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Modeling and simulation of two port proportional slip-in cartridge valve based on AMESim

Wenzhu Wang[1, 2], Rendong Wu[1, 2], Chaolong Yuan[1, 2], Baohua Chang[1, 2] and Dong Du[1, 2, 3]

[1] Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China;
[2] Key Laboratory for Advanced Materials Processing Technology, Ministry of Education, Beijing 100084, China;

[3] E-mail: dudong@tsinghua.edu.cn

Abstract. Two port proportional slip-in cartridge valves are critical components of the heavy duty press hydraulic system. Their performance, especially the static flow rate under different valve opening size and the valve response time, is important to the press velocity control precision. So, it is necessary to build an accurate model of the valve to analyse different parameters' influences on the valve performance. Based on the analysis of the valve structure and working principle, the valve model is established by the AMESim. The valve flow rate under different valve opening size ratio is calculated using the simulation model. The rated flow rate calculated by the simulation model is 0.33% less than the sample value, and the variation trend of the calculated flow rate curve is consistent with the manual curve. This demonstrates the considerable effectiveness of the valve simulation model. Then, the influences of the spring stiffness, the pilot oil pressure and the pilot valve gain on the valve poppet response time are analysed using the simulation model, respectively. This research may offer the basis for the whole hydraulic system building and control strategy designing.

1. Introduction

Since the 1980s, proportional valves, cartridge valves have been developed fast. The proportional cartridge valve emerged with the increasing control demand of HPLFRHS (high pressure, large flow rate hydraulic system). This kind of valve usually has a high-frequency pilot valve and a cartridge main valve. Therefore, it has the advantages of large flow rate and quick response [1]. Hence it has been widely used in HPLFRHS [2-4].

Direct commissioning of HPLFRHS is costly and has certain risks. Therefore, HPLFRHS need to be analyzed theoretically to ensure their reliability before being constructed and commissioned. A reasonable simulation model of the hydraulic system can be used to pre-test the control algorithm. The test risks can be reduced and the debugging efficiency can be improved [5]. The flow rate of a heavy duty multi-function hydraulic press is mainly controlled by a type of proportional slip-in cartridge valve. The performance of the valve will directly affect the speed control accuracy of the moving beam of the press. In order to model the entire hydraulic system, it is necessary to accurately model the valve.

Several researchers have investigated the modeling of the valve. Yao et al. [6] built the model of the variable flow gain proportional throttle cartridge valve from mathematical derivation. Han et al. [7] established a nonlinear mathematical model of a two-stage proportional cartridge valve including the pilot stage and the main stage of the cartridge valve. Based on the model, the authors analyzed the influences of the design parameters on the static and dynamic characteristics of the valve, and therefore improved the valve performance. Compared to cumbersome mathematical formula derivation, AMESim provides a graphical modeling method based on the physical models of hydraulic components, which improves the modeling efficiency [8]. Also, this software provides a basic components library HCD (Hydraulic Component Design), which provides the possibility of modeling increasingly kinds of hydraulic components [9]. Therefore, AMESim is widely used in the field of hydraulic valve or system modeling. Yu et al. [10] established a large-flow dual-active electro-hydraulic proportional cartridge-type throttle valve by AMESim. The step response characteristics of the valve were analyzed and the main parameters of the valve were determined by simulation method. Kong et al. [11] built an active proportional cartridge valve model based on AMESim, and then the injection molding system model of the die casting machine was built. Xiao et al. [12] established the two-way proportional cartridge valve model with the HCD library of AMESim, and the parameters' influences on the static and dynamic performance of the valve were analyzed. Han et al. [13] optimized the poppet structure of a proportional cartridge valve with numerical simulation method, and then built the valve and hydraulic system model with AMESim. Simulation results validated the poppet parameters' optimizing. Overall, the existing research mostly focuses on the modeling of the valve that directly drives the poppet by the pilot valve. However, there is little research on the proportional cartridge valve with a pilot rod.

This paper analyzed the structure and working principles of the two port proportional slip-in cartridge valve. Then, the simulation model of the valve was established with AMESim. The rated flow rate calculated by the simulation model is 0.33% less than the sample value, and the variation trend of the calculated flow rate curve is consistent with the manual curve. This demonstrates the considerable effectiveness of the valve simulation model. Then, the influences of the spring stiffness, the pilot oil pressure and the pilot valve gain on the valve poppet response time are analyzed using the simulation model, respectively. This research may offer the basis for the whole hydraulic system building and control strategy designing.

