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SPOOL POSITION CONTROL OF PIEZOSTACK VALVE SYSTEM OPERATED AT VARIOUS TEMPERATURES

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This paper proposes a spool valve system actuated by a piezostack actuator and investigates control performance from room temperature to high temperature (150℃) using fuzzy PID controller. In order to achieve this goal, a piezostack driven spool valve system is designed and an experimental apparatus is setup to evaluate control performance with high temperature conditions. The experimental apparatus consists of a heat chamber, pneumatic-hydraulic cylinders, a hydraulic circuit, a pneumatic circuit, thermal insulator, and electronic devices such as a computer, data acquisition (DAQ) board, sensors, and a high voltage amplifier. The piezostack actuator is insulated from heat because the piezostack actuator cannot generate the blocking force if the actuator is heated to higher than Curie temperature. After designing a fuzzy algorithm integrated with PID controller, experimental implementation is realized. Experimental results are compared between room temperature condition and high temperature conditions. The experiment results are presented in both time and frequency domains.

Keywords: Piezostack Actuator, High Temperature, Spool Valve, Fuzzy Algorithm

1. Introduction

Piezoelectric actuators have salient features for actuating such as fast frequency response, high actuating force and infinite control resolution. Therefore, piezoelectric actuators are widely used for various control applications. The lead-zirconate-titanate (PZT) piezoelectric material are widely used for piezoelectric actuators because the PZT material can convert electronic to mechanical largely. However, the PZT piezoelectric material can use low temperature conditions up to 80^{o}C since the material has low Curie temperature. However, the working temperature is over then 100^{o}C in many industrial fields. *Li*, *Schranz,* and *Senousy* studied about properties of the piezostack actuators under high temperature [1-4]. Furthermore, *Chio* researched the dynamic properties and control capability of a piezostack actuator at various temperature conditions up to 190^{o}C [5].

The hydraulic valve system is widely integrated for control mechanical system because the hydraulic system can change hydraulic power to mechanical power easily and has high power density. The performance of mechanical system integrated hydraulic system is seriously influenced by flow and pressure control valve. The solenoid servo valve is the most widely used since it has low price. However, the solenoid valve cannot provide high precision and fast response [6, 7]. The one of the solutions to resolve the problems is using the piezoelectric actuators for a hydraulic valve.

Consequently, a valve system actuated piezostack is proposed and evaluated at from low to high temperature conditions up to 150 ^{o}C. In order to reach the goal, a piezostack direct drive valve (PDDV) system is designed firstly. After briefly explaining the valve system, the dynamic equation is driven. Second, the experimental apparatus for various temperature conditions are designed and described. Furthermore, fuzzy PID controller is designed which can change I gain for control of spool displacement in various temperature conditions. Finally, the temperature of working condition is controlled by a heat chamber and the performance evaluation of the valve system is conducted using a gap sensor. The output results are displayed and discussed in time domain.

2. Piezostack direct drive valve

Figure 1 shows a schematic diagram of proposed PDDV system. The valve consists of a piezostack actuator, a displacement amplifier, a spool valve, and a gap sensor. The parts are installed on base structure. The spool valve consists of a housing, a return spring, a sleeve, and a spool. The spool can move only axial direction because it is placed in sleeve with 3 ㎛ of gap. The return spring is used to return of initial spool location since a unipolar piezostack actuator is considered in this research. The displacement amplifier is used to complement one of the piezostack faults which make small displacement. In this study, a lever-hinge amplification method is applied since the amplifier has clear effect. The amplified displacement form piezostack can generate spool displacement. The spool displacement is observed by a gap sensor (KD-2306 2SMT, KAMAN). The non-contact gap sensor is used because a non-contact type is not effect of a system. The outlet port has rectangular shape for linear flow rate control and inlet port has circle shape and always opened. A constant pressure is applied to inlet port and flow rate can be controlled by outlet opened area from spool displacement.

In this research, a positive and normal closed spool valve is considered. As mentioned, the flow rate can be controlled by open area. The open area (AO) can be calculated as follow:

$$\begin{aligned} &|x_s| < \varepsilon, && A_o = 0 \\ &\varepsilon < |x_s| < (\varepsilon + a), && A_o = 2 \times D_S \times sin^{-1} \frac{H_S}{D_S} \times (x_S - \varepsilon). \\ &|x_s| \geq (\varepsilon + a), && A_o = 2 \times D_S \times sin^{-1} \frac{H_S}{D_S} \times a \end{aligned} \tag{1}$$

where D_s, and H_s, are a diameter of spool and a height of the outlet port. x_s, ε and a are a displacement of spool, overlap area, and width of outlet port. Finally, flow rate (Q_S) can be obtained as follows:

$$Q_s = C_d A_O \sqrt{2\Delta P / \rho}\ . \tag{2}$$

where C_d, ρ, and ΔP are a discharge coefficient, a density of hydraulic oil, and pressure drop. The C_d value is defined from 0.6 to 0.65 and it function of Reynolds number and cavitation number [8]. VG 46 is used and 879 kg/m3 for this research. The stacked piezoelectric actuator (pst150/20/80/V25, PIEZOMECHANIK) is used to generate initial displacement. The guaranteed working temperature is 80°C because of PZT piezoelectric material. The lever-hinge amplifier can magnify the displacement from piezostack and amplification ratio is 21. The valve system is designed for 200Hz of the maximum operating frequency.

