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Displacement Control of Flexible Pneumatic Cylinder Using Disturbance Observer and Smith Compensator

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***Abstract*—This study is concerned with flexible pneumatic cylinder. The cylinder can be used in the various fields such as life support, medical, welfare systems which require light-weight, high flexibility, and high cleanliness. However, the control of the cylinder is insufficient and then it is needed to improve its control performance for widening of applications of the cylinder. Therefore, we propose combination of disturbance observer, which has a function of model matching, and Smith compensator, which compensates time delay of the system, with conventional PI control. To evaluate the control performance of the proposed control, some experiments are carried out. As a result, it is confirmed that the control performance of the proposed control can be drastically improved. In particular, it can be seen that the proposed control is effective for time delay of the system. The flexible cylinder with the proposed control scheme will be used in rehabilitation devices in practice.**

***Index Terms*—flexible pneumatic cylinder, disturbance observer, Smith compensator, displacement control, time delay**

I. INTRODUCTION

A cylinder is one of important actuators driven by fluid power systems such as oil hydraulic, water hydraulic, and pneumatic systems. Generally, it has high stiffness and is used in industrial machines. On the other hand, when it is used in life support, medical, and welfare systems which require light-weight, high flexibility, and also high cleanliness, it is difficult to use such a typical cylinder. Thereby we proposed a novel flexible cylinder [1]. The cylinder can drive flexibly because it consists of a flexible tube as a rod, steel balls, end connectors, and a slide stage. The detail is described in Chap. Ⅱ.

However, the cylinder has a problem to be solved. The problem is that its control performance is low because of its nonlinearity caused by relatively high frictional force between the inner steel ball and the tube. For such a reason, the cylinder cannot be applied when high accuracy is required. Although a low friction type flexible cylinder was proposed, it has not achieved sufficient control performance [2, 3]. Therefore, we focus on improvement by application of model based control theory. Specifically, disturbance observer [4] and Smith compensator [5] are applied.

If disturbance observer can be used, the control performance of the cylinder is improved because the observer can reduce influence of frictional force. Nevertheless, it’s not sufficient. The cylinder has relatively large time delay and it strongly relates the control performance of the cylinder. As a compensation of the time delay, Smith compensator is applied. We can design its parameters easily by combing the disturbance observer. The observer has a function of model matching which is able to make the plant match a reference model. In other words, an unknown system can also be regarded as a known system corresponding the reference model. Thus the cylinder, which is an unknown system, can be regarded a known system even if it has many unknown parameters such as frictional force and time delay. Although the design of Smith compensator generally requires a precise known system, the observer can make the application of the compensator be possible.

On the other hand, conventional PI control is applied for the displacement control of the cylinder. The application of PI control is reasonable because the cylinder can be transformed from an unknown complex system into a known simple system by disturbance observer and Smith compensator. Its control performance is examined by experiments of displacement control of the cylinder.

In Chap. Ⅱ, a construction and an operation principle of the flexible cylinder are described. In addition, the advantages and disadvantages of the cylinder are also shown. In Chap. Ⅲ, detail of disturbance observer, Smith compensator, and proposed control scheme are described. In particular, derivation and fundamental principles of the observer and the compensator are described. Moreover, whole block diagram of the proposed controller is introduced. In Chap. Ⅳ, experimental results of

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displacement control of the cylinder are shown and then the control performance of the proposed control is compared with conventional PI control by quantitative analysis. It is confirmed that disturbance observer and Smith compensator can work correctly.

II. FLEXIBLE PNEUMATIC CYLINDER

This chapter shows the construction and the operation principle of the flexible pneumatic cylinder as shown in Fig. 1. The cylinder consists of a flexible rubber tube, steel balls (diameters of 9 mm and 3 mm), a slide stage which is made of acrylic plates. The large steel ball is inside of the rubber tube and it is moved by pressurized air. The slide stage has two brass rollers and the small steel balls to hold the steel ball inside of the tube. This means that the slide stage and the inner ball can be moved simultaneously by pressurized air from both sides. Fig. 2 shows the developed flexible cylinder.

The cylinder has advantages which are light-weight, high flexibility and backdrivability because the main parts of the cylinder are the flexible rubber tube and the acrylic parts. They are very important to use the cylinder in life support, medical, and welfare systems. However, the cylinder has problems which are relatively large frictional force and time delay and this leads to degradation of the cylinder control performance. In fact, although the cylinder is applied for rehabilitation device, the result of the sufficient control performance couldn't be achieved.