2. Valve model building

2.1. Valve structure

The two port proportional slip-in cartridge valve is composed of three stages: those are pilot valve, pilot rod and main valve. The pilot valve is used to control the pilot rod directly. A position transducer is mounted on one side of the pilot rod. The other side of the pilot rod is functionally connected with the main valve which contains the poppet and the sleeve. The valve structure is shown in Figure 1 (a). The valve schematic diagram is shown in Figure1 (b), in which the pilot valve is described as a three-position four-way proportional valve and a two-position two-way valve is used to represent the assembly of the pilot rod and the main valve. The X port and the Y port are connected to the pilot oil source and the oil tank, respectively. The G1 port and G2 port are auxiliary oil ports, which can help to decompress the control chamber in some occasions. The port B and the port A are connected to the high pressure oil source and the oil tank, respectively.

The pilot rod moving in the valve seat hole is just like a double-acting hydraulic cylinder. The upper control chamber E and the lower control chamber H are connected to the pilot valve through the hole F and hole G, respectively. The rod position information is detected and sent to the pilot valve with the position transducer. Thus, the rod position can be exactly controlled by the pilot valve. The poppet has two holes, namely hole I and hole C, which work as flow restriction orifice. The upper end of the hole I is coaxial with the pilot rod. The size of the upper end of the hole I is matched with the lower end of the pilot rod. Therefore, the flow area of the orifice I (the upper end of the hole I) can be adjusted by the position difference between the pilot rod and the poppet. The poppet has an inverted conical surface at the inlet port B. This enables the poppet to obtain a lifting force from the high pressure oil at inlet port B. The lifting force can push the poppet to follow up with the pilot rod. There is a v-notch under the poppet which can increase the flow range and improve the control performance at low flow rate conditions.

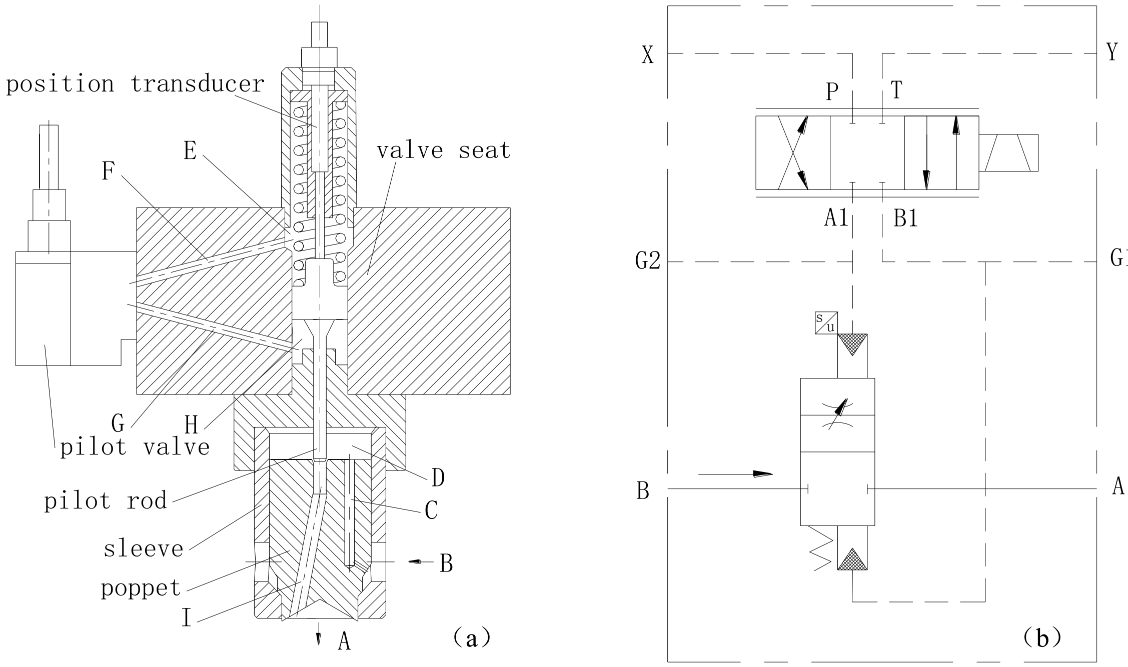

Figure 1. Diagram of proportional cartridge valve: (a) Structure diagram; (b) Schematic diagram.

2.2. Working principle
The proportional cartridge valve with pilot rod is an electric position feedback valve. The pilot rod position information detected by the position transducer is converted into an electrical signal. This signal is compared with a given signal. Then, a control signal is calculated and conveyed to the proportional pilot valve. This pilot valve will move the pilot rod up or down or just stay still. The poppet will move after the pilot rod. The position difference between them is small. As a result, the pilot rod position can be approximately regarded as the poppet position. The control diagram is shown in Figure 2.

