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Design and Modelling of a Hydraulic System for Detecting Solenoid Valve Based on Bond Graphs Method

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Abstract. A novel system is developed in this paper for detecting solenoid valve which is a key component in many industries as automobiles, power equipment, chemical engineering, etc. The numerical model of system is developed by the Bond graphs method, which is widely utilized because they enable easy identification of the parameter process and consider interactions within the hydraulic system. The system model is divided into mechanical section, hydraulic section and electromagnetic section and established to analyse the dynamic performance of the system respectively. Simulations are implemented to verify the rationality of the designed system. In the end, it demonstrates that the simulations results are consistent with the pressure control law of solenoid valve, and the designed system can meet the detecting requirements of solenoid valve.

1. Introduction

The solenoid valve is suitable for many industries due to its advantages of long life, good sensation and high resistance to temperature and pressure. A pressure control solenoid valve (PCSV) driven by magnetic coil is research object in this paper. It is installed on the hydraulic plate of main oil circuit in automatic transmission (AT) to ensure the precise control of the oil pressure. It plays an important role to link the electronic control system and the hydraulic control system. And its performance has a great influence on the efficiency and service life of the AT. The failure frequency of the PCSV is high because of various reasons in reality, and it will firstly cause a shift shock. After a long time, the clutch plate and the brake band will be worn out, resulting in more serious failure and even traffic accident. Therefore, research on the detecting system will help improve design and development efficiency of PCSV product and quality control of mass production.

In fact, lots of investigations were carried out to design new-type structures or control methods of solenoid valve, and there is very few research of detecting system especially for the electromagnetic valve in AT of automobile. There is still some research that focused on the detection of solenoid valve. In [1], it showed the result of the design testing of large butterfly valves under high flow conditions. Improvement and dynamic analysis of an electromechanical valve system were done by Nida BIRGUL to determine the work limits at different valve lifts in [2]. In [3], the characterization of magnetic stability in spin valve test device was analyzed for determining both the direction and magnitude of the difference in magnetization. Abovementioned studies are all about the characteristics of the valve in a specific working environment or on existing test equipment. There are some investigations about novel valve's test tool or test system. Design of the hydraulic system supporting pilot-operated valve test bench was described in [4]. Besides, a solenoid valve performance testing platform was designed by describing in details the electronic control system, the work system and the realization of the function of each part in [5].

It can be included that most previous studies are limited to the description of the hardware and software design and detecting ideas about valve detecting system, not exploring the dynamic performance of the system. A fully functional detecting system for PCSV is developed in this paper, and its mathematical model is established to analyze its dynamic performance based on bond graphs method. The Bond graphs method is very available in modeling because they enable easy consideration of the hydraulic system parameters at each junction [6], so it is widely used to build up the non-linear mathematical dynamic model of hydraulic system. Besides, the classical PID controller is adopted to control because of the advantages of relatively simple, wide adaptability and strong vitality and the Kirchhoff's and Ohm's laws are used to model the electrical circuit of system for a more accurate performance.

2. Design and model of detecting system

2.1. Design of hydraulic system

The pressure control principle of PCSV is force balance with hydraulic force, electromagnetic force, spring force and friction force. For satisfying the detecting requirements, the block diagram of the system newly built in this paper and the control schematic of PCSV are both shown in the Figure 1. Motors and pumps are used to supply power, and the safety valve is used to ensure the safe pressure of system. Filters are also required for not absolutely pure ATF oil. Besides, the option of the electronically controlled throttle valve is to reduce the fluctuation of pressure. Moreover, the hot/cold cycle unit is combined to change oil temperature. The ECU board is used to send current command to the valve. It easily can be seen that it is a very complex system because of strong coupling of hydraulic, mechanical and electromagnetic subsystems. A Fixture is needed to fix the tested PCSV. In addition, pressure sensors for obtaining P_s and outlet pressure P_c are respectively installed on corresponding port.

