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Pneumatic valve with a pressure regulator for bimorph type PZT actuator

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Abstract The pressure regulator which is used for controlling the reducing pressure in the piezoelectrically driven pneumatic valve has been studied. The pneumatic valve of this study is two-stage type and consists of a piezoelectric actuator, a controller, a poppet valve and a pressure regulator. Nominal flow of 50 lpm, maximum operating pressure of 0.9 MPa and frequency characteristic of 10 Hz or higher are required in this pneumatic valve. The pressure regulator is needed because piezoelectric actuator has no ability to control the pressure of 0.9 MPa directly. In this study, a bimorph type PZT actuator of 25.2 mm(L)× 7.2 mm(W)×0.5 mm(H) with constant of -220×10^{-12} CN^{-1} was proposed and investigated. Maximum operating force of 0.052 N and maximum displacement of 63 μm were achieved from the fabricated PZT actuator. From the analysis results, an orifice diameter of 0.6 mm was selected for a piezoelectric actuator. The pressure regulator which can be operated under 0.15 MPa easily was designed and manufactured. Performance and effects of design parameters were simulated by the Simulink of Matlab software, and it was confirmed that the performance characteristics of manufactured pressure regulator are superior in the common use pressure range of 0.5 to 0.7 MPa. The results show that the proposed pressure regulator is suitable for the pneumatic valve with a PZT actuator.

Keywords Pressure regulator · Pneumatic valve · PZT actuator · Reducing pressure control · Solenoid actuator

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Nomenclature

A_p	Cross-sectional area of poppet [m^2]
A_r	Control part area of pressure regulator [m^2]
A_{r1}	Inlet area of pressure regulator [m^2]
B_p	Friction coefficient of poppet [N·s/m]
B_r	Friction coefficient of pressure regulator [N·s/m]
D_r	Control part diameter of pressure regulator [m]
D_{r1}	Inlet diameter of pressure regulator [m]
G_m	Mass flow of solenoid actuator [kg/s]
G_p	Mass flow of poppet [kg/s]
G_r	Mass flow of pressure regulator [kg/s]
k	Specific heat ratio
k_p	Spring constant of poppet [N/m]
k_r	Spring constant of pressure regulator [N/m]
m_p	Mass of poppet [kg]
m_r	Spool mass of pressure regulator [kg]
P_m	Control pressure of poppet [Pa]
P_o	Output pressure of poppet [Pa]
P_r	Control pressure of pressure regulator [Pa]
P_s	Supply pressure [Pa]
Q_m	Control flow of poppet [m^3/s]
Q_p	Output flow of poppet [m^3/s]
Q_r	Flow of pressure regulator [m^3/s]
R	Air constant
S_{em}	Effective area of solenoid actuator [m^2]
S_{ep}	Effective area of poppet [m^2]
S_{er}	Effective area of pressure regulator [m^2]
T	Absolute temperature [^{o}K]

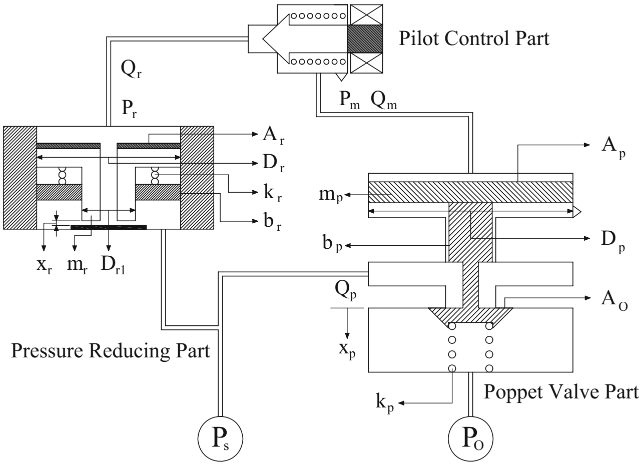

Fig. 1 Pneumatic valve model

V_o Air volume of poppet [m^3]
V_p Air volume of pilot part [m^3]
V_r Air volume of pressure regulator [m^3]
V_{r0} Control part initial volume of pressure regulator [m^3]
x_{po} Initial displacement of poppet spring [m]
x_r Displacement of pressure regulator [m]
ρ Air density [kg/m^3]