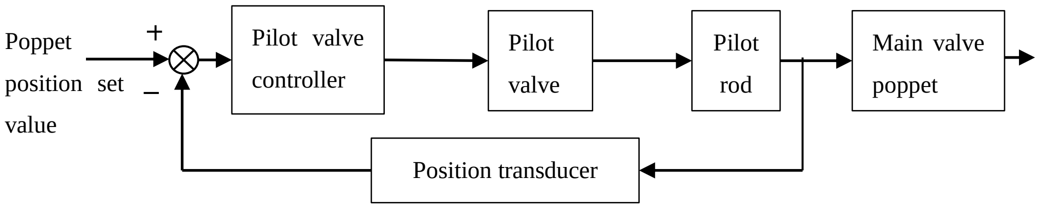

Figure 2. Control diagram of the valve.

When power off or the pilot valve input signal is zero, the pilot valve will be at neutral position. Then, the pilot rod control chamber E and the control chamber H will be closed. Therefore, the pilot rod will keep still. At the same time, if the pilot rod is at the lowest position, the orifice I at the top of the poppet will be closed. Oil will flow from inlet port B to the control chamber D through the hole C until the oil pressure of the control chamber D rises to coincide with the pressure at the inlet port B. Afterwards, the main valve will be closed with hardly any leakage.

If the pilot rod is not at the lowest position, oil in the control chamber D can flow to the outlet port A through the hole I. Then, the oil pressure in the control chamber D will decrease. The force caused by the oil at the inlet port B will be bigger than the resultant force including the poppet gravity and the force caused by the control chamber oil. The poppet will be pushed to the pilot rod by the force difference. Hence, the position difference between the pilot rod and the poppet will decrease. The flow area of the adjustable orifice I will reduce, but the size of the orifice C will keep the same. Therefore, the oil entering the control chamber D is more than the oil flowing out from the orifice I. Consequently, the oil pressure in the control chamber D will be bigger than before. Finally, the poppet will stay close to the pilot rod. The pressure difference between the inlet port B and the control chamber D will keep in a dynamic balance state. The opening size of the main valve can approximately keep constant.

If the input signal of the pilot valve is not zero, assuming that the signal is a positive one. The pilot valve shown in Figure 1(b) is at the right position, and the pilot oil will flow from port P to the port A1 of the pilot valve. This means the pilot oil flow to the control chamber H through the hole G. The oil in the control chamber E will flow out through the hole F. It means the oil flow from port B1 of the pilot valve to the port T. Then, the pilot rod will obtain a resultant force which makes it move up. Therefore, the oil in the control chamber D will flow to the outlet port A through the orifice I. Oil pressure in the control chamber D will decrease. Thus, the poppet will move up to the pilot rod. Consequently, the main valve is open. When the signal is negative, the valve works in a similar manner to the positive signal case. The displacement of the pilot rod is proportional to the setting signal. At the same time, the poppet moves after the pilot rod. Then, the opening size of the main valve poppet is approximately proportional to the setting signal, ignoring the small displacement difference between the poppet and the pilot rod. The position information of the pilot rod is monitored in real time by the position transducer and fed back to the controller to form a closed loop control.

A schematic structural view of the upper end of the orifice I and the lower end of the pilot rod is shown in Figure 3.

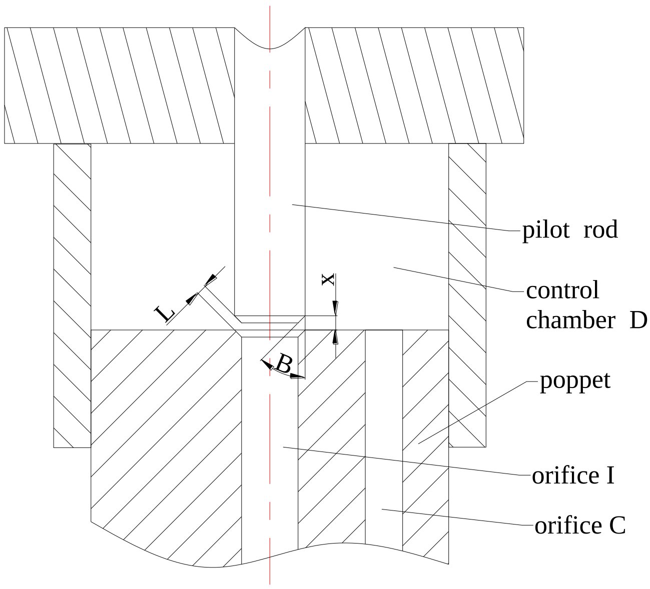

Figure 3. Schematic structural view of the orifice I and the pilot rod.

Flow area width is as follows:

$$L = x \sin B \tag{1}$$

Where x is the displacement difference between the poppet and the pilot rod, B is half of the cone angle at the lower end of the pilot rod.

