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A High Speed Electro-hydraulic No Leakage Servo Valve Using Multilayered Piezoelectric Devices (PZT) and an Observer

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ABSTRACT

In this study, a high-speed servo valve with no outer leakage is developed, which is used to drive flexible hydraulic actuators (FHA) for extreme environments. In the valve, multilayered PZT devices are used to drive a spool directly and quickly. A bellows is also used to prevent outer leak from the clearance between the spool and the sleeve. Employing a disturbance observer, the lack of the system damping of the valve is improved by feeding back the estimated velocity of the spool, as well as the estimated disturbance is fed back to eliminate effectively the hysteresis between input voltage and output displacement of the PZT devices.

1. INTRODUCTION

We have proposed and fabricated a Flexible Hydraulic Actuator (FHA)[1], which has no leakage and no need for lubrication. Through a comparison with the mathematical model in static and dynamic behavior, the validity of the actuator is ascertained. Also, a single arm manipulator system using two FHAs is investigated[2]. In order to drive manipulators hydraulically in extreme environments, however, it is necessary that not only leakage of actuators but also that of servo valves should be avoided. To prevent the leakage of an servo valve at present, it seals an oil by making use of a gasket and O-ring around the axis. Because of its sliding parts, however, the oil film attached to the axis of valve will be fatal in extreme environments.

In the previous report[7], a newly devised high speed electro-hydraulic servo valve was proposed as a servo valve to drive a FHA[2]. The following are the main features of the servo valve. It seals an oil by bellows for no sliding parts and uses lever mechanisms with multilayered piezoelectric device (PZT)[3] to drive a spool. It makes use of velocity feedback control and disturbance observer to remove such a nonlinearity as hysteresis. It is ascertained that the servo valve has the maximum displacement 100μm and the resonant frequency 270Hz.

In this paper, based on a design principle obtained in the previous study[7], we attempted to obtain a high responsiveness of spool-driving system, and investigated characteristics of this driving system experimentally. In the newly devised servo valve, improved lever mechanisms and PZT devices connected in series are used.

2. STRUCTURE AND CHARACTERISTICS OF THE SERVO VALVE

2.1 Construction of the Servo Valve

Construction of the newly devised servo valve is shown in **Fig.1**. The servo valve consists of one-land three-ports type. The maximum displacement of the spool is 100μm and the diameter of the spool is 12mm. Under supply pressure of 3MPa, the amount of flow rate through the load ports is maximum 10 l/min (1.7×10^{-4} m^3/s). The PZT devices[6] are connected with the lever mechanisms through a piece of steel ball. The spool is supported by lever mechanisms with the aid of steel balls on both sides, which is driven with differential motion. A piece of permanent magnets is attached to two points of the spool and the lever parts. Hence, it can be detected a displacement by magnetic reluctance devices with no contact. A semiconductor type pressure transducer is installed to measure pressures in the load ports.

In order to avoid an outer leakage from the servo valve, bellows is used. Therefore, the oil is perfectly sealed up. The bellows is installed on both sides of the sleeve. The both sides of bellows is fixed to the spool and the sleeve through metal components. Because the expansion and contraction of the bellows is accompanied by the spool, sliding parts does not exist on the outside. Between the port and the bellows, owing to pressure canceller equipped to spool, high pressure is not applied to bellows directly.

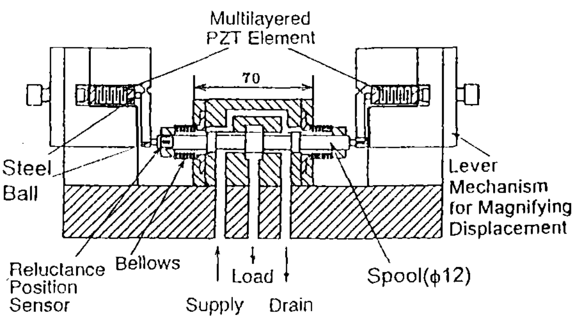

Fig. 1 Construction of servo valve

3. REALIZATION OF A HIGHER SPEED SERVO VALVE

3.1 Modification of Lever Mechanisms

On the basis of the results of the previous paper, we aim at improving the servo valve having the same displacement and higher responsiveness than twice of the previous report[7] in the frequency range. We attempt to drive the spool with higher speed, by fabricating a lever mechanisms which are based on actuators using connected two PZT devices in series. That is to say, lever mechanisms are modified as shown in **Fig.2**. Besides to higher speed-up, it resulted from getting hold of the characteristics of lever mechanisms in the previous paper. Roughly speaking, the enlargement rate is decreased to seven times comparing to the previous ten times and the width of fulcrum is made thin to 0.7mm. A section of lever parts is carved in H type for a ditch. A mass is reduced to maintain high stiffness concerning displacement direction as much as possible. A stiffness (a spring constant at cantilever) is twenty-two times of the previous study[7].

