A Nozzle Flapper Electro-Pneumatic Proportional Pressure Valve Driven by Piezoelectric Motor

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***Abstract*—Electro-pneumatic proportional valve, as an important electro-pneumatic conversion element in pneumatic technology, has been widely applied in many pneumatic servo control systems. A novel nozzle flapper type electro-pneumatic proportional pressure valve driven by piezoelectric motor instead of the traditional torque motor was proposed in this paper. The structure and working principle of this type electro-pneumatic proportional pressure valve were described. And a mathematical model was established. A testing system was developed and the prototype valve was tested. Testing results showed that under the 0.3 MPa working pressure, an output performance of linearity ±0.5%, resolution 0.1%, hysteresis ±0.5% were obtained.**

***Keywords*-pneumatic; electro-pneumatic proportional pressure valve; nozzle flapper; piezoelectric motor**

I. Introduction

As a device of electro-pneumatic conversion element in pneumatic control system, the electro-pneumatic proportional valve transforms input signals (customarily voltage or current) into the output mechanical displacement of valve core. Thus, the pressure and flow of output air can be controlled and the control of pneumatic actuators would be accomplished. Electro-pneumatic proportional pressure valves realize transformation among computer signals, sensor's feedback signals and pneumatic control signals by close-loop feedback. Consequently, they have varieties of advantages, such as superior control accuracy and excellent integration [1-3].

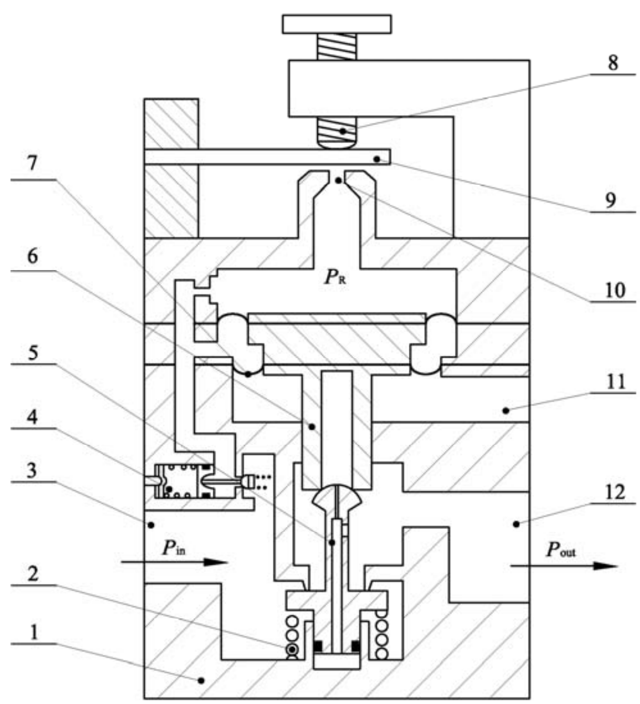
Proportional electromagnet or torque motor is mainly used as electro - mechanical conversion device of traditional proportional flow control valve. The phenomenon is due to the shortcomings of electromagnet like slow response, large volume, heat and electromagnetic interference. As the actuator for fluid control valve, the frequency response and control precision of the valve is difficult for further improvement [4, 5]. With the deep research of intelligent materials, especially the development of piezoelectric ceramic materials, piezoelectric actuators based on converse piezoelectric effect are widely used in fluid control valve [6-8]. At present, there are two typical piezoelectric valves, one of which is driven by rigid displacement actuator (PMA or PZT), another type is driven by resonant displacement actuator [9-12].

This paper proposed a nozzle flapper type electro-pneumatic proportional pressure valve based on piezoelectric motor driving. The structure and working principle of this new electro-pneumatic proportional pressure valve were analyzed and a mathematical model was established. A testing system, which was employed to test the performance of electro-pneumatic proportional pressure valve, was developed.

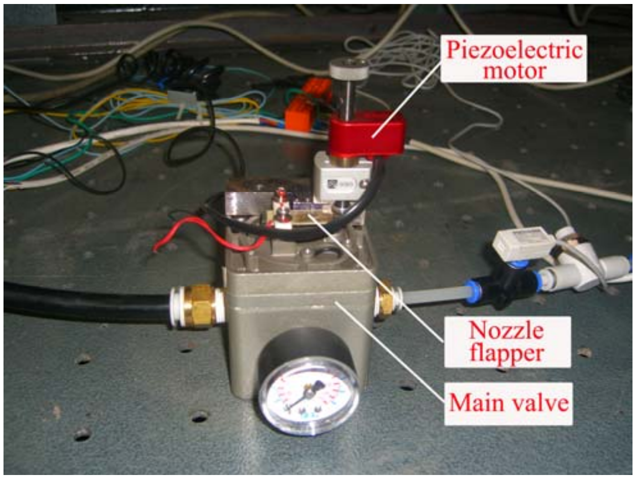
II. Structure and Principle of the Valve

