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Precise Position Control of Pneumatic Servo System Considered Dynamic Characteristics of Servo Valve

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ABSTRACT

Precise positioning system is required in the fields of semi-conductor manufacturing process. A pneumatic servo table system is one of a precise positioning system. The features of the table are little friction force and little heat generation. Generally, the controller of this system is designed by neglecting the characteristics of servo valves. However, in high frequency band, the response of this system becomes unstable because of the characteristics of the valves. In this paper, we demonstrate that by considering the characteristics of servo valves, the position control of a pneumatic servo table could be improved. First, the dynamic characteristics of servo valves were examined. It became clear that the characteristics could be described as a second-order system. Then, the servo table system was designed as a fifth-order system. It became clear that the position accuracy of this system were greatly improved.

KEY WORDS

Pneumatic System, Precise Positioning, Servo Valve, Pole Assignment

NOMENCLATURE

a	:	acceleration	[m/s^2]
f	:	frequency	[Hz]
j	:	jerk	[m/s^3]
K_a	:	table acceleration gain	[V/(m/s^2)]
K_n	:	flow rate gain	[m/(s V)]
K_p	:	table proportional gain	[V/m]
K_{ps}	:	valve proportional gain	[V/m]
K_{sv}	:	linearized servo valve gain	[m^2/V]
K_v	:	table velocity gain	[V/(m/s)]
K_{vs}	:	valve velocity gain	[V/(m/s)]
K_{vlv}	:	valve gain	[m/(s^2 V)]
s	:	Laplace operator	[1/s]
Se	:	effective area	[m^2]
α	:	parameter of α–β diagram method	[-]
β	:	parameter of α–β diagram method	[-]
ζ	:	damping ratio	[-]
ω_0	:	nominal angular frequency	[rad/s]
ω_n	:	natural angular frequency	[rad/s]

(suffix)

t	:	value of servo table system
s	:	value of servo valve
ref	:	reference value

INTRODUCTION

Precise positioning systems are very important in the fields of semi-conductor manufacturing process. In this region electro-motion systems are widely used, but the heat from the motor disturbs the position controllability and the machining accuracy.

To overcome the heat generation problem, we tried to construct pneumatic precise positioning system. The features of the pneumatic system are little heat and little magnetic field generation. However, the control of this system is very difficult because of the nonlinearity of pneumatic system such as stick-slip phenomena [1] [2].

We have developed a pneumatic servo table system with air bearing. The stick-slip phenomena were overcome by using air bearing. This system reached high positioning accuracy. However, in high gain region, the response of this system becomes unstable. The reason of this unstable response is the dynamic characteristics of the servo valve. Generally in a pneumatic servo system, the dynamic characteristics of the servo valve are neglected. Because the dynamic characteristics of the servo valve is sufficiently high compared to that of the pneumatic servo system.

In this paper, the dynamic characteristics of the servo valve were measured experimentally. It can be described as a second-order system. Therefore, the model of the servo table system considered the dynamic characteristics of the servo valve becomes a fifth-order system. After that, we proposed the design method of the controller of this system. To realize the proposal control method, the servo valve that can be set freely the dynamic characteristics is necessary. Then we developed a novel servo valve, which named as the precise position controllable servo valve.

By considering the dynamic characteristics of the valve, it is cleared that the rapidness and the position accuracy of this system are greatly improved.

PNEUMATIC SERVO TABLE

Pneumatic Servo Table

The pneumatic servo table system is one of a precise positioning system using air power. This system has an air bearing on the sliding surface to reduce friction force. By using an air bearing, this system can control the slider position accurately.

Figure 1 and 2 show the photo and the schematic diagram of this system. This system is constructed from a pneumatic actuator with air bearing, a pair of servo valves and a PC to control system.