To begin with, **Figure 3** shows experimental results of static characteristics of the two new lever mechanisms (A from within A, B). As the input voltage V_p changes statically from 0V to 100V, the displacement of spool-support parts of lever mechanisms is measured. At this point, a peculiar hysteresis of PZT devices is shown in Fig.3. **Figure 4** shows the recorded displacement of spool-support parts of lever mechanisms when the input voltage is step-wise changed at ±6V range for transient response experiments. The figure indicates the input voltage and the displacement in descending order when the step input is up and

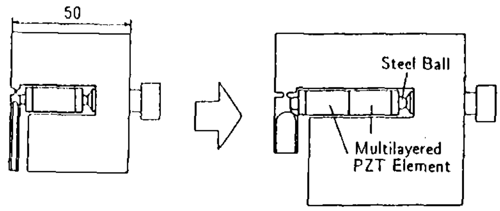

Fig. 2 Modification of lever mechanisms

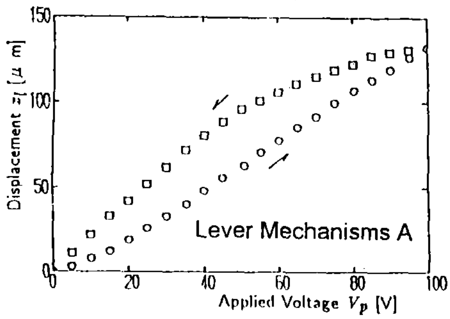

Fig. 3 Static characteristics of lever mechanisms

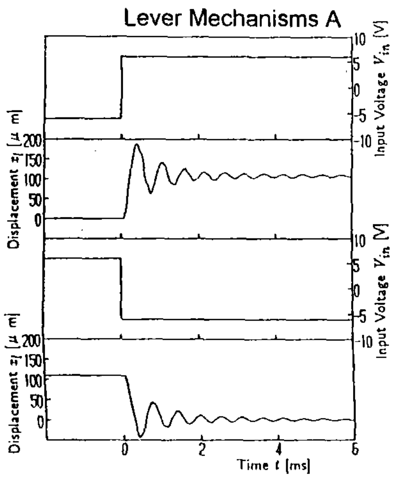

Fig. 4 Experimental results of transient response

down, respectively. From the results, it is ascertained that the resonant frequency of the single lever mechanism is about 1.4kHz.

3.2 Characteristics of the Driving System

This two lever mechanisms are installed in a servo valve, which are driven with differential motion. Those support the spool from right and left on tips of the lever parts. In this paper, spool and bellows are used just as those had used in the previous paper[7].

First of all, an experimental result of static characteristics about this driving system is shown in **Fig.5**. It shows the spool displacement when the input voltage is statically changed at ±8V range.

Next, **Figure 6** shows an experimental result of transient response when the input voltage is stepwise changed between -6V and +6V. The spool displacement is measured when the input voltage is stepwise changed. In this experiment, the input voltage is applied to lever mechanisms A, at the same time, the voltage of inverse phase is given to lever mechanisms B.

As a result, the resonant frequency is about 550Hz in this driving system, besides the system indicates an oscillatory transient response.

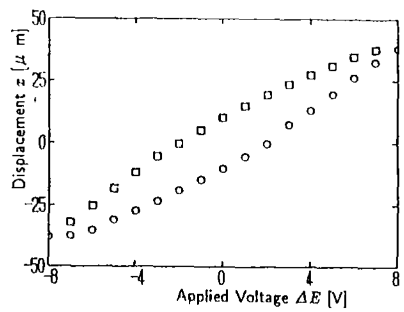

Fig. 5 Static characteristics of spool displacement

3.3 Application of a Disturbance Observer

As the result of the transient response experiment, it is obvious that the system has a weak damping and an oscillatory transient response. It is one of problems resulted from using PZT devices. Therefore, a velocity feedback control method is performed to give a sufficient damping. In this consequence, the overshoot is decreased and settling time