A. Structure of the Proportional Pressure Valve

Fig. 1 shows the schematic diagram of nozzle flapper type electro-pneumatic proportional pressure valve driven by piezoelectric motor. The valve is mainly consisted of valve body 1, spring 2, supply outlet 3，small-sized regulator 4, lower valve 5, upper valve 6, diaphragm 7, piezoelectric motor 8, elastic flapper 9, nozzle 10, pressure-reduction output 11 and output outlet 12. Among them, the supply pressure is P_{in}, back-pressure chamber pressure is P_R, output pressure is P_{out}, the distance x between elastic flapper and nozzle is input signal while the output pressure P_{out} is output pressure signal.



(a) Structure of proportional pressure valve



(b) Photo of proportional pressure valve

Figure 1. Electro-pneumatic proportional pressure valve driven by piezoelectric motor

The piezoelectric motor (Picomotor™ Actuator Model 8303, New Focus, USA), which is used in this paper, has a maximum load of 22 N, a maximum linear output speed of 1.2 mm/min, and a minimum incremental motion of 30 nm. This motor, which uses piezoelectric substrate as oscillator, outputs displacement through the friction drive between the oscillator and output shaft. Stator and rotor are connected by precise thread, oscillator (stator) generates rotating traveling wave along the direction of the thread, their frictional connection is guaranteed by the pre-pressure between output shaft (rotor) and oscillator (stator), so sub-micron grade amplitude of the oscillator can be delivered to output shaft. Thus, the resolution of this motor can be down below 30 nm.

B. *Principle of the Proportional Pressure Valve*

When the input signal x increases, the flapper is caused to deflect and close the nozzle. This results in a decrease in the nozzle's output flow and an increase in the air-lock between flapper and nozzle. Consequently, the back-pressure chamber pressure P_R rises and acts upon the upper surface of the diaphragm, thus forces the upper valve down. So, the output pressure is enlarged when the opening of lower valve increases. Conversely, when the input signal decreases, the flapper tends to higher place and the air-lock decreases. The back-pressure chamber pressure is reduced and the lower valve goes up due to the spring force. The output pressure falls down because the lower valve's opening decreases. In conclusion, the output pressure can be controlled and adjusted via controlling input signals and they satisfy linear proportional relationship. But the distance between the flapper and nozzle is controlled by piezoelectric motor's output displacement.

III. Mathematical Model of the Valve

A. *Mathematical Model of Piezoelectric Motor*

Speed control of piezoelectric motor can be achieved by adjusting amplitude ratio V of input voltage and feedback voltage. Under different displacement step signal, response characteristics were tested, as is shown in Fig. 2.

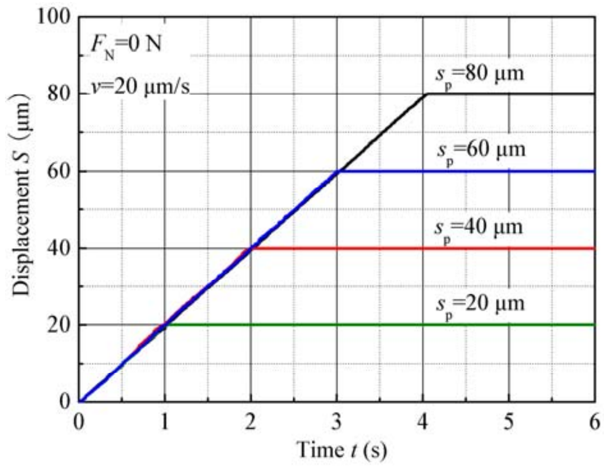


Figure 2. Step response curve with different displacement inputs

Simplified model of the piezoelectric motor can be established by system identification method, transfer function between motor output speed ω and input signal V is shown as below

$$G(s) = \frac{\omega(s)}{V(s)} = \frac{A}{J_r + \delta} = \frac{K}{Ts+1} \tag{1}$$

where A is ratio coefficient of stator amplitude and input voltage, J_r is rotor moment of inertia, δ is damping moment coefficient, gain coefficient K is assumed to be 50, time constant T is assumed to be 0.005.

According to Eq. (1), position servo control model of piezoelectric motor can be established, it is shown in Fig. 3.