Thus, the flow area can be calculated as follows:

$$A = \pi\left(d + x \sin B \cos B\right) * x \sin B \tag{2}$$

Where d is the diameter of the orifice I.

Then, according to the theory of equivalent valve flow area [14], the equivalent diameter of the variable orifice can be calculated as follows:

$$de = 2\sqrt{(d + x\sin B\cos B) * x\sin B} \tag{3}$$

The angle B is a constant value. Thus, the equivalent variable orifice diameter is proportional to the displacement difference between the pilot rod and the poppet.

2.3. Valve simulation model

Based on the analysis of the structure and working principle of the proportional cartridge valve, the valve model was established by using hydraulic component library, mechanical component library and HCD library of AMESim, as shown in Figure 4.

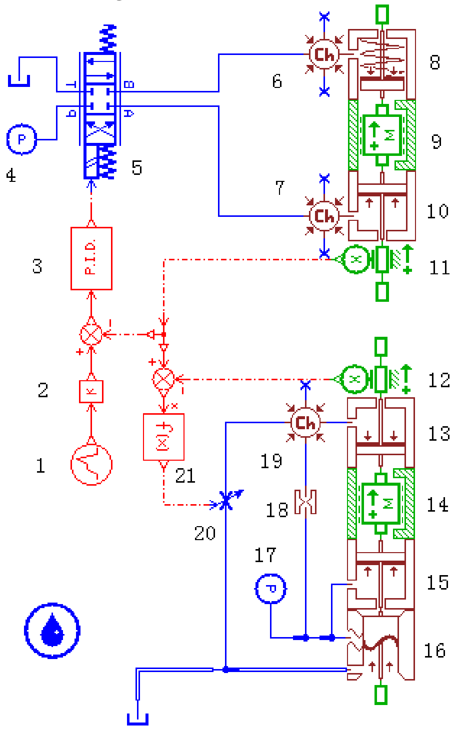

Figure 4. Simulation model of the proportional cartridge servo valve.

The three-position four-way valve 5 was used to build the pilot valve. The pilot rod is similar to the double-acting piston cylinder. Hence the piston module 8 with return spring and the piston module 10 without return spring were used to build the control chamber E and the control chamber H, respectively. Module 9 was used to simulate the mass and rod displacement of the pilot rod. Module 11 was used to simulate the position transducer.

The main valve consists of five functional parts, namely control chamber D, inlet port B, outlet port A, orifice C and orifice I. The volume change of control chamber D is proportional to the poppet displacement. So, it could be built with the piston module 13. The poppet has an inverted conical surface at the inlet port B, and the diameter of the upper surface of the conical portion is larger than the lower portion diameter. Module 15 could properly simulate the inlet port B. The orifice C will not change during the working time, and a fixed orifice module 18 was used to simulate it. The orifice I and the pilot rod work together to control the oil flow from control chamber D to the outlet A. They work just like a variable orifice. As a result, it was proper to simulate this part with module 20. The displacement difference between the pilot rod and the poppet was calculated first. Then, the signal was sent to the variable orifice 20 through the functional module 21. Module 14 was used to simulate the

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mass and stroke information of the poppet. In practice, there is no position transducer mounted on the poppet. But, in order to calculate the equivalent diameter of the variable orifice 20, the displacement sensor module 12 was used to measure the position of the poppet. The modules 6, 7, and 19 were used to simulate the volume of the control chamber E, the control chamber H and the control chamber D, respectively. Because of the existence of the v-notch on the poppet, the flow area will change in a more complex way with the valve opening size. Therefore, the module 16, which can set the flow area by a function or a table related to the valve opening size, was used to simulate the outlet A.

3. Results and discussion

The two port proportional slip-in cartridge valve has several sizes. Size 63 was widely used in the 680MN multi-function hydraulic press system. Its rated flow rate is 1843L/min according to the manual curve. A v-notch poppet is used to increase the flow range, which means flow rate can change a smaller value at an identical poppet displacement, and therefore improves the control ability. Thus, the size 63 valve was analyzed in this paper. In order to simulate the valve opening and closing process in one simulation loop, the simulation time should be longer than the valve action time. Generally, the valve response time, namely valve opening time or valve closing time, is less than 0.2 second. Thus, the simulation duration time was set as 0.5 second. Usually, the response time can be tens of milliseconds. Then, the sampling time was set as 10^{-5}second, for the sake of increasing the resolution of the calculated results. After building the valve model using AMESim, simulation was run on a PC having the following specifications: Processor is Intel(R) Core(TM) i7-4700MQ CPU @2.4GHz and the RAM (random access memory) is 32GB.