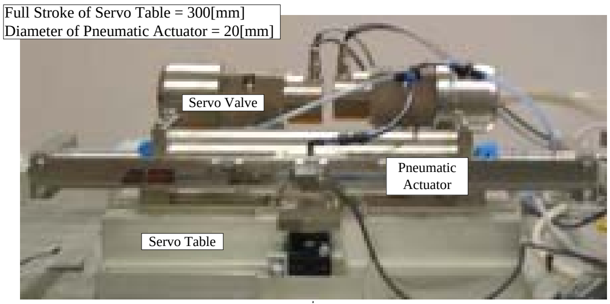

Figure 1 Photo of Pneumatic Servo Table System

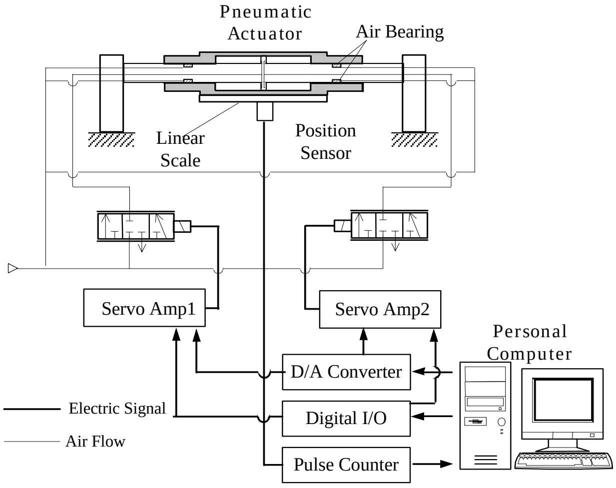

Figure 2 Schematic Diagram of Pneumatic Servo Table System

Third-order Model

From linearized equations of this system, the open-loop transfer function of the pneumatic actuator is given as a third order transfer function [3].

$$P_n(s) = \frac{K_n \omega_{nt}{}^2}{s(s^2 + \omega_{nt}{}^2)} \tag{1}$$

The natural angular frequency ω_{nt} is under 60[rad/s]. On the other hand, that of the servo valve ω_{ns} is over 600[rad/s]. From this relation, the dynamic characteristics of the servo valves are negligible. By neglecting the dynamic characteristics of the servo valve, the open-loop transfer function of the servo valve is given by;

$$P_s(s) = K_{sv} \tag{2}$$

A PDD^2 control method was applied to this system. This control method feedbacks position, velocity and acceleration. As a result, the closed-loop transfer function in the 3rd-order model is given by [3]

$$G_n(s) = \frac{K_{sv} K_n K_p \omega_{nt}^{2}}{D(s)}$$

$$D(s) = s^3 + K_{sv} K_n K_a \omega_{nt}^{2} s^2 + (1 + K_{sv} K_n K_v)\omega_{nt}^{2} s + K_{sv} K_n K_p \omega_{nt}^{2} \qquad (3).$$

Figure 3 shows the block diagram of the 3rd-order model. We designed the feedback gains by α-β diagram method [4]. By using α-β diagram method, K_v and K_a are dominated by K_p, α and β.

$$K_a = \frac{\alpha K_p^{1/3}}{\left(K_{sv} K_n \omega_{nt}^{2}\right)^{2/3}} \qquad (4)$$

$$K_v = \frac{\beta\left(K_{sv} K_n K_p / \omega_{nt}\right)^{2/3} - 1}{K_{sv} K_n} \qquad (5)$$

The parameter α and β are defined from a suitable gain margin and a phase margin. After that, K_v and K_a are dominated by K_p. In this third-order model, the rapidness and the position accuracy are dominated by the value of K_p. To improve these performances, the large value of K_p is required. However, this system becomes unstable in the experiments when K_p is increased.

This unstable phenomenon is considered to be because of the linearization of the system. Therefore, we studied the main factor of this instability. It became clear that the main factor was the dynamic characteristics of the servo valve. Therefore, the control model that considered the dynamic characteristics of the servo valve must be considered.

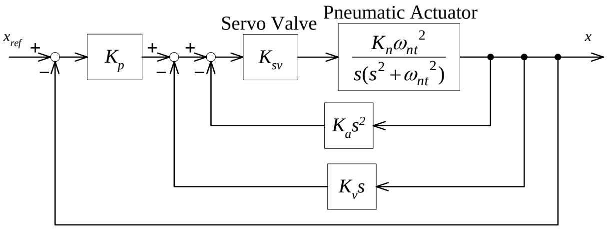

Figure 3 Block Diagram of 3rd-order Model

Fifth-order Model

We measured the dynamic characteristics of the servo valve experimentally. Figure 4 shows the experimental result of the dynamic characteristics of the servo valve made by FESTO MPYE-5-M5-010 B-SA.