1 Introduction

Piezoelectric actuators have many advantages such as high stiffness, fast frequency response, low energy consumption and have been used in applications that control the fluid and require precise positioning control in recent years. However, the bender type piezoelectric actuators like unimorph and bimorph have some problems for control of pneumatic and hydraulic fluid because PZT actuator does not have a constant operating force in the control region independently on the stroke position [1]. This actuator is only used for very low pressure and low frequency response system due to the low output force compared to the solenoid actuator [3–6]. This is why its use is restricted in industrial field application. For the purpose of solving the abovementioned

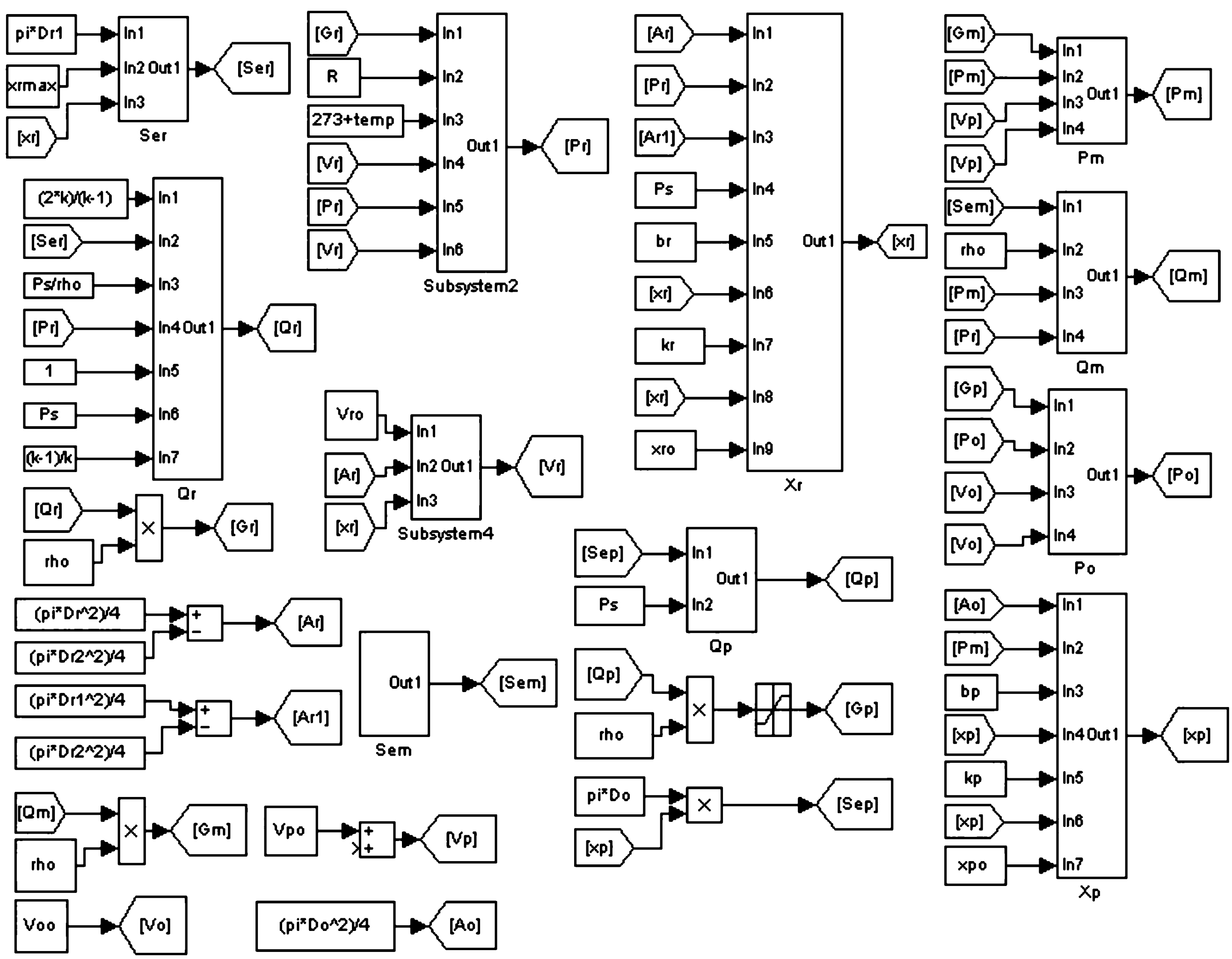

Fig. 2 Simulink block for analysis

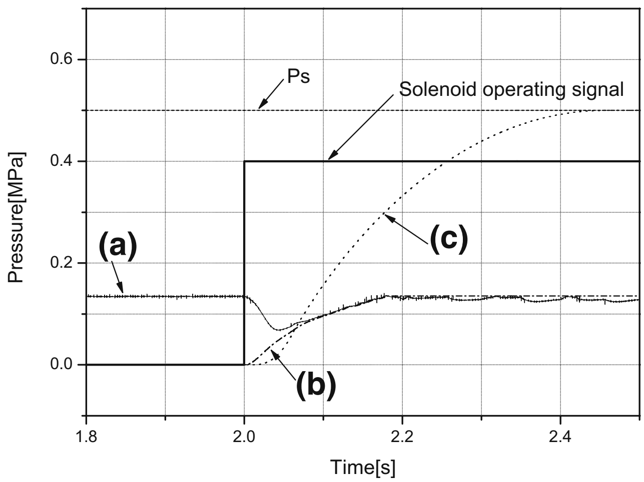

Fig. 3 Theoretical analysis results

problems, it is desirable that the actuator is fabricated as a multilayer for applications in the high pressure system [2], but this method also limits the displacement directly. In this study, bimorph type PZT actuator of 25.2 mm(L)×7.2 mm (W)×0.5 mm(H) with constant of -220×10^{-12} CN^{-1} was proposed and investigated [1]. Maximum operating force of 0.052 N and maximum displacement of 63 μm were obtained from the fabricated actuator. From the analysis results, the orifice diameter of 0.6 mm for a piezoelectric actuator was derived and a pressure regulator which can be operated under 0.15 MPa easily was designed and manufactured. Performance and effects of design parameters were simulated using Simulink/Matlab software. It was confirmed that the performance characteristics of the manufactured pressure regulator is superior in the pressure range of 0.5 MPa to 0.7 MPa.