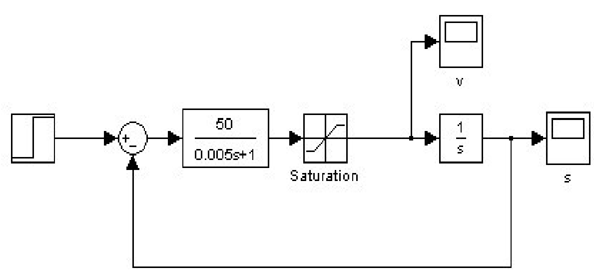


Figure 3. Position servo control model of piezoelectric motor

B. Mathematical Model of Nozzle Flapper Valve

Mathematical model of nozzle flapper valve is also the relationship between back-pressure chamber pressure P_R and the distance x between elastic flapper and nozzle.

Make the following assumptions: the volume changes of back pressure chamber are neglected and the gas is ideal gas. Temperature and pressure fields in the chamber are uniformly distributed.

Flow equation of the orifice of back pressure chamber is:

$$q_1 = \begin{cases} C_d A_1 P_1 \sqrt{\dfrac{2k}{(k-1)RT}\left[\left(\dfrac{P_R}{P_1}\right)^{\frac{2}{k}} - \left(\dfrac{P_R}{P_1}\right)^{\frac{k+1}{k}}\right]}, \dfrac{P_R}{P_1} \geq 0.528 \\ C_d A_1 P_1 \sqrt{\dfrac{k}{RT}\left(\dfrac{2}{(k+1)}\right)^{\frac{k+1}{k-1}}}, \dfrac{P_R}{P_1} \leq 0.528 \end{cases} \tag{2}$$

where q_1 is mass flow of orifice, C_d is Flow coefficient, A_1 is orifice area, T is gas temperature, R is gas constant, k is specific heat ratio, k = 1.4 on the condition of 20 ℃ air.

Flow equation at the place of flapper nozzle is

$$q_2 = \begin{cases} \pi C_d d_1 x P_R \sqrt{\dfrac{2k}{(k-1)RT}\left[\left(\dfrac{P_0}{P_R}\right)^{\frac{2}{k}} - \left(\dfrac{P_0}{P_R}\right)^{\frac{k+1}{k}}\right]}, \dfrac{P_0}{P_R} \geq 0.528 \\ \pi C_d d_1 x P_R \sqrt{\dfrac{k}{RT}\left(\dfrac{2}{(k+1)}\right)^{\frac{k+1}{k-1}}}, \dfrac{P_0}{P_R} \leq 0.528 \end{cases} \tag{3}$$

where q_2 is mass flow of flapper, d_1 is Nozzle diameter, x is distance between flapper and nozzle, P_0 is atmospheric pressure, 1.013×105 Pa in custom. At steady state, $q_1 = q_2$.

C. Mathematical Model of Main Valve

Here, the quality of the upper valve core and the quality of lower valve core were considered together, the elastic stiffness of reset spring at lower valve and diaphragm spring was also considered together. According to Newton's Second Law, balance equation for valve core is

$$P_R A_R - P_1 A_S + K_f y - \eta\dot{y} - m\ddot{y} + mg - F_0 = 0 \tag{4}$$

where A_R is upper valve core area, A_S is upper diaphragm-lower diaphragm area difference, y is valve core displacement, η is damping coefficient, m is valve core mass, contains upper and lower valve core, K_f is spring stiffness, contains diaphragm spring and reset spring, F_0 is pre-tightening force of reset spring.

Pressure differential equation of being researched gas chamber

$$\frac{dP}{dt} = \frac{\kappa}{V}\left(Q_m RT - P\frac{dV}{dt}\right) \tag{5}$$

For back-pressure chamber

$$Q_R = \frac{P_R A_R}{RT}\dot{y} + \frac{V_0 + A_R y}{kRT}\frac{dP_R}{dt} \tag{6}$$

where V_0 is original volume of back-pressure chamber, $V_R = V_0 + yA_R$.