It can be described as a second-order transfer function given in Eq. (6).

$$P_s(s) = \frac{\omega_{ns}^{2}}{s^2 + 2\zeta_s \omega_{ns} s + \omega_{ns}^{2}} \qquad (6)$$

$$\omega_{ns} = 150[\mathrm{Hz}], \qquad \zeta_s = 0.35$$

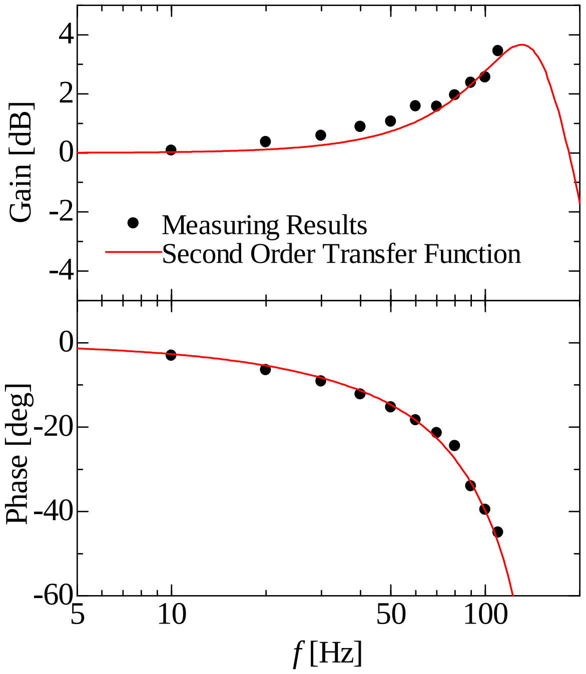

Figure 4 Bode Diagram of Commercially Available Servo Valve

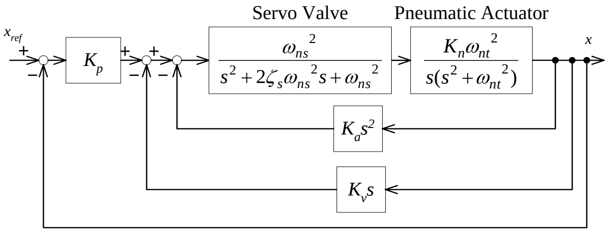

Figure 5 Block Diagram of 5th-order Model

From Eq. (1) and (6), the open-loop transfer function of this system with the dynamic characteristics of the servo valve is derived as a 5th-order function.

$$P_{all}(s) = \frac{\omega_{ns}^2}{s^2 + 2\zeta_s \omega_{ns} s + \omega_{ns}^2} \frac{K_n \omega_{nt}^2}{s\left(s^2 + \omega_{nt}^2\right)} \qquad (7)$$

Then, the block diagram of whole system is shown as the Figure 5. The closed-loop transfer function is given by

$$\begin{aligned} G(s) &= \frac{K_{sv} K_n \omega_{ns}^2 \omega_{nt}^2 K_p}{D(s)} \\ D(s) &= s^5 + 2\zeta_s \omega_{ns} s^4 + (\omega_{ns}^2 + \omega_{nt}^2) s^3 + \\ &\quad \omega_{ns} \omega_{nt}^2 \left(2\zeta_s + K_{sv} K_n \omega_{ns} K_a\right) s^2 + \\ &\quad \omega_{ns}^2 \omega_{nt}^2 \left(1 + K_{sv} K_n K_v\right) s + \\ &\quad K_{sv} K_n \omega_{ns}^2 \omega_{nt}^2 K_p \end{aligned} \qquad (8).$$

Root Locus on Fifth-order Model

We examined the varying of the pole of this system from the root locus. Figure 6 shows the root locus of this system. From Figure 6, it is cleared that the pole, which dominated by the servo valve characteristics, moves unstable plane when K_p is over 80.

To stabilize this system, a high performance servo valve that can set freely ω_{ns} and ζ_s is required. Then, we developed a novel servo valve which named the precise position controllable servo valve

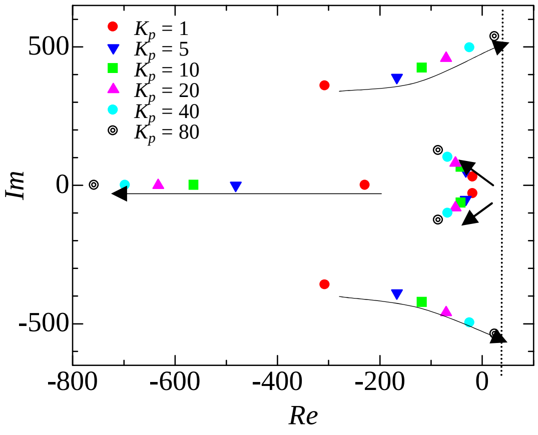

Figure 6 Root Locus of 5th-order Model

PRECISE POSITION CONTROLLABLE SERVO VALVE

A pneumatic precise position controllable servo valve has been developed[5]. Figure 7 and 8 show the external view and schematic diagram of this servo valve.