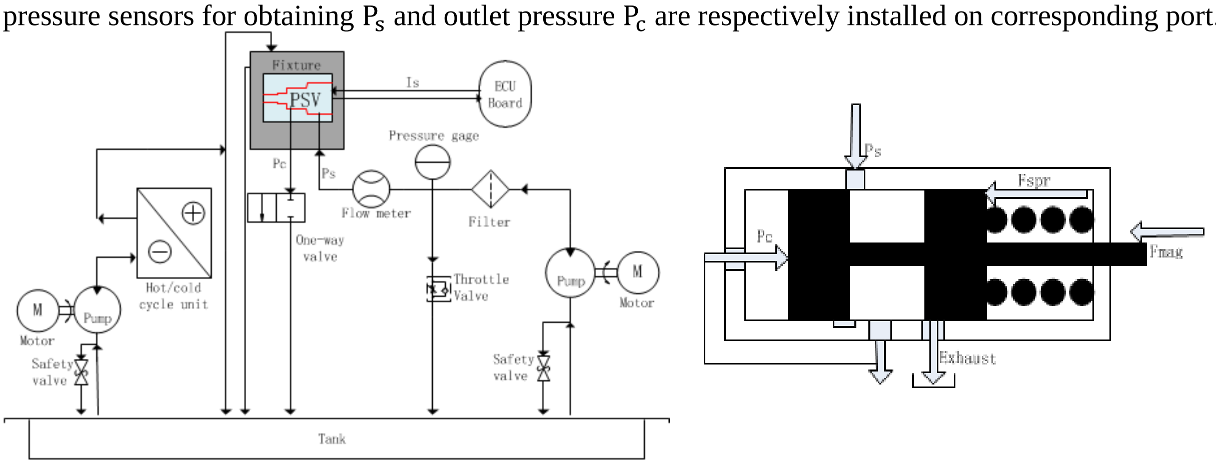

Figure. 1 The block diagram of the detecting system and the control schematic of PCSV

2.2. Modeling of hydraulic system

Some assumptions and simplifications are made to develop the mathematical model equations of the system, such as there is no leakage through entire pipeline, etc.

2.2.1. Model of mechanical section

Although there are many advanced control theories and methods, the classical PID is still the most common form of controller used in motor control. The gear pump selected in this equipment is a fixed quantity pump and is installed directly with the motor, so the flow Q discharged by the pump can be expressed as $Q = \eta_v V_p v$. And the mathematical model of mechanical section including motor and pump can be expressed as:

$$\frac{dQ}{dt} = \eta_v V_p \left\{ K_p \frac{d(P_s - P_{ss})}{dt} + K_i (P_s - P_{ss}) + K_d \frac{d^2(P_s - P_{ss})}{dt^2} \right\}, \tag{1}$$

in which P_{ss} is the expected value of control pressure; K_p, K_i, K_d are proportional coefficient, integral time constant and differential time constant of PID controller separately. η_v is the volumetric efficiency and V_p is the displacement of pump.

2.2.2. Model of hydraulic section

The mathematical model of the hydraulic section can be derived regularly according to the Bond graphs, which are shown in Figure 2.

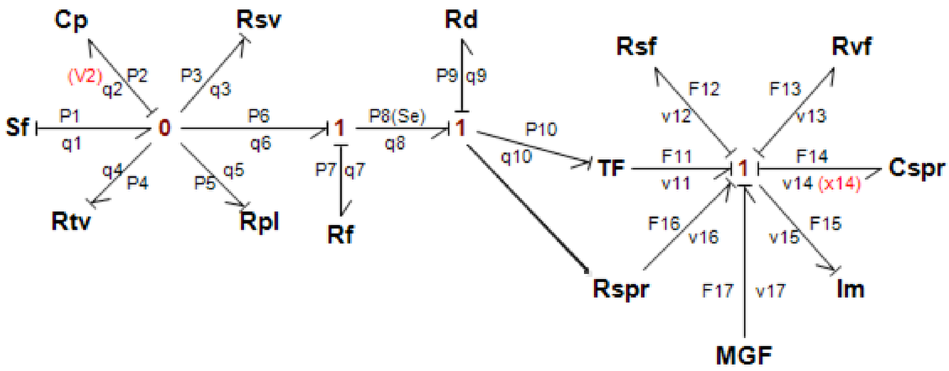

Figure. 2 The Bond graphs of hydraulic part

The input of the bond diagram S_f is equal to the given liquid flow Q. Nodes 1-6 connected with the 0-junction and nodes 6-11 connected with the 1-junction represent the characteristics of the pipeline fluid between pump and valve. And nodes 12-17 represent the internal mechanical characteristics of PCSV. The element TF represents the transformer factor. Meanwhile, the 0-junction represents the flow loss through the hydraulic system and the 1-junctions denote liquid power loss. R_{spr} represents the initial spring compressive force and S_e expresses the liquid pressure force at inlet port of valve. the nodes 1-10 can be expressed by Expressions:

