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Research Article

Study on a linear relationship between limited pressure difference and coil current of on/off valve and its influential factors

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ABSTRACT

On/off solenoid valves with PWM control are widely used in all types of vehicle electro-hydraulic control systems respecting to their desirable properties of reliable, low cost and fast acting. However, it can hardly achieve a linear hydraulic modulation by using on/off valves mainly due to the nonlinear behaviors of valve dynamics and fluid, which affects the control accuracy significantly. In this paper, a linear relationship between limited pressure difference and coil current of an on/off valve in its critical closed state is proposed and illustrated, which has a great potential to be applied to improve hydraulic control performance. The hydraulic braking system of case study is modeled. The linear correspondence between limited pressure difference and coil current of the inlet valve is simulated and further verified experimentally. Based on validated simulation models, the impacts of key parameters are researched. The limited pressure difference affected by environmental temperatures is experimentally studied, and the amended linear relation is given according to the test data.

1. Introduction

Hydraulic actuators have many desirable properties, such as reliable, clean, low cost and fast acting, that makes them a natural choice for various types of electro-hydraulic braking control systems in passenger vehicle, including anti-lock braking system (ABS), vehicle stability control (VSC), and regenerative braking system (RBS) [1–4].

With development of automotive technology and increased requirements on brake safety, comfort and high-efficiency, improvement in precise and effective braking control is in need. To achieve high-performance modulation of braking pressure, proportional valve with digital control is the most effective and direct way. It can achieve a continuous control of hydraulic fluid flow, leading to a linear control of hydraulic pressure.

Although some of the proportional valves have been developed with application of advanced nonlinear control techniques [5–8], this kind of approach is usually highly cost and complicated with hardware, which restricts their practical applications and on the other hand makes on/off valves driven by pulse width modulated (PWM) inputs widely used in vehicle's braking control system [9]. For example, the electrically-controlled braking system (ECB), which has been employed in commercialized Toyota HEV Prius, is comprised of fourteen solenoid valves. Among the fourteen valves in use, however, only two are proportional valves, while the others are all on/off ones [10]. Similar situation can also be found in slip-control boost (SCB) braking system developed by famous braking component supplier TRW [11].

By utilizing on/off solenoid valves with PWM control, the costs and complexity of the system do can be reduced effectively and acceptable control accuracy can be obtained, but nonlinearity of the modulated pressure is increased mainly due to the inherently nonlinear discrete behavior of on/off valve and flow. Thus, to improve the modulation performance, researchers worldwide have been carried out comprehensive research in parameter design and control method of hydraulic actuators.

Champagne and Stephens [12] carried out research on valve actuator parameters optimizing to enhance the dynamic performance of the control valve. The effects of supply pressure, step size, load margin, flow, fluid volume and design style are investigated. Muto and Yamada etc. [13] proposed a method for realizing the smooth motion of the system by adjusting the phase difference between the input signals to the valves. In the system to which this method was applied, it was confirmed that the dynamic performance of the hydraulic actuator was remarkably improved. Ahn and Yokota [14] designed a modified PWM algorithm increasing the system response of on/off valves, and proposed an on/off algorithm for control parameters using a learning vector quantization neural network, guaranteeing the effectiveness of the proposed control with

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various external loads. Varseveld and Bone [15] used the typical two-valve circuit and tried to improve the input–output linearity of the whole system by changing the valve pulsing schemes, and they obtained a quasi-linear input–output behavior. Actuating performance of valves in a portable hardware-in-the-loop (HIL) device for automotive diagnostic control systems was studied in [16]. Jeong and Kim [17] studied the impacts of three major system variables, namely the on- and the off-times of the valve and the system configuration coefficient, on the mean pressure and the pressure ripple amplitude under PWM control. Intelligent algorithm was designed and proved to have good robustness and uncertainty handling properties in identification and position control of servo hydraulic rotary actuators including servo valves [18]. Wang and Song etc. [19] studied a simulation model of an on/off valve in ABS/ESP using PWM control with high modulation frequency at 2–4 kHz, and discussed the quasi-proportional function of valve under different duty cycles. The present authors modeled the dynamics of a pneumatic valve, researching the PWM regulation of pneumatic brake [20–22]; and studied the hydraulic pressure-increase rates under varied PWM duties of on/off valves, developing a threshold hydraulic pressure modulation algorithm for regenerative braking control of an electric car [4,23]. Nevertheless, the existing research on on/off valve control is mainly focusing on novel modulation method and algorithm based on PWM control, which can achieve the quasi-linear modulating performance, but a linear modulation effect has rarely been seen.