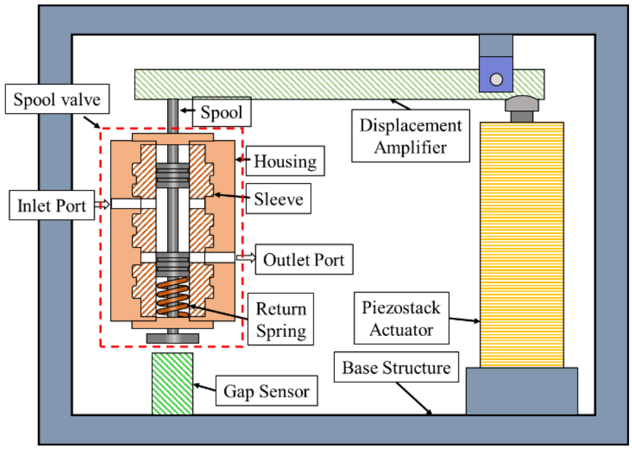


Figure 1: Schematic diagram piezostack valve

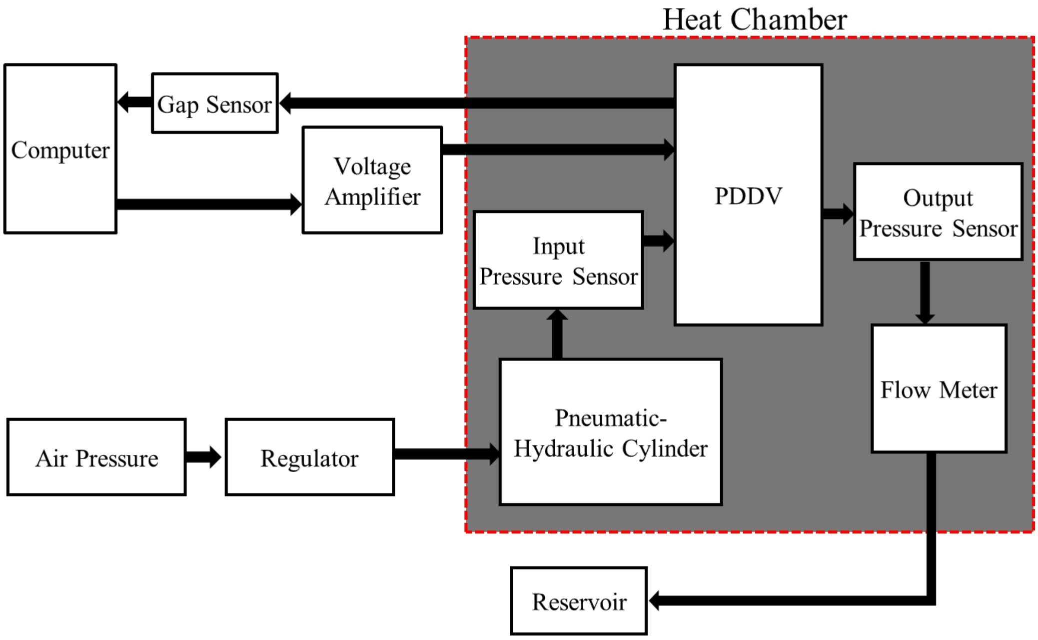


Figure 2: Schematic diagram of experimental apparatus

3. Experimental apparatus

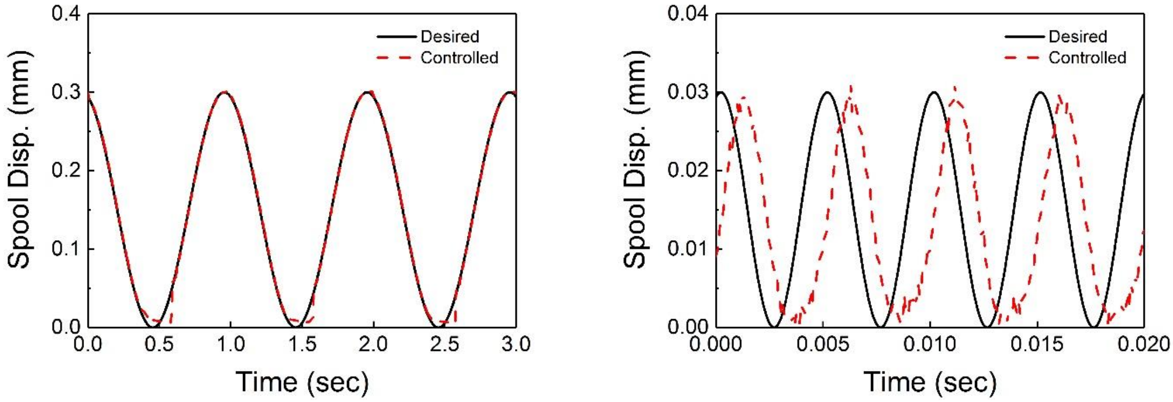
An experimental apparatus is designed for evaluating of proposed valve system. Figure 2 shows a schematic diagram of experimental apparatus with heat chamber (BK-HTDO-8100, Bookwang C&C co., Ltd.). The goal of this research is 150 ^{o}C of working temperature and 200 Hz of working frequency. In order to experiment with high temperature, all sensors are used which are high temperature resisted sensors. As shown in the figure 2, two pressure sensors and a flow meter are used for evaluation of the valve system. The heat chamber can regulate temperature of inside of chamber room temperature to 300 ^{o}C. Therefore, the manufactured valve system is installed inside of heat chamber for heating of piezostack actuator. Two pressure sensors (210-40-011-04, Paine Electronics, LLC) are connected before and after the PDDV and flow meter (FT-08AEYB-LEA-3) is also connected after the valve system. A control signal is generated by a computer and the signal is amplified using a voltage amplifier (EC750SA, NF Corporation) using D/A converter (DS1104 R&D Controller Board, dSPACE). The amplified voltage is applied to piezostack as shown in the figure. All sensors data is saved by computer using A/D converter (DS1104 R&D Controller Board, dSPACE).