$$\begin{aligned}
&C_p:\quad P_2 = \frac{1}{C_p} V_2, V_2 = \int q_2 dt, && R_{sv}:\quad q_3 = \frac{1}{R_{sv}} P_3, && R_{tv}:\quad q_4 = \frac{1}{R_{tv}} P_4, \\
&R_{pl}:\quad q_5 = \frac{1}{R_{pl}} P_5, && R_f:\quad P_7 = R_f q_7, && R_d:\quad P_9 = R_d q_9,
\end{aligned} \tag{2}$$

where C_p is the liquid capacity of the pipeline. V_2 represents the volume which is the integral of q_2. R_{sv}, R_{tv}, R_{pl}, R_f and R_d are the liquid resistance of the safety valve, the throttle valve, the pump leakage, the filter, and the damper orifice respectively. The fluid characteristics between node 1 and node 10 can be given by combined Expressions in (2) as:

$$\dot{V}_2 = S_f - \left(\frac{1}{R_{sv}} + \frac{1}{R_{tv}} + \frac{1}{R_{pl}} \right) \frac{1}{C_p} V_2 - q_{10}, \tag{3}$$

The internal hydraulic characteristics of the valve are denoted by 1-junction of nodes 11-17and the Bond graphs modeling process can be described by Expressions below[6-8]:

$$\begin{aligned}
&R_{sf}: F_{12} = f_S \mathrm{sign}\left(\frac{dx_{14}}{dt}\right), && R_{vf}: F_{13} = f_R \frac{dx_{14}}{dt}, && C_{spr}: F_{14} = k\, x_{14}, \\
&I_m: F_{15} = m \frac{d^2 x_{14}}{dt^2}, && R_{spr}: F_{16} = k x_0, && \mathrm{MGF}:\ F_{17} = F_{mag},
\end{aligned} \tag{4}$$

Where f_S stands for the static friction coefficient, f_R stands for the viscosity friction coefficient, and k is the spring constant. m is the mass of the spool of valve. x_0 represents the initial spring compress. And for all above, x_{14} is the displacement of the spool. The internal hydraulic characteristics of PCSV can be expressed by combined Expressions (4) as:

$$F_{mag} = m\frac{d^2x_{14}}{dt^2} + f_R\frac{dx_{14}}{dt} + f_S\text{sign}\left(\frac{dx_{14}}{dt}\right) + 2k\,x_{14} - kx_0, \tag{5}$$

2.2.3. Model of electromagnetic section

The mathematic model of the electromagnetic force in this paper fully considers the influencing factors such as the number of coil turns, working air gap and drive current, etc. to ensure the accuracy. With some simplifying assumptions, the mathematical expression of electromagnetic force is given by: [7, 9]

$$F_{mag} = \frac{\mu_0 AN^2}{2k_f{}^2\delta^2}I_s{}^2, \tag{6}$$

where μ_0 is magnetic permeability of the medium, which is a constant here. A is the bearing area of spool. N is the turns of the coil, and $\delta = x_{14}$ is the air gap between the armature and coil. I_s is the drive current. k_f is used as the magnetic flux leakage coefficient.

Constant current command requires an infinite voltage at excitation onset and this infinite voltage requirement is limited by the voltage saturation. However DC voltage excitation is simpler in execution, because it allows for a known valve excitation input using widely available power electronics to guarantee an operating point within the limits of the solenoid. The effects of saturation and eddy currents have been neglected to obtain the following equation by Applying Kirchhoff's law [6, 10]:

$$V_s = RI_s + I_s\frac{dL}{dt} + L\frac{dI_s}{dt}, \tag{7}$$

where V_s is the excitation voltage. R is the total resistance of the coil. L is the inductance of the solenoid coil, and $L = N^2\mu_0 A/\delta$ by assuming that the permeability of the medium in the air gap is equal to μ_0. Combining Equations (6) and (7), we can characterize the transition action based upon analyzing the current through the solenoid when energized by a DC voltage source as:

$$\frac{I_s}{\delta}\frac{d\delta}{dt} - \frac{dI_s}{dt} = \frac{\delta(RI_s - V_s)}{N^2\mu_0 A}, \tag{8}$$

3. Simulation and result

To verify the developed model and discuss the performance of detecting system, we combined Matlab and Vissim software to simulate the control characteristics of PCSV. The major specifications for PCSV and hydraulic system used in the simulations are listed in Table 1.