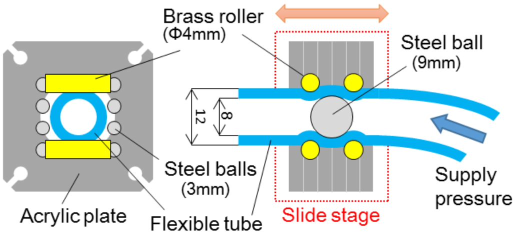

Figure 1. Construction of flexible pneumatic cylinder.

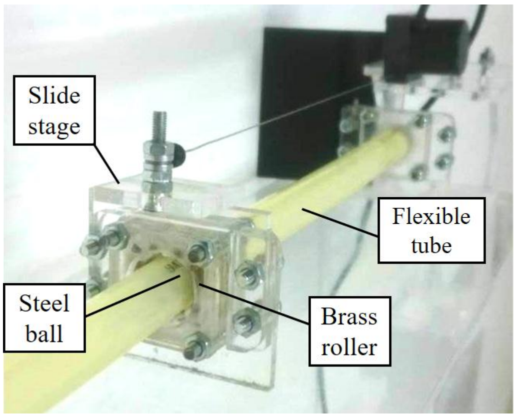

Figure 2. Proposed flexible pneumatic cylinder [1].

III. PROPOSED CONTROLLER

This chapter describes important functions of disturbance observer and Smith compensator.

A. Disturbance Observer

It is assumed that $u(t)$, $y(t)$, $d(t)$, and $P(s)$ in Fig. 3 are an input signal, an output signal, disturbance, and a transfer function of a plant, respectively. Then, following equation is obtained as

$$Y(s)=P(s)\{U(s)+D(s)\}. \tag{1}$$

When disturbance observer, which is a minimal dimension observer estimating disturbance $d(t)$, is applied to this system, estimated disturbance is expressed as

$$\hat{D}(s)=Q(s)P_n^{-1}(s)Y(s)-Q(s)U(s)\,, \tag{2}$$

where $Q(s)$ is a disturbance observer filter, $P_n(s)$ is a transfer function of a reference model [6]. Fig. 3 shows a block diagram of disturbance observer.

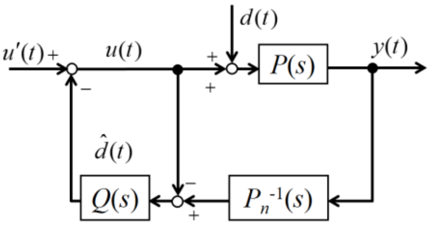

Figure 3. Block diagram of disturbance observer.

In Fig. 3, transfer functions from an external input $u'(t)$ to an output $y(t)$ and from disturbance $d(t)$ to $y(t)$ are shown as

$$\frac{Y(s)}{U'(s)}=\frac{P(s)}{1-Q(s)+Q(s)P_n^{-1}(s)P(s)}\,, \tag{3}$$

$$\frac{Y(s)}{D(s)}=\frac{P(s)\{1-Q(s)\}}{1-Q(s)+Q(s)P_n^{-1}(s)P(s)}\,, \tag{4}$$

respectively. Essentially, $Q(s)$ acts as a low-pass filter and then it is seen that $Q(s)$ is equivalent to 1 when frequency of the input is less than the cutoff frequency of $Q(s)$. It means that the transfer function from disturbance $d(t)$ to the output $y(t)$ is zero in (4), that is, disturbance has no affection on the output. In the same way, the transfer function from $u'(t)$ to $y(t)$ corresponds to the reference model $P_n(s)$ when frequency of the input is less than the cutoff frequency of $Q(s)$. It is the important function of disturbance observer which is called model matching. Note that the filter $Q(s)$ has roles which decide stability, robustness, and noise reduction.

B. Smith Compensator

Generally, time delay may degrade stability and control performance of systems. For instance, time delay-to-time constant ratio strongly relates to difficulty of control in first order systems [7]. It is important to compensate time delay and Smith compensator is a well-known and effective method to improve. Fig. 4 shows a block diagram of Smith compensator. In Fig. 4, $r(t)$, $y(t)$, $C(s)$, $S(s)$, L are reference signal, output signal, transfer function of controller, transfer function of Smith compensator, time delay of the plant, respectively.

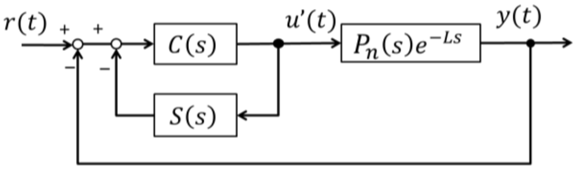

Figure 4. Block diagram of Smith compensator.