To generate input pressure, air pressure is used with regulator. The regulated air pressure is applied to pneumatic-hydraulic cylinder. The cylinder can change air pressure to hydraulic pressure. The hydraulic oil goes to reservoir tank through PDDV and sensors. At the same time, input and output pressure and flow rate is observed.

4. Results and discussion

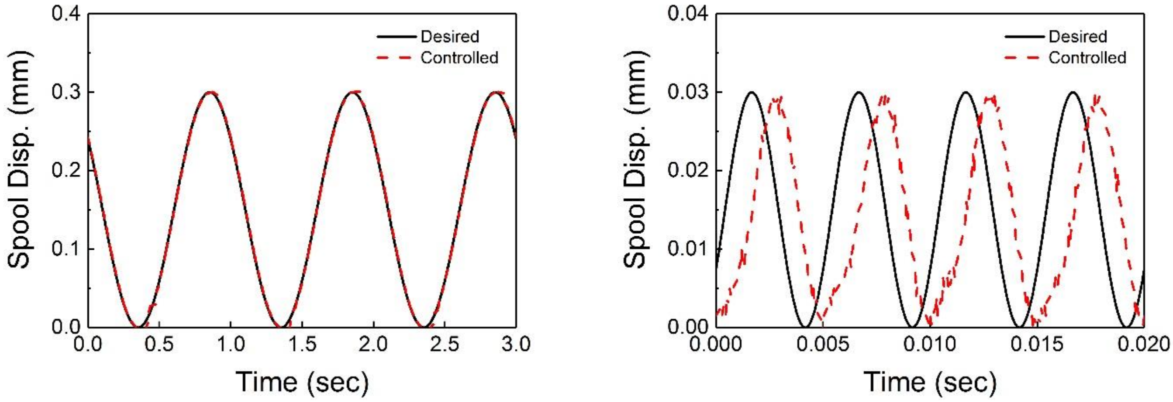
For control of the valve system, fuzzy PID controller is designed for I gain because the I gain is the most effective factor for displacement control. Figure 3 shows the tracking control result at 30 ^{o}C. As shown in the figure 3(a), the spool displacement can follow accurately without error and time delay with low frequency and temperature. However, the result of spool displacement has a phase delay with 200 Hz of operating frequency. The phase delay is observed as 75.6^{o}. The phase delay is caused by the return spring because the stiffness of return spring is small to remove phase delay. In spite of delay, the displacement of spool can follow as well. Figure 4 shows the control result at 150

$^{\circ}$C. The results have almost same properties as same as low temperature. However, at high temperature, the shape of displacement is distorted more than shape of displacement at low temperature since the stiffness of piezostack actuator is decreased due to thermal effect and a phase delay is also observed as 79.2°.



(a) 1 Hz (b) 200 Hz

Figure 3: Tracking control results at 30 $^{\circ}$C



(a) 1 Hz (b) 200 Hz

Figure 4: Tracking control results at 150 $^{\circ}$C

5. Conclusion

In this study, a PDDV was designed and performance evaluation was conducted with room and high temperature conditions. In order to evaluate, an experimental apparatus was designed with heat chamber. The PZT piezostack actuator was used to generate displacement and displacement amplifier was used to resolve the one of weakness of piezostack. The spool valve was used to control flow rate and control target was selected as the displacement of spool because flow rate is directly related with displacement of spool. The response time was observed at 30 and 150°C. Performance of displacement tracking control was evaluated in both room and 150°C. At 1 Hz with both temperature case, the valve had good control performance without error. However, the phase delay was observed at 200 Hz operating frequency and observed 75.6° and 79.2° with room and high temperature condition. As the results, the temperature condition is not the main factor of phase delay. In the near future, the stiffness of return spring will be redesigned to remove the phase delay.

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