Table 1 Major Specification for PSV and Other Input Parameters.

Parameter	Value	Unit	Parameter	Value	Unit
A	0.36π	mm^2	ρ	0.0009	kg/cm^3
C_d	0.7		C_p	0.08	cm^5/kg
p_v	30	kg/cm^2	R_{sv}	0.5	$kg\cdot s/cm^5$
k	1.7	N/mm	R_{tv}	0.2	$kg\cdot s/cm^5$
m	0.195	kg	R_{pl}	1.5	$kg\cdot s/cm^5$
X_1	1.4	mm	R_f	0.6	$kg\cdot s/cm^5$
N	1200	turns	R_d	0.4	$kg\cdot s/cm^5$
μ_0	$4\pi\times10^{-7}$	$Wb/A\cdot m$	η_v	0.92	
K_f	3.5		V_p	8.0	cm^3/rev
f_S	0.15	$N\cdot s/m$	K_p	5.5	
f_R	90	$N\cdot s/m$	K_i	20	
R	5.0	Ω	K_d	0	

3.1 The step response characteristics

Figures 3 is the step response curve of pressure at 1.2A with two inlet pressure 275kPa and 1850kPa respectively. The response times are about 0.18s and 0.08s separately and the stable times are nearly 0.62s and 0.22s. Both of the response and steady speed increase as the inlet pressure increases. And the stable outlet pressures are about 262kPa and 1222kPa. It depicts that within a certain range, the outlet pressure has a lot to do with the inlet pressure at same input current value, and the outlet pressure increases as the inlet pressure increases. There are positive and reverse curves of inlet pressure p_s and outlet pressure p_c separately corresponding to step rising edges and falling edges in Figures 3b and 3d. The growth of final control pressure p_c is proportional to the increment of current approximately, which is consistent with the characteristics of the PCSV studied here.