In this paper, a linear relationship between limited pressure difference and coil current of an on/off valve in its critical closed state is proposed and researched, which has a great potential to be applied to improve hydraulic control performance. The hydraulic braking system of case study is modeled. The linear correspondence between limited pressure difference and coil current of the inlet valve is simulated and further verified experimentally. Based on validated simulation models, the impacts of key parameters of valve on the limited pressure difference are researched. And the linear relationship proposed affected by environmental temperatures is also experimentally studied. According to the test data, the amended linear relation is given. Finally, some concluding remarks are provided.

2. Linear relationship between limited pressure difference and coil current of on/off valve

Take the inlet valve of the hydraulic braking system, a typical normally opened outflow valve shown in Fig. 1, as an example. Regarding the endpoint of valve core in the valve-closed state as the

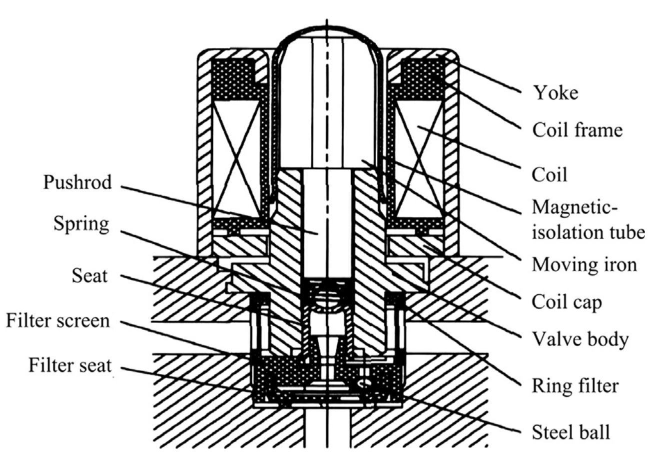

Fig. 1. Configuration of the inlet valve in hydraulic braking system.

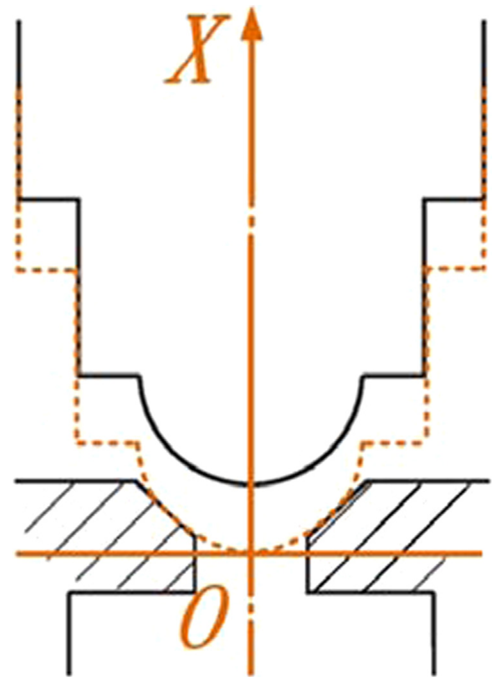

Fig. 2. Diagram of the coordinate system of inlet valve.

origin, the OX coordinate system was established, as Fig. 2 shows. OX is the movement direction of valve core, pointing forwards.

In valve closed state, the axial balance equation of valve core can be expressed as:

$$-F_e+F_s+F_h+F_N=0 \tag{1}$$

where F_e is the electromagnetic force, F_s is the spring force, F_h is the hydraulic force, and F_N is the supportive force.

However, when valve reaches a critical state, i.e. it is still closed ($x_v=0$), but it's just about to open, the supportive force will disappear ($F_N=0$), thus Eq. (1) can be expressed as:

$$-F_e+F_s+F_h=0 \tag{2}$$

The electromagnetic force acting on valve core is mainly determined by coil current I, turn number N, the air gap length l, and the magnetic reluctance of air gap R_g. The amount of electromagnetic force can be given by the relation:

$$F_e=(I\times N)^2/(2R_g\times l) \tag{3}$$

Linearizing Eq. (3), the electromagnetic force can be represented as follows:

$$\begin{aligned}F_e&=\frac{\partial F_e}{\partial i}I(t)+\frac{\partial F_e}{\partial x_e}x_v(t)\\&=K_i\times I(t)+K_{xe}\times x_v(t)\end{aligned} \tag{4}$$

Under critical balanced state, the valve opening is $x_v=0$, thus:

$$F_e=K_i\times I(t) \tag{5}$$

where K_i is the current–force gain, and K_{xe} is the displacement–force gain.

For a normally opened valve, in the coordinate system defined, the spring force can be given by the relation:

$$F_s=K_s\times(x_0+x_m-x_v) \tag{6}$$

When reaching the valve critical balanced state ($x_v=0$),

$$F_s=K_s\times(x_0+x_m) \tag{7}$$

where x_0 is the pretension displacement of return spring, x_m is the maximum displacement of return spring, x_v is the displacement of return spring, and K_s is the stiffness coefficient.