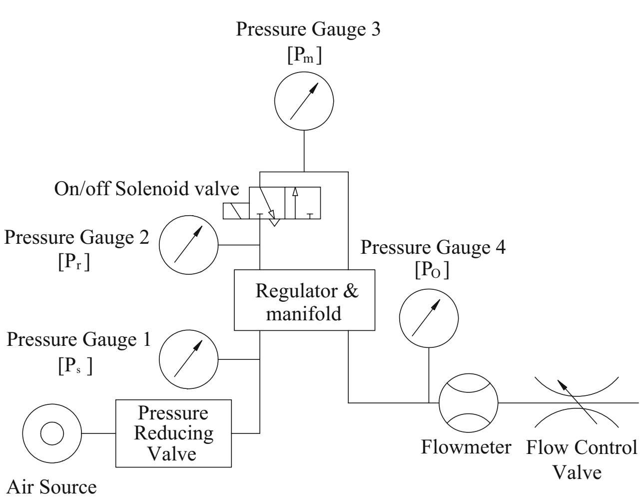

Fig. 4 Pneumatic circuit for experiment

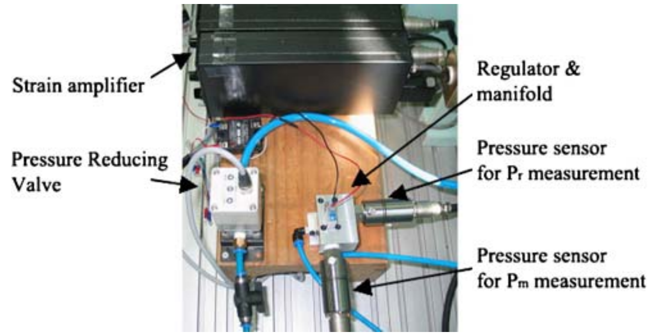

Fig. 5 Photo of experimental setup

2 Theoretical analysis

2.1 Pneumatic valve modeling

Figure 1 shows the subject of this study, the pneumatic valve. The pneumatic valve consists of the pressure-reducing part, pilot control part and poppet valve part. The pressure regulator is for the pressure-reducing part and the bimorph-type piezoelectric actuator is for the pilot control part. The quantity of flow through the poppet valve, Q_p is determined by the pressure of the pressure-reducing part, P_r and the displacement of the poppet, x_p driven by the control pressure of the poppet, P_m from the pilot control part. The purpose of the study is to evaluate the characteristics of a pressure regulator so that a solenoid actuator can be installed instead of a piezoelectric actuator in the pilot control part on the back of the pressure-reducing part [7]. The flow and kinetic equation of the pressure-reducing part can be expressed as Eq. 1 through Eq. 4.

$$Q_r = S_{er}\sqrt{\frac{2k}{k-1}\frac{P_s}{\rho}\left(1-\left(\frac{P_r}{P_s}\right)^{\frac{k-1}{k}}\right)} \tag{1}$$

$$G_r = Q_r\rho \tag{2}$$

$$\frac{dP_r}{dt} = \frac{1}{V_r}\left\{G_rRT - P_r\frac{dV_r}{dt}\right\} \tag{3}$$

$$F = P_m \cdot A_p = m_r\frac{d^2x_r}{dt^2} + b_r\frac{dx_r}{dt} + k_r(x_r + x_{r0}) \tag{4}$$

Equation of continuity and equation of the displacement relation can be expressed as follows. By inserting the solenoid actuator in the pilot control part from which characteristics can be verified in substitute for a piezoelectric actuator, this study can verify the characteristics of the pneumatic valve [8]. As shown in Eq. 8 the displacement of

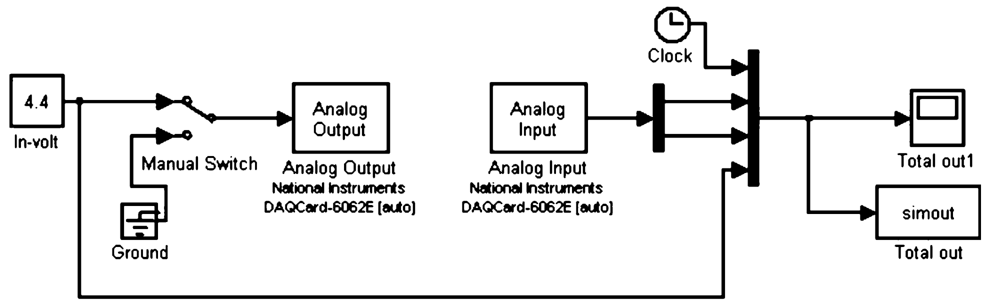

Fig. 6 Data acquisition block using simulink

the solenoid actuator, x_m is expressed as the first order lag element.