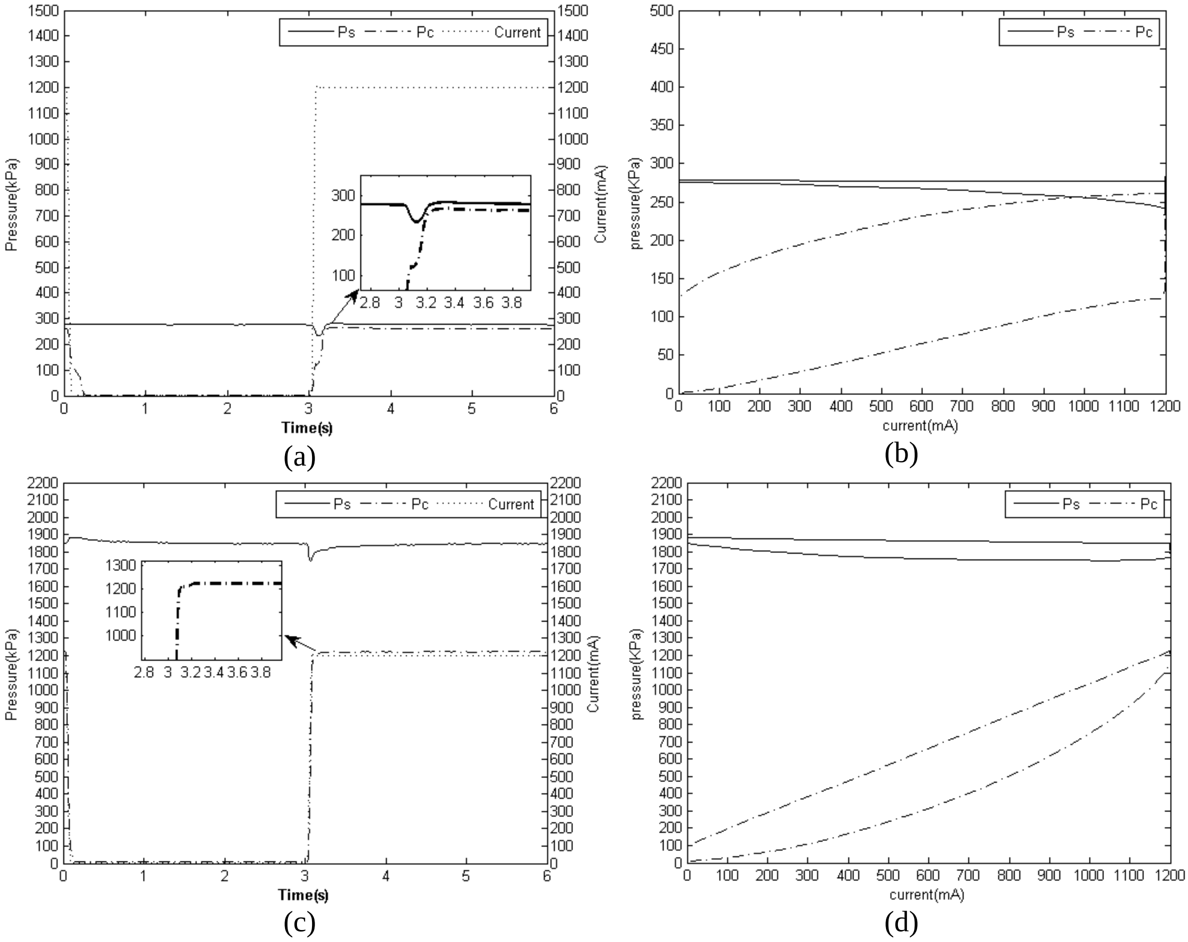

Figure. 3 Step response characteristics of PSV: (a, b) p_{ss}=275kPa; (c, d) p_{ss}=1850kPa.

3.2 The hydraulic control characteristics

This test mainly considers the overall adjustment ability of the PCSV. Figures 7(a-d) are the hydraulic control characteristic curve at step triangular current curve which the current step I_d is 60mA and the duration of each current step T_i is 600ms, the I_{max} is 1.2A. The expected inlet pressures p_{ss} are 275kPa, 1200kPa and 2100kPa respectively. When p_s is stable near 275kPa in Figure 7a, the maximum value of p_c is about 275kPa no matter how the input current increases. While the maximum changes to about 1130kPa as p_s is tuned to about 1200kPa in Figure 7b. Besides, it can be seen in Figure 7c that p_c can just largest creases to 1208kPa at 1.2 A which is the peak value of current when p_s is stable around 2100kPa. Whether the responsibility of the pressure control to the current change at each step, or the stability of the control pressure within each step, it shows a good performance. In addition, the control pressure curve separately corresponding to the rising and falling processes of current is symmetrical, which demonstrates the high repeatability accuracy of the pressure control. As shown in Figure 7d, the connections between current and control pressure p_c under different inlet pressures can be interpreted clearly. Obviously, there is a certain dead zone in the curve and the

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control characteristic is linear only when the given current signal exceeds this dead zone range, which is also just the characteristic of PCSV studied in this paper.

