneto-mechanical characteristics of MSMA into consideration, a compact actuator is designed to drive high speed switching valve. The simulation analysis and experimental verification are carried out. The main conclusions can be drawn as follows.

1. MSMA based actuator with a compact double-layered configuration and spring to recover material deformation can be implemented into hydraulic switching valve. By analyzing the recovery force in demagnetization state and simulating the dynamic characteristics of the actuation system, the operating process of the actuator can be described accurately. The simulation results show that the working range of the actuator is reduced as the input current of coil decreases. The working range is up to 0.67 mm under the pre-stress of 5 N, and the working range is up to 0.6 mm under the spring stiffness of 4–6 N/mm.

2. The high-speed switching valve designed with the MSMA based actuator turns out to have good performance by simulation analysis. Compared with the traditional type of valves with armature of electromagnet, it is easier to achieve faster response because no movement takes place during actuation. Flow field obtained in simulation shows that when the valve opening and the pressure difference increase, the flow velocity of the oil flow and the flow rate increases accordingly. Change of pressure difference as well as the valve opening can lead to variation of the output flow rate, and the maximum flow rate can go up to 18.17 L/min corresponding to the conditions with 5 MPa pressure drop across the valve.

3. The dynamic characteristics test results of MSMA based hydraulic switching valve obtained by simulation show that the output flow rate is 8 L/min and the response time is 1 ms under coil current of 5 A. Excited by square wave input signal, the output flow rate of the valve will oscillate for a certain time when the frequency is relatively low. The experimental results show that when the pressure drop is 1 MPa, the opening time is 5 ms and the flow rate can reach 0.88 L/min. When the valve opening is 0.7 mm and the pressure difference is 1.75 MPa, the flow rate from experiment and simulation is 8.53 and 9.24 L/min respectively, and the relative error is 7.6%. Design of actuator as well as valve based on MSMA is verified and facilitates to develop high speed switching valve for high hydraulic systems.

**Declaration of conflicting interests**

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