To realize high dynamic characteristics, the performance of the displacement sensor to measure the spool position of the servo valve is very important. The resolution of this position sensor is submicron order. Because the friction force of the spool disturbs the controllability of the servo valve, we attached an air bearing to this servo valve.

The control method of this servo valve is the PD-control. Then, the block diagram of this valve is derived as Figure 9. The closed-loop transfer function of this servo valve is given by

$$P_{nv}(s) = \frac{K_{vlv} K_{ps}}{s^2 + K_{vlv} K_{vs} s + K_{vlv} K_{ps}} \qquad (9).$$

From Eq. (6) and (9), the control gains are given by

$$\begin{aligned} K_{ps} &= \omega_{ns}^2 / K_{vlv} \\ K_{vs} &= 2\zeta_s \omega_{ns} / K_{vlv} \end{aligned} \qquad (10).$$

It is clear that we can design ω_{ns} and ζ_s at a certain value by gain tuning.

The response of this servo valve was examined. In this experiment, ω_{ns} and ζ_s was set 300[Hz] and 0.7. Figure 10 shows the step response of the spool position. The spool position is settled promptly. Figure 11 shows the frequency response of the spool position at the frequency of 50[Hz]. The spool position follows well with the reference trajectory.

Figure 12 shows the bode diagram of this valve. It is cleared that this valve can set ω_{ns} and ζ_s freely as we desired, and the dynamic characteristics are greatly improved compared with the commercially available one (Figure 4).

Figure 7 Photo of Precise Position Controllable Servo Valve

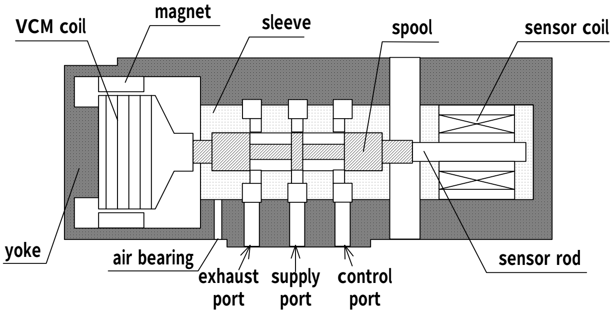

Figure 8 Schematic Diagram of Precise Position Controllable Servo Valve

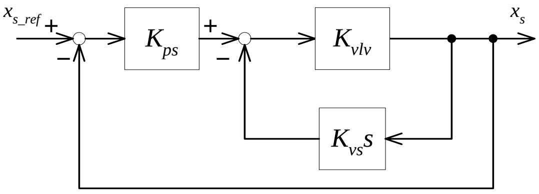

Figure 9 Block Diagram of Developed Servo Valve

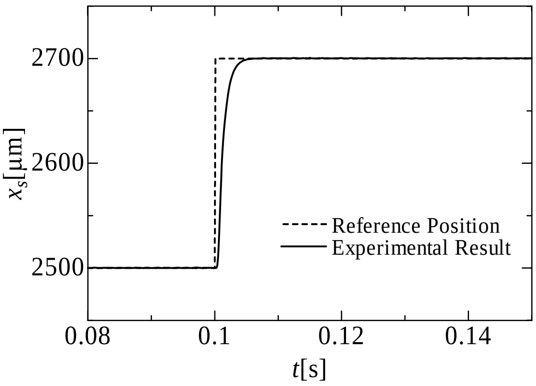

Figure 10 Step Response of Developed Servo Valve

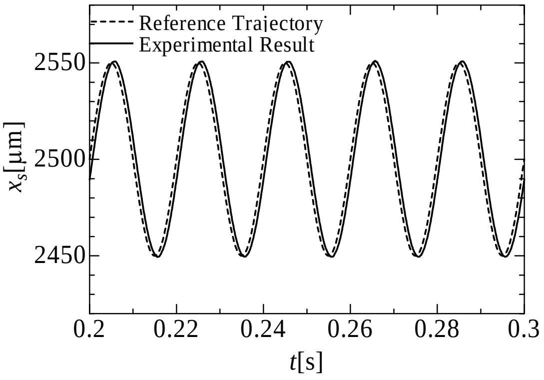

Figure 11 Frequency Response of Developed Servo Valve (*f* =50[Hz])