3.1. Valve performance

Flow rate under different valve opening size and response time are two important characters for the speed control of the press. In practical application, the pilot oil pressure is 95bar. Thus, the pressure source module 4 was set as the same value.

3.1.1. Flow rate. The signal given by the module 1 was set as a 0~10 slope signal. Oil pressure of the inlet port A was set as 5bar by the pressure source module 17. The valve flow rate calculated by the simulation model was compared with the one given by the valve manual, as shown in Figure 5.

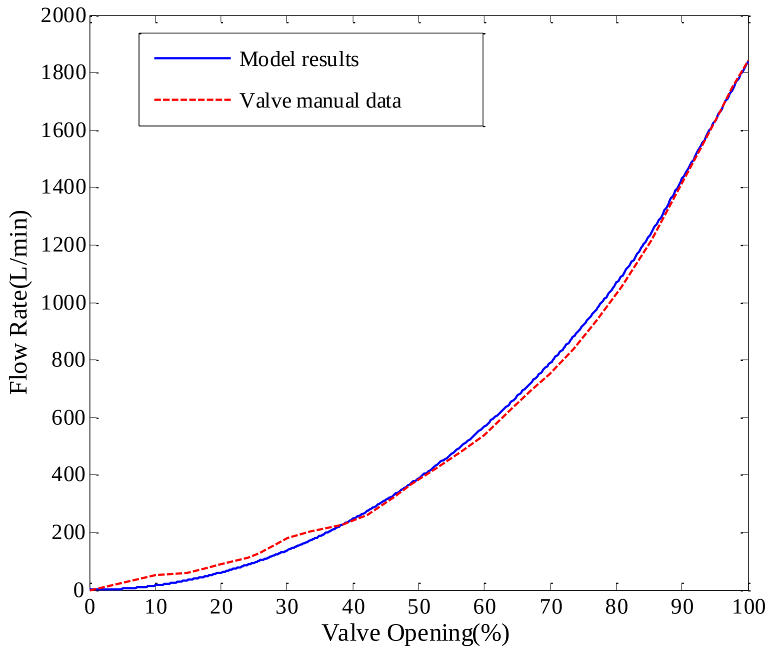

Figure 5. Comparison of flow rate variation along with the valve opening ratio.

Under no-load condition, the simulated flow rate of the valve is a little smaller than the sample one when the valve opening ratio is less than 38%. Then, the simulated flow rate becomes a little bigger than the manual data until the valve opening ratio reaches 95%. When the valve opening ratio is between 95% and 100%, the percentage error of the calculated flow rate is -4.1%~-0.33%. The maximum flow rate of the simulated valve given by the valve manual curve at a differential pressure of 5bar is 1843L/min, while the simulation model's maximum flow rate at the same condition is 1837 L/min. The simulated flow rate is a little smaller than the sample one, and the percentage error is about -0.33%. Thus, the valve model's maximum flow rate under certain conditions is consistent with the sample one. The flow rate variation trend of the simulation model is consistent with the sample one, as shown in Figure 5. That is, the slopes of the two curves are both increasing with the opening size ratio of the valves. The flow rate differences between the model results and the valve manual data may be caused by the simplicity of the valve structure. Moreover, the conditions of the flow rate experiment which got the valve manual data might be complicated to simulate in the model. In general, the simulation model of the proportional cartridge valve with pilot rod is reasonable.

3.1.2. Valve response. In order to get the step response characters, the pressure of the inlet port A was set to the rated value 700bar. Practically, the valve opens from 0 to 100% when the input signal changes from 0 to 10V. A square signal was used because we want to obtain the opening and closing step response characters in one simulation loop. The start time of the square signal is set arbitrary, but the end time should be longer enough to avoid affecting the opening step response characters. In this paper, 0.3s is proper for the end time when the start time is set as 0.1s. Thus, the square control signal changed from 0 to 10 at 0.1 second and changed from 10 to 0 at 0.3s. The opening time was defined as the time interval during which the stroke ratio get to 95 percentage of the steady-state value from the beginning of the opening step signal. The closing time was defined as the time interval between the beginning of the closing step signal and the time when the stoke ratio reaches 5 percentage of the steady-state value. The stroke step response of the pilot rod and the poppet is shown in Figure 6.