To control chamber, assume the volume is a constant of V_C

$$Q_C = \frac{V_S}{kRT}\frac{dP_C}{d_t} \tag{7}$$

According to Sanville flow equation, pressure-mass flow equation of valve port is

$$Q_m = \begin{cases} \dfrac{AP_u B}{\sqrt{T}}\varphi\left(\dfrac{P_d}{P_u}\right), \dfrac{P_d}{P_u} \geq 0.528 \\ \dfrac{AP_u D}{\sqrt{T}}, \dfrac{P_d}{P_u} \leq 0.528 \end{cases} \tag{8}$$

According to law of conservation of mass, mass flow continuity equation is

$$Q_R = Q_1 - Q_2 = \frac{dm_R}{dt} = \frac{d}{dt}(\rho_R V_R) \tag{9}$$

$$Q_C = Q_3 - Q_4 = \frac{dm_C}{dt} = \frac{d}{dt}(\rho_C V_C) \tag{10}$$

where Q_R is mass flow of back-pressure chamber, Q_C is mass flow of control chamber, ρ_R is gas density of back-pressurechamber, ρ_C is gas density of control chamber, V_R is volume of back-pressure chamber, V_C is volume of control chamber.

D. Mathematical Model of the Valve

As is known from basic equations, this system is a nonlinear system. Based on these derived basic equation, it can use modular design to establish the nonlinear model of this valve by Matlab/Simulink, the nonlinear model is shown in Fig. 4.

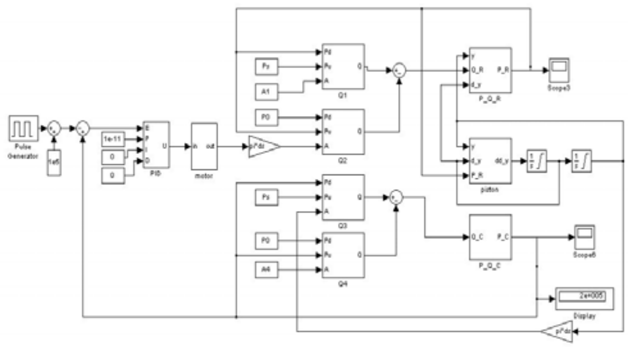


Figure 4. Nonlinear model of the pneumatic pressure valve driven by piezoelectric motor

IV. TEST OF CHARACTERISTICS

A. Realization of Testing System

In order to realize the tests and control of electro-pneumatic proportional pressure valve, this article established a testing system based on LabVIEW, which is illustrated in Fig. 5.

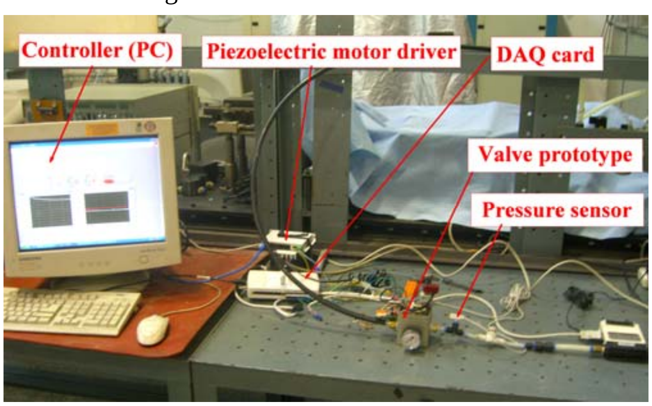


Figure 5. Photo of the testing system

The system primarily includes air source, air filter, pressure regulator, lubricator, new type electro-pneumatic proportional valve prototype, pressure sensor PSE540-R06 (SMC, Japan, has a pressure range of 0~1 MPa and a linearity of ±1% F.S. or less and a repeatability of ±0.2% F.S.), DAQ card NI-USB6211 (produced by NATIONAL INSTRUMENTS, USA, with 16 analog input channels has an AD sampling resolution of 16 bit and a sampling rate of 250 kS/s), computer, and piezoelectric motor driver.

B. Testing Results

Testing output pressure under different flapper displacement, open-loop output-input characteristics were obtained and compared with the simulation curve, its result is shown in Fig. 6. It can be seen that experimental curve and the simulation curve are in good agreement. The effective displacement of the flapper is almost the same.