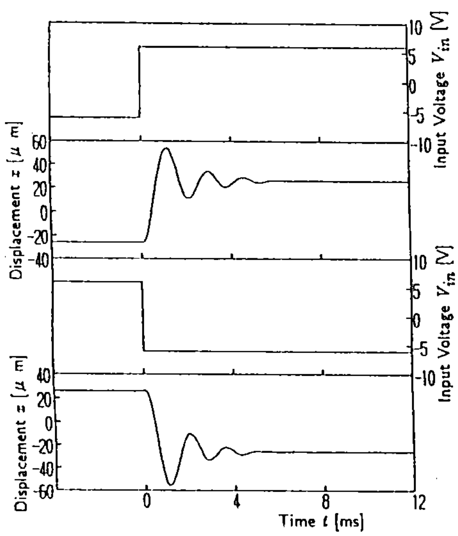

Fig. 6 Transient response experimental results of spool displacement

resulted shortly. However, the desired displacement can not be obtained. Hence, a disturbance observer is applied to the system in the similar manner of the previous paper[7]. The control system feeds back an estimated disturbance and an estimated velocity simultaneously by means of an observer[2)5)]. On account of feeding back the estimated disturbance, it attempted a robust control and compensated a nonlinearity like amplitude dependence based on the hysteresis between PZT devices and lever mechanisms. On account of feeding back the estimated velocity, it gives a sufficient damping to the system and tried to stabilize the system. On construction of a disturbance observer, the block diagram of the servo valve is shown in **Fig.7**. The model of a high speed up driving system is approximated as a quadratic system. Here, the relation between the generated force by the PZT devices and the spool displacement including lever mechanisms is approximated as a quadratic system. The transfer function of the system is given as follows:

$$X(s) = \frac{a_2}{s^2 + a_1 s + a_2} X_r(s) \qquad (1)$$

$$a_1 = \frac{C}{M} \qquad a_2 = \frac{K}{M}$$

where, X_r is an input displacement modeled so as to be proportional to an input voltage V_{in}.

A discrepancy of an output between a model and an actual system is regarded as a kind of disturbance imposed on an input. The extended state equation including the disturbance d is

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}x_r \qquad (2)$$

$$y = \boldsymbol{C}\boldsymbol{x} \qquad (3)$$

$$\boldsymbol{x} = \begin{bmatrix} \dot{x} \\ x \\ d \end{bmatrix} \quad \boldsymbol{A} = \begin{bmatrix} -a_1 & -a_2 & a_2 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad \boldsymbol{B} = \begin{bmatrix} a_2 \\ 0 \\ 0 \end{bmatrix} \qquad (4)$$

$$\boldsymbol{C} = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} \qquad (5)$$

From above equation, a disturbance observer is derived as follows:

$$\dot{\hat{\boldsymbol{x}}} = \boldsymbol{A}\hat{\boldsymbol{x}} + \boldsymbol{B}x_r + \boldsymbol{K}(x - \hat{x}) \qquad (6)$$

Where, ^mark presents an estimated value of state variables.

Furthermore, if poles of the observer are set in the left direction on real axis as far as possible from origin, it is possible to increase the estimating speed. However, if the magnitude of the poles is large too much, an observer could become nearly differentiator. Hence, the

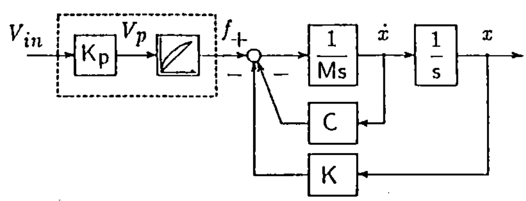

Fig. 7 Block diagram of servo valve

system may have stability problem as well as problems received strongly an influence of noise ingredient. The disturbance observer is implemented by means of using a quadratic Runge-Kutta method on a micro computer. According to higher response of the system, it is necessary to enlarge poles. Because the estimated velocity has a great of magnitude value in a calculation, with appropriate scaling, we realize the sampling frequency 12.5kHz in real time by means of assembler description. As a result, triple poles of -8000[rad/s] are set as poles of the observer. Hence, the observer gain is given as follows.

$$K = \begin{bmatrix} k_1 & k_2 & k_3 \end{bmatrix}^T = \begin{bmatrix} 1.2\times10^8 & 2.1\times10^4 & 4.3\times10^4 \end{bmatrix}^T \quad (7)$$

Damping constant of the observer model, ξ, and velocity feed back gain, K_v, are determined as ξ=0.4, K_v=0.0009[s], respectively. **Figure 8** shows the block diagram of the disturbance observer and the velocity feed back at the system. **Figure 9** shows the block diagram of the disturbance observer.