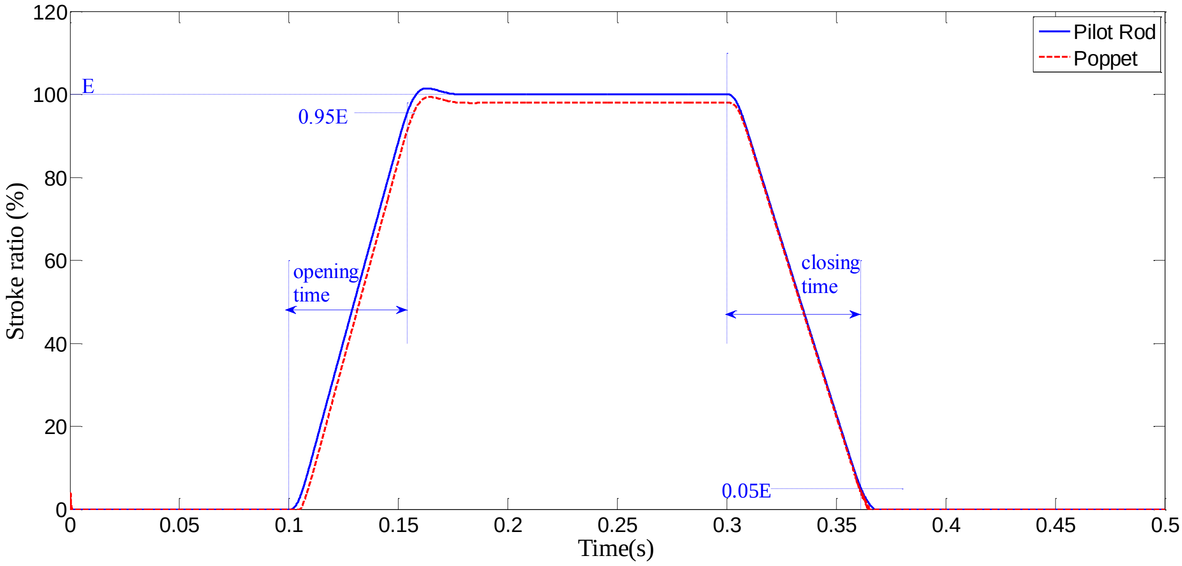

Figure 6. Displacements percentage under step response.

Figure 6 illustrates that the main valve poppet always moves after the pilot rod during the opening and closing process. The opening time of the poppet and the pilot rod are 55.2ms, 53.7ms, respectively. The poppet opening time is 2.8% longer than the one of pilot rod. This is because only when the pilot rod moves up first, the poppet can be pressed to open by the differential pressure between the inlet port B and the control chamber D. When it comes to closing process, the pilot rod will go on moving a little time to disappear the stroke difference between the rod and poppet, so the situation will change.

The poppet closing time is 60.7ms, which is 1% shorter than the rod closing time 61.3ms. In a word, the poppet can follow up the pilot rod well and has a fast response.

3.2. Parameters analysis

The valve response time is important to the velocity control precision. During the actual production process, the pilot oil pressure and the spring stiffness may be changed by some uncertain reasons. The parameters of the pilot valve controller can influence the vale response. In order to improve or keep the valve response performance, it is essential to analyze their effects on the valve response.

For analyzing the various parameters' effects on the valve response, AMESim batch function was used with the control variable method. The pressure of the inlet port was set to the rated value 700bar.

3.2.1. Effect of the spring stiffness. The spring stiffness calculated from the spring size is about 35N/mm. During the practical application, the stiffness may decrease after a long time working. In some other occasions, the spring may be changed to a larger one. In order to figure out the effect of the spring stiffness on the valve response, the spring stiffness was set as a series values from 5 N/mm to 65 N/mm and the step is 10 N/mm. The step response of the poppet will change, as shown in Figure 7 (a). The opening time and closing time of the pilot rod and poppet is shown in Figure 7 (b).