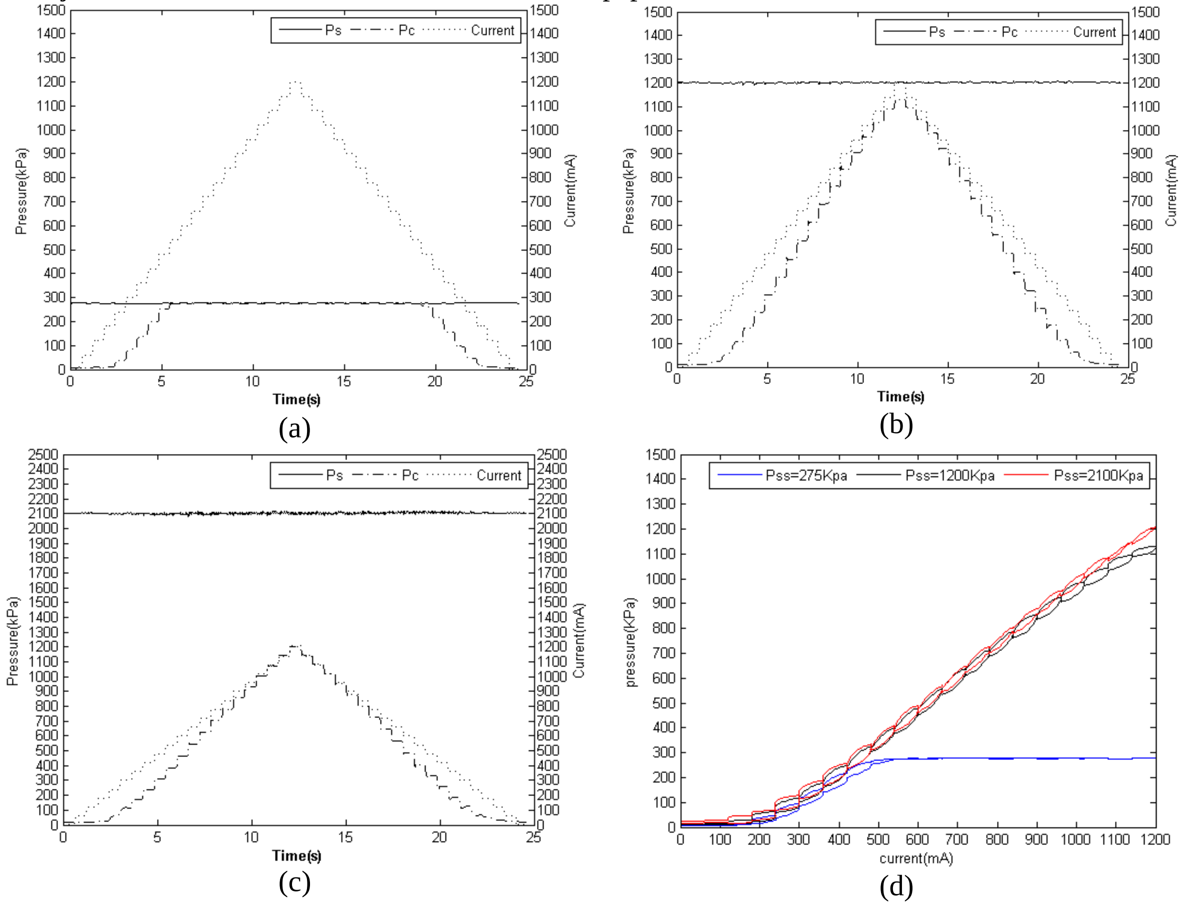

Figure. 4 the hydraulic control characteristic of PCSV at step triangular current curve with: (a) p_{ss}=275kPa, (b) 1200kPa and (c) 2100kPa; (d) variation of pressure p_c over current.

4. Discussion

In the prior section, we showed that the overall performance of designed system satisfies the requirements of the detection of solenoid valve, and the modeling method of the system is effective and highly accurate. The simulation results are basically consistent with the characteristics of the PCSV study in this paper. However, we discuss the problems of system model here, and the optimization work in the further study will be explained.

Whether in the step response test or in the hydraulic control characteristic test, it can observed that the control effect of the p_s will show some flutter phenomenon. It indicates that The PID control method of p_s used in this paper does not respond quickly and stably to variation of system variables. So a more intelligent adaptive control algorithm is needed to control p_s, like the control scheme of adaptive fuzzy-PID. The fuzzy logic controller can be used to tune the parameters k_p, k_i and k_d of PID controller in real time. In fact, many other intelligent control methods also can be utilized for pressure control here.

Likewise, there are hysteresis of p_c whether in Figure 3d or in Figure 4d because of the magnetic hysteresis of the ferromagnetic material and the friction between the armature and the sleeve. In order to moderate the influence of hysteresis to the control precision of PCSV, an AC signal of a certain frequency can be superimposed in the DC control signal as the flutter signal. The effect of the flutter signal is to create a continuous additional vibration in the armature that keeps the spool in motion, thus eliminating the effect of static friction and ferromagnetic material on control performance. In addition, the PCSV needs to match different frequencies and amplitudes of the loaded flutter signal when control current or oil temperature changes to meet the rapid response requirement of the solenoid valve.

5. Conclusions

This study has introduced a design of novel system for testing the PCSV and the mathematical model of system based on bond graphs methods. This system is coupled sophisticatedly with mechanical, hydraulic and electromagnetic system. The internal structure of valve that exists the interaction between the electromagnetic force and the spring force is considered in modelling process. In simulations, we choose to implement the step response characteristics test and hydraulic control characteristics test under different inlet pressures and different input currents in this paper. The results of simulations proved that this designed testing system can perfectly show the characteristics of the PCSV. The mathematical model of system created in this paper is highly straightforward and accurate. People can utilize the system to attain many indicators such as the range of dead zone, the maximum value of control pressure, the hysteresis etc. of PCSV product. In a word, the test system developed here will be very helpful in the manufacture or analysis of solenoid valve.

Acknowledgments

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