$$Q_m = S_{em}\sqrt{\frac{2k}{k-1}\frac{P_r}{\rho}\left(1-\left(\frac{P_m}{P_r}\right)^{\frac{k-1}{k}}\right)} \tag{5}$$

$$G_m = Q_m\rho \tag{6}$$

$$\frac{dP_m}{dt} = \frac{1}{V_p}\left\{G_mRT - P_m\frac{dV_p}{dt}\right\} \tag{7}$$

$$x_m = 1 - e^{-\frac{t}{\tau}} \tag{8}$$

The equation of continuity and equation of motion in the poppet valve can be expressed as follows:

$$Q_p = S_{ep}\sqrt{\frac{2k}{k-1}\frac{P_s}{\rho}\left(1-\left(\frac{P_o}{P_s}\right)^{\frac{k-1}{k}}\right)} \tag{9}$$

$$G_p = Q_p\rho \tag{10}$$

$$\frac{dP_o}{dt} = \frac{1}{V_o}\left\{G_pRT - P_o\frac{dV_o}{dt}\right\} \tag{11}$$

$$F = m_p\frac{d^2x_p}{dt^2} + b_p\frac{dx_p}{dt} + k_p(x_p + x_{p0}) \tag{12}$$

Figure 2 shows the Simulink block to analyze the piezoelectric pneumatic valve. Using Eq. 1 through Eq. 12, the control pressure of the pressure regulator, P_r, the control pressure of the poppet, P_m, and the output pressure of the poppet, P_o, can be solved in an analytical strategy. In addition, it is constructed to easily verify the characteristics of the piezoelectric pneumatic valve in accordance with changes in design parameters.

2.2 Results of theoretical analysis

Figure 3 shows the results of the theoretical analysis using the Simulink block shown in Fig. 2, and the supply pressure used for the analysis is 0.5 MPa. (a) of Fig. 3 shows the pressure characteristics of the pressure-reducing part, which are very stable and fast acting. The point of 2 s shows the characteristics when the closed solenoid actuator is open, which showed a little pitching but fast recovery. The settling time of the pilot pressure shown in (b) of Fig. 3 is less than 0.18 s, which proves to be a system with very fast response. Curve (c) of Fig. 3 shows the output pressure of the poppet with a settling time of less than 0.4 s, that is also stable without over-shooting and vibration.

3 Experimental results and discussion

3.1 Experimental setup

Figure 4 shows the circuit for the experiment on the pneumatic valve. To investigate the characteristics of the pressure regulator, pressure gauges were installed in the front and back of the pressure regulator. They were installed to generate pressure from the operation of the on-off solenoid valve.

Figure 5 shows the test rig manufactured based on the standard of the pneumatic circuit shown in Fig. 4. Figure 6 shows the block diagram configured by the Simulink software. The data sampling was conducted at a speed of 1 kHz.

3.2 Experimental results and discussion

Figure 7 shows the experimental characteristics of the pneumatic valve. In Fig. 7(a) displays the characteristics when the solenoid valve is on and off, and (b) and (c) display the characteristics when the solenoid valve is on or off, respectively. The experiment was conducted by inputting 24 V DC voltage to the on-off solenoid in the form of step. It was verified that the dead time of the output pressure of the poppet is 60 ms when it is on and 83 ms when it is off. It was