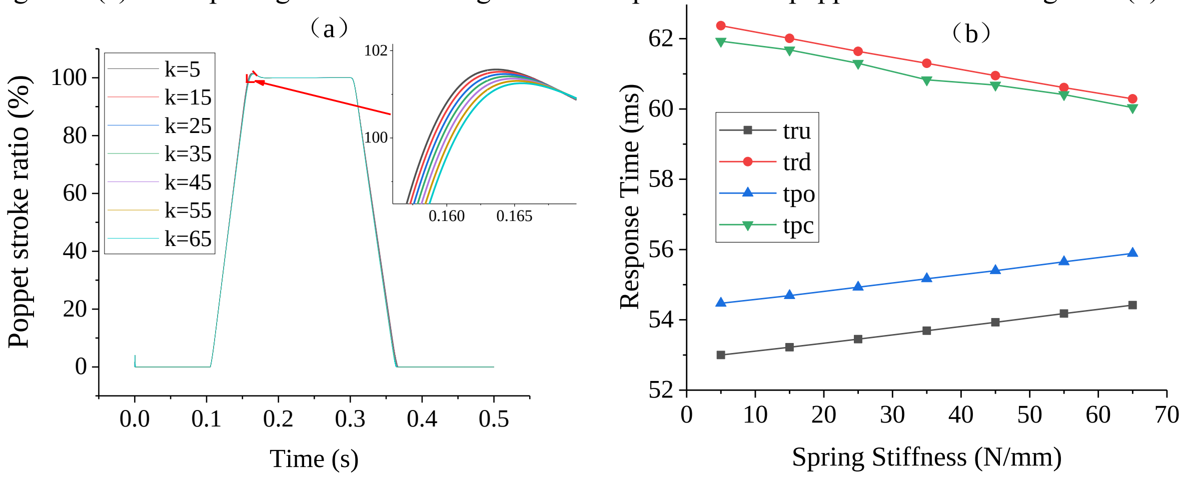

Figure 7. Step response under different spring stiffness: (a) Poppet stroke ratio; (b) Response time.

It can be seen from Figure 7 (a) that the poppet step response changes little when the spring stiffness changes from 5 N/mm to 65N/mm. But the response time really changes according to the spring stiffness, as shown in Figure 7 (b). The pilot rod opening time t_{ru} increases proportionally to the increasing of spring stiffness, and the pilot rod closing time t_{rd} decreases at the same time. This is because when the spring stiffness increases, the pilot rod will need greater force to open it and less force to close it. Thus, the time used to produce the oil pressure changes accordingly. The poppet opening time t_{po} and closing time t_{pc} change along with the time change of the pilot rod. This means the poppet follows up the pilot rod well under different spring stiffness.

3.2.2. Effect of the pilot oil pressure. Normally, the pilot oil pressure can change from 50bar to 95bar in practical application. Under abnormal occasions, the pilot oil pressure may decrease less than 50bar. This paper focuses on the pilot oil pressure's influences on the valve response. Thus, the pilot oil pressure was set as 35bar-95bar. The poppet stroke response is shown in Figure 8 (a). The opening and closing time change along the pilot oil pressure is shown in Figure 8 (b).

When the pilot oil pressure increases from 35bar to 95bar, the slopes of the poppet stroke ratio curves become bigger, and there is also a little overshoot appears little by little, as shown in Figure 8 (a). The biggest one is 1.4% when the pilot oil pressure is 95bar. This is because when the pilot oil pressure increases, the pilot rod can get bigger force to open or close. So, the pilot rod opening time t_{ru} and closing time t_{rd} will both decrease, as shown in Figure 8 (b). The pilot rod opening time decreases from 91.78ms to 53.68ms, and the pilot rod closing time decreases from 92.55ms to 61.31ms. Accordingly, the poppet opening time decreases from 93.22ms to 55.16ms, and the pilot rod closing time decreases from 90.88ms to 60.83ms. Obviously, the pilot rod opening time is always smaller than the poppet opening time, and the pilot rod closing time is always bigger than the poppet closing time. This means the poppet follows up the pilot rod well. There is also a trend that the poppet closing time becomes bigger than the poppet opening time when the pilot oil pressure increases. This is because when the pilot oil pressure increases, the oil force acted on the pilot rod will increase. Thus, the difference of the cross-section area of the chamber H and chamber E will be amplified.

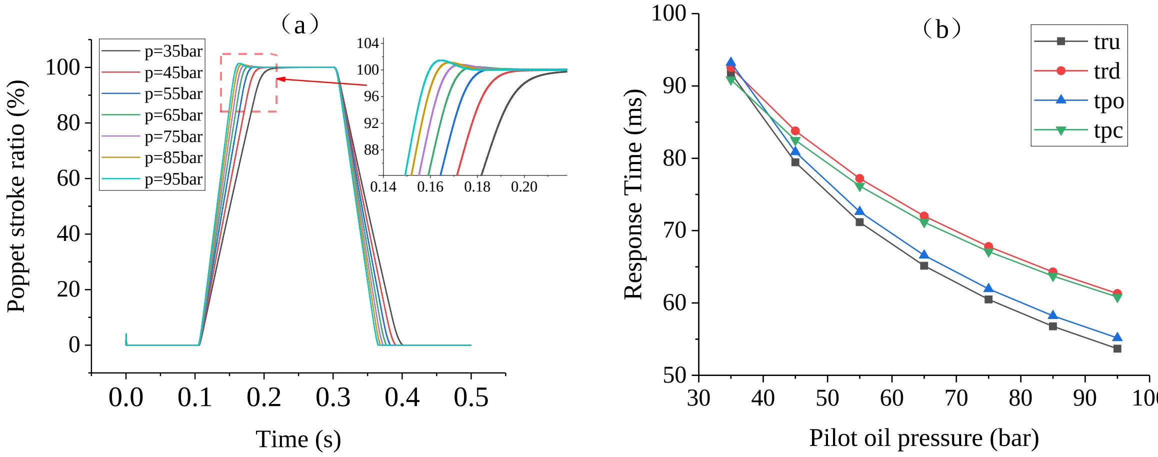

Figure 8. Step response under different pilot oil pressure: (a) Poppet stroke ratio; (b) Response time.