Using the disturbance observer mentioned above, we investigate the system performance experimentally. To begin with, a sinusoidal wave (the amplitude 30μm, frequency 1Hz), as an input displacement is applied. **Figure 10** shows the recorded results of the spool displacement. Horizontal axis denotes the input displacement, and vertical axis denotes the spool displacement. From the results, we conclude that the spool displacement followed well the input displacement and a hysteresis of PZT devices is effectively removed from the driving system. Next, **Figure 11** shows the experimental results of transient response . The figure shows the spool displacement, the

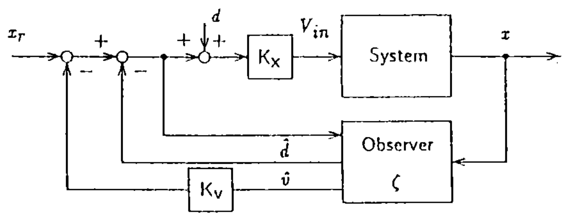

Fig. 8 Block diagram of system using disturbance observer

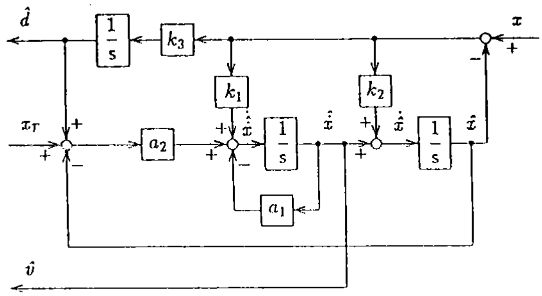

Fig. 9 Block diagram of disturbance observer

estimated disturbance and the estimated velocity in descending order. From the results, an overshoot is removed, a damping characteristics is rather improved and a settling time resulted shortly about 2ms. The spool displacement seems to be dependent on influences of the amplitude due to the hysteresis and saturations. We can see that the output displacement is in good agreement with the input because an insufficiency of displacement is compensated as a disturbance. **Figure 12** presents a comparison with the result of frequency response experiment in the case with observer and with no observer. The amplitude of sinusoidal wave input is 30μm. Using a disturbance observer, an amplitude-dependence by hysteresis and an influence of strain are removed, a flat gain is obtained and a phase delay in lower frequency region is decreased as well. It is ascertained that a disturbance estimated observer is also effective to the higher response driving system.

4. CONCLUSIONS

In this study, it is the purpose to develop a high-speed servo valve with no outer leakage to drive a FHA. The following is the features of the servo valve. It could get rid of external leakage from the valve that is sealed up using bellows. The spool maximum displacement, 100μm, and the frequency band width, 500Hz, resulted from using PZT devices and lever mechanisms. Furthermore, as a control method concerning under damping and nonlinearities of the spool displacement, disturbance estimation compensation method based on disturbance observer is applied to feed back an estimated disturbance and an estimated velocity simultaneously. As a result, it is ascertained that using a disturbance observer is effective in removal of the nonlinearities and is suitable to this type of servo valves.

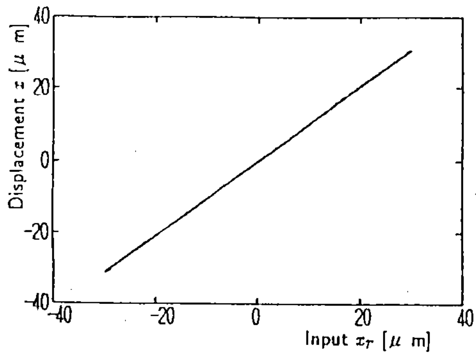

Fig. 10 Static characteristics of spool displacement

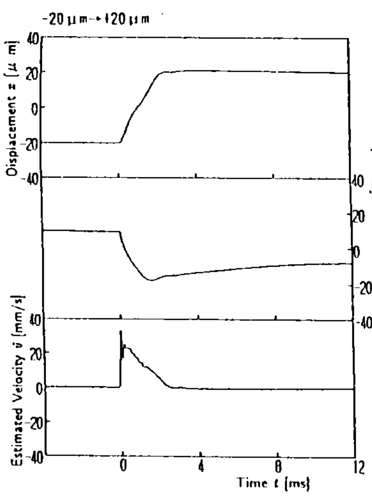

Fig. 11 Experimental results of spool displacement in the transient response

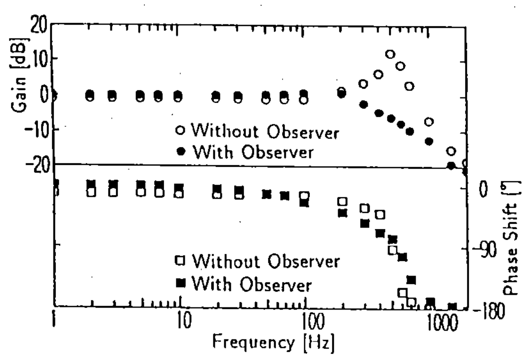

Fig. 12 Comparison with the results of frequency response experiment in the case with observer and with no observer

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