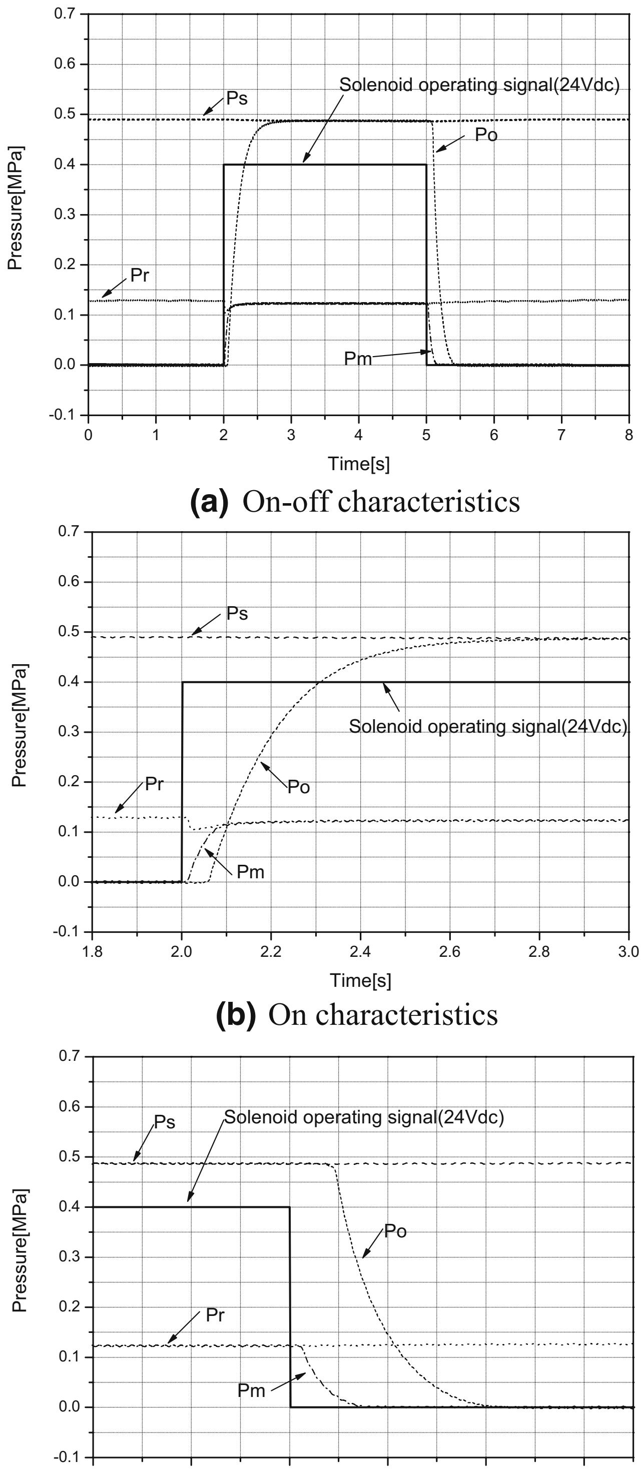

Fig. 7 Pneumatic valve characteristics. (**a**) On-off characteristics, (**b**) on characteristics, (**c**) off characteristics