3.2.3. Effect of the pilot valve gain. Usually, the pilot valve can get a bigger control signal when the pilot valve gain increases. Normally, 3000 is a proper value. In order to obtain the influence laws of the valve gain on the valve response, the valve gain value was set from 50% to 150% of the normal value. Thus, the pilot valve gain k1 was set as 1500, 2000, 2500, 3000, 3500, 4000, 4500, respectively. The poppet stroke response is shown in Figure 9 (a). The opening and closing time change along the pilot oil pressure is shown in Figure 9 (b).

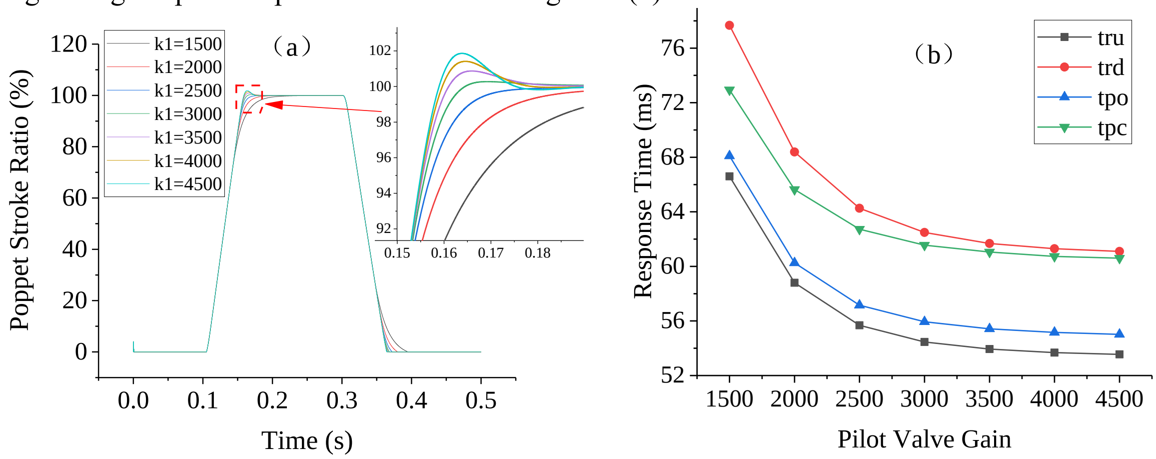

Figure 9. Step response under different pilot valve gain: (a) Poppet stroke ratio; (b) Response time.

Figure 9 (a) shows that increasing the valve gain make the poppet stroke ratio reach its maximum or minimum value quickly but cannot change the curve slope of the most opening of closing process. Reasons of this may be that when the valve gain is increased, the pilot valve will keep larger opening size for a longer time during the opening or closing process. So, more pilot oil can flow to the pilot rod control chamber. Then, the pilot rod can be moved more quickly. Thus, the poppet response is faster. Since the pilot oil pressure keeps unchanged, the maximum force acted on the pilot rod will be the same when the pilot valve opens. Thus, the velocity of the pilot rod will not change during this process. Then, the curve slope of the process will keep the same. The valve response time decreases quickly when the pilot valve gain increases from 1500 to 3000, then the descent rate becomes smaller when the pilot valve gain increases from 3000 to 4500. This is because the effect of the pilot valve gain on the response time is from its controlling of the pilot valve opening size and its duration time. When the pilot valve gain increases, its effect on the pilot valve will decrease. So, the response time of the pilot rod and poppet decreases quickly first and then decreases slowly. The poppet opening time t_{po} is always longer than the rod opening time t_{ru}, and the poppet closing time t_{pc} is always shorter than the rod closing time t_{rd}. This means the poppet follows up the pilot rod well.

4. Conclusions

From analysing the two port proportional slip-in cartridge valve's structure and then simulating it with AMESim, conclusions can be drawn as follows:

(1) Under no-load condition, the valve flow rate curve calculated by the simulation model is basically consistent with the sample curve with 5bar pressure drop. This demonstrates the considerable effectiveness of the valve model.

(2) The orifice I and the lower end of the pilot rod can work together as an adjustable orifice. Its diameter can be calculated by the displacement difference between the pilot rod and the poppet.

(3) Under no-load condition, the poppet can follow up the pilot rod well. Compare to the spring stiffness, the pilot oil pressure has a more obvious effect on the poppet response time. The pilot valve gain also has a clearly influence on the response time.

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