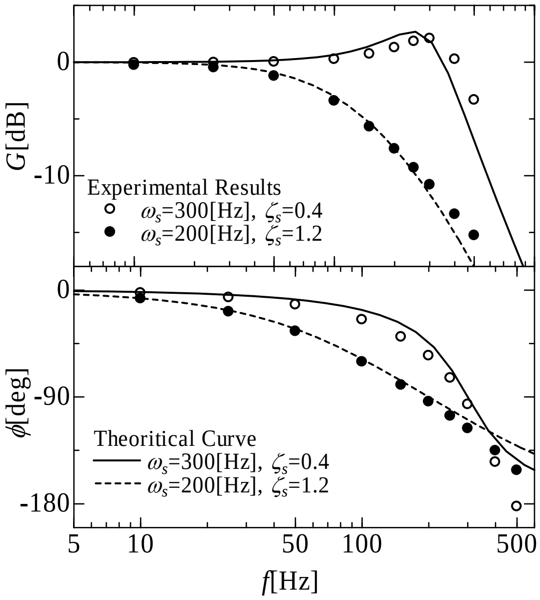

Figure 12 Bode Diagram of Servo Valve

CONTROL METHOD AND EXPERIMENTAL RESULTS

A control method for this fifth-order system was considered. We selected the pole assignment method as ITAE criterion. The ITAE criterion is given by

$$G(s) = \frac{\omega_0{}^5}{s^5 + 2.8\omega_0 s^4 + 5.0\omega_0{}^2 s^3 + 5.5\omega_0{}^3 s^2 + 3.4\omega_0{}^4 s + \omega_0{}^5} \tag{11}$$

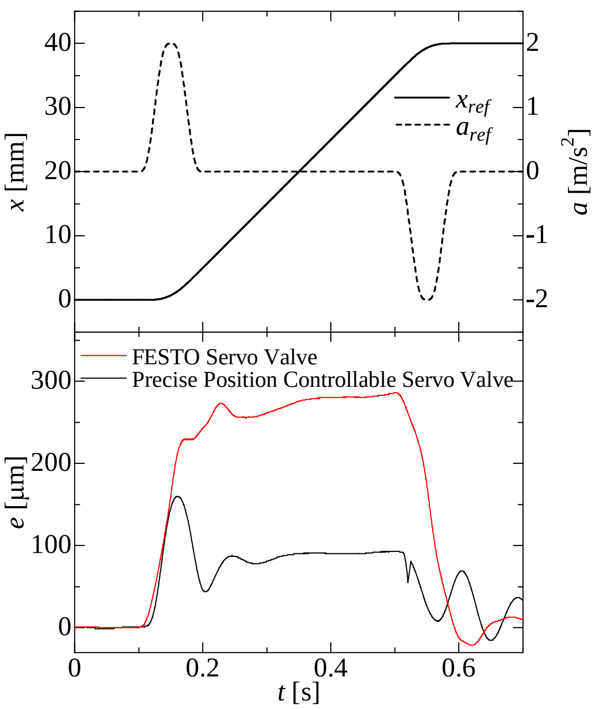

Figure 13 Reference Trajectory and Experimental Results

From Eq. (8) and (11), the dynamic characteristics of the servo valve and the feedback gains of the pneumatic servo table system were determined.

Figure 13 shows the experimental results of the proposal controller and that of the previous control method.

Upper figure shows the reference trajectories of the system. The position reference trajectory is designed as 5th-order curve to control this system accurately. Lower figure shows the position error of the servo table. It is clear that the position error is greatly improved compared with a commercial available servo valve by using ITAE criterion control method.

CONCLUSION

We constructed a pneumatic servo table system considered the dynamic characteristics of the servo valve. It became clear that the dynamic characteristics of the servo vale effects to the performance of the pneumatic servo table.

In this paper we introduced a precise position controllable servo valve. This valve can set freely the dynamic characteristics by gain tuning. We measured the dynamic characteristics of this servo valve. From the dynamic characteristics measurement, it is cleared that the dynamic characteristics of the servo valve is a twice of that of a commercially available one.

We constructed a pneumatic servo table system with the precise position control servo valve. The ITAE criterion pole assignment method was used for the gain tuning of this system.

The position following error of the servo table is reduced by the proposal control method. The maximum position error is reduced to half and the steady velocity error is reduced to one-third. It was shown that the controllability of the servo table is improved by using the precise position controllable servo valve.

We aim decrease of the following error of the servo table by studying better gain tuning method.

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