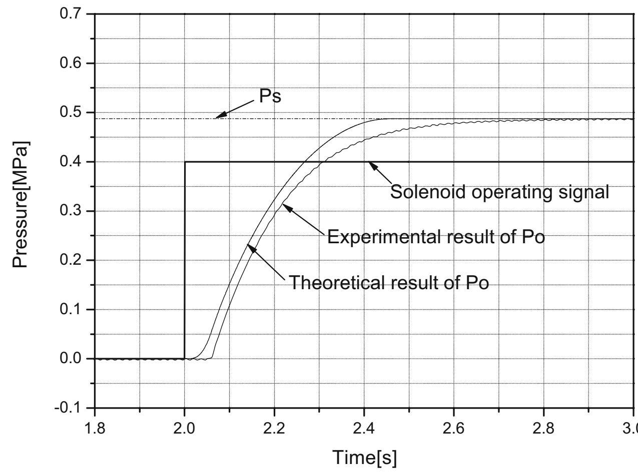

Fig. 8 Output pressure results of poppet

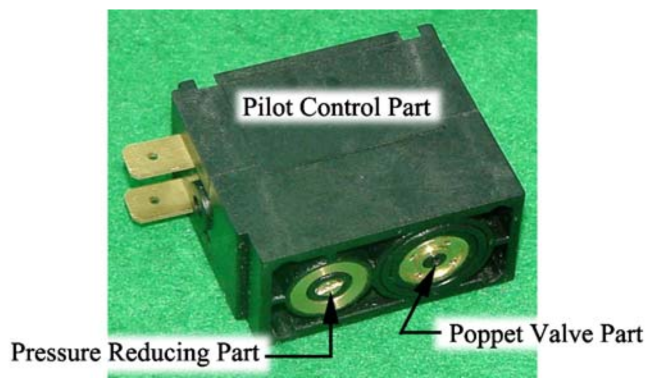

Fig. 9 Manufactured pneumatic valve

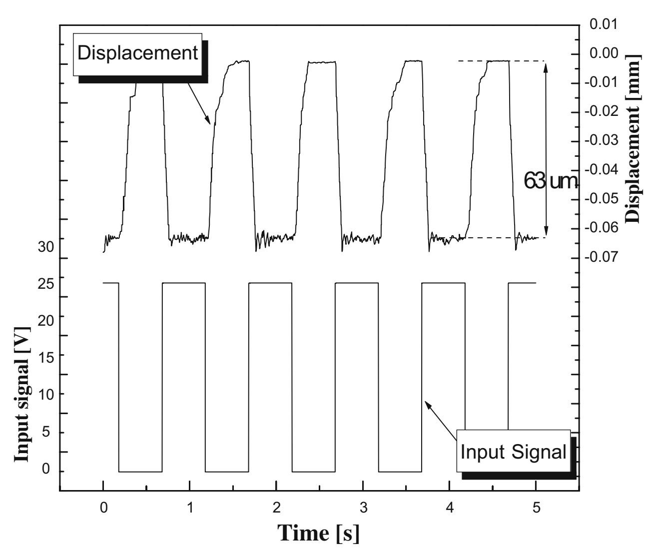

Fig. 10 Displacement characteristics of piezoelectric actuator

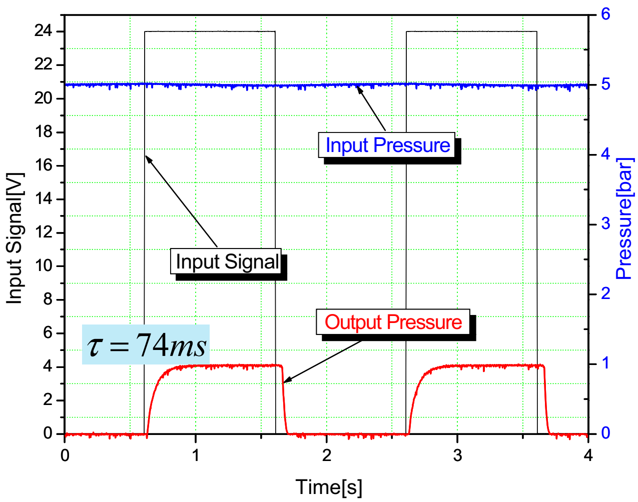

Fig. 11 Step response characteristics of manufactured pneumatic valve

also verified that the time constant is 150 ms when it is on and 98 ms when it is off. The time constant of the control pressure of the pressure regulator was 45 ms during both on and off. The pressure regulator very stably controlled the pressure without impact wave. Figure 8 shows the results of the output pressure of the poppet. The theoretical and experimental results coincided well. The reason for the more delayed response in comparison with the theoretical result is considered to be caused by the friction of the poppet and the flow coefficient is not appropriately compensated.

3.3 Proposed pneumatic valve

Figure 9 shows the pneumatic valve manufactured by inserting the bimorph-type piezoelectric actuator with the size of 25.2 mm(L)×7.2 mm(W)×0.5 mm(H) and -220×10^{-12} CN^{-1} of the piezoelectric constant in the pilot control part instead of the solenoid actuator explained in Fig. 1. The piezoelectric actuator used in the pneumatic valve has a maximum operating force of 0.052 N, a maximum displacement of 63 µm, and square wave frequency of 15 Hz at −9 dB gain (Fig. 10) [1]. Figure 11 shows the characteristics of the step response of the piezoelectric pneumatic valve. Its time constant is 74 ms, which proved to be a valve with fast response and good stability.

4 Conclusions

In this study, as a basic research to provide the PZT micro valve with a pressure regulator to a fluid control, a pressure regulator and a poppet type directional control valve were manufactured and experiments were carried out. The validity of this theoretical study was established through the experiment. The results of this study indicate that a pressure regulator for PZT micro valve for high pressure system application can be constructed and multilayer PZT actuator produces a compact package.

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