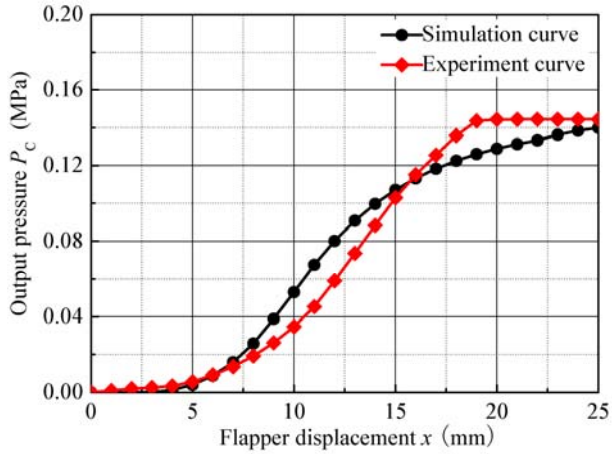
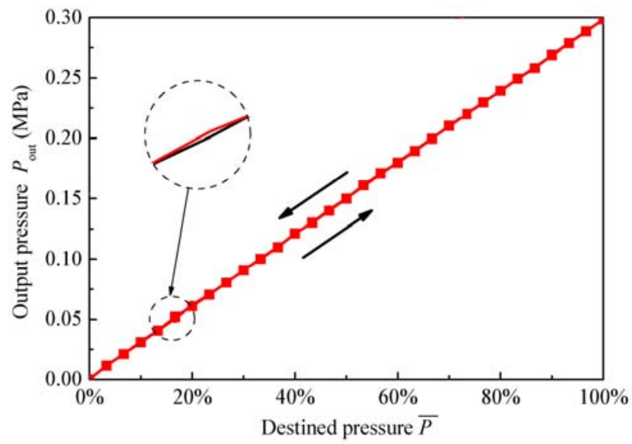
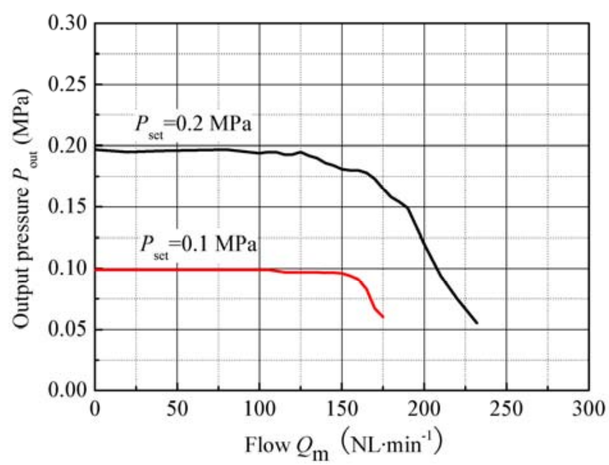


Figure 6. Open-loop output-input characteristics experimental curve versus simulated curve

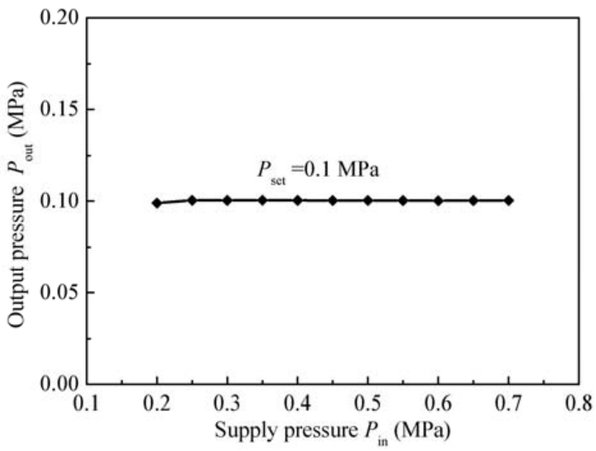
Close-loop static characteristics of electro-pneumatic proportional pressure valve were tested by the testing system. The testing results are illustrated in Fig. 7.



(a) Pressure-regulating characteristics of the valve



(b) Pressure-regulating characteristics of the valve



(c) Pressure characteristics of the valve

Figure 7. Test of close-loop static characteristics

Results of the test show that under the 0.3 MPa working pressure, the valve's linearity is ±0.5%, resolution 0.1%, hysteresis ±0.5%, the dynamic response time is about 2s approximately. Because of continuous displacement output capability of piezoelectric motor, this pneumatic proportional pressure valve does not exist problems affecting the valve's stability such as drift and zero-drift. Thus, the nozzle flapper type electro-pneumatic proportional pressure valve based on piezoelectric motor driving has higher stability and control precision than traditional electro-pneumatic proportional pressure valve, which is a promising pneumatic pressure valve.

V. CONCLUSION

The electro-pneumatic proportional pressure valve is a transition element between input electrical signal and output pressure signal in pneumatic system. In this paper a novel nozzle flapper type electro-pneumatic proportional pressure valve driven by piezoelectric motor was presented. The valve prototype has a two-stage structure with a nozzle flapper. The displacement of the flapper is controlled by a linear piezoelectric motor, and the output flow and pressure of the valve can be regulated. The prototype was developed and close-loop static characteristics were tested. The testing results indicate that compared to the traditional electro-pneumatic proportional pressure valve, this novel prototype valve has a higher stability and control precision.

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