Smith compensator can compensate the time delay of the plant by separating the time delay from the control system. However, if the transfer function $S(s)$ cannot be selected correctly, the compensator cannot work well. Theoretically, $S(s)$ is derived from a following equation [8].

$$S(s) = P_n(s)\left\{e^{L\cdot s} - 1\right\}. \tag{5}$$

From the view point of the block diagram, the time delay can be removed from control loop by using (5) as shown in Fig. 5. Thus, it is found that the control performance of plant with time delay can be improved by using Smith compensator.

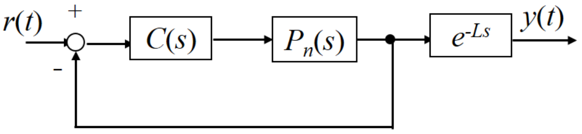

Figure 5. Equivalent block diagram of Smith compensator.

C. Proposed Control

A combination of disturbance observer, which has functions of disturbance reduction and model matching, and Smith compensator, which compensates the time delay, is applied to the flexible cylinder as shown in Fig. 6. Typical PI control is also applied to the cylinder as a control scheme. Although the PI control has simple structure and low robustness, it is sufficient to apply the control scheme to the cylinder because the transfer function of the cylinder can match the reference model by model matching and the time delay of the cylinder can be ignored by Smith compensator.

On the other hand, the displacement control system of the cylinder includes an integrator in general. It means that the reference model should be selected as an unstable model and it should be avoided. We apply disturbance observer to the velocity control system of the cylinder which is a stable system without the integrator and then design a feedback control system, which consists of the PI controller and Smith compensator, for displacement control of the cylinder.

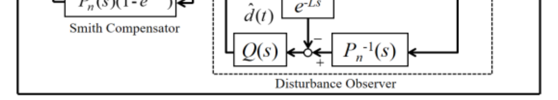

Figure 6. Block diagram of proposed control system.

IV. EXPERIMENT OF DISPLACEMENT CONTROL

To evaluate of the control performance of the proposed control scheme for displacement control of the flexible cylinder, experiments of displacement control of the cylinder is carried out. First, experimental setup and conditions are described. Then, experimental results under no-load condition are shown.

A. Experimental Setup and Conditions

In this section, the experimental setup and conditions are described. Fig. 7 and Fig. 8 show the schematic diagram of the control system for displacement control of the cylinder and the experimental setup for displacement control, respectively. The system consists of the flexible cylinder, two on/off valves SV_1 and SV_2 (Koganei Corporation, G010E1), a proportional valve PV (Koganei Corporation, KFPV300-2-60-FM-S13-03), a wire type encoder WLE (MUTOH INDUSTRIES LTD., DS-025), two regulated DC power supplies (Takasago Ltd, LX035-1A), a compressor (NAKATOMI Corporation, cp-2000) and a PC with dSPACE which is a well-known model-based development tool for Hardware-in-the-Loop simulation [9].

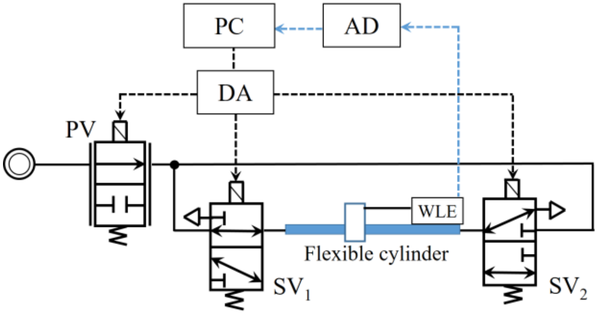

Figure 7. Schematic diagram of control system.

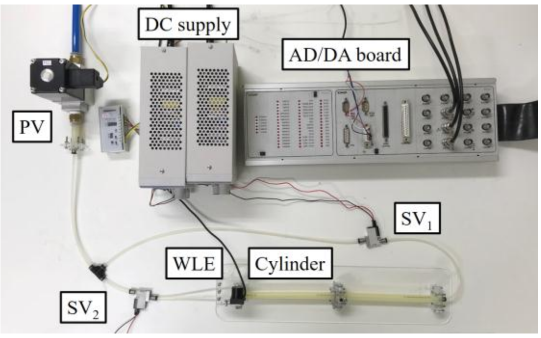

Figure 8. Experimental setup of the displacement control.

A whole transfer function from $r(t)$ to $y(t)$ including the proposed controller can be obtained as (6) because the time delay e^{-Ls} can be moved to outside of the control loop using Smith compensator. Therefore, taking a consideration of only the dynamics of the whole system, we can design reference trajectory of the displacement control of the cylinder.

$$\frac{Y(s)}{R(s)} = \frac{\frac{k_p}{15}s + \frac{k_i}{15}}{s^3 + 2s^2 + \frac{k_p}{15}s + \frac{k_i}{15}} \cdot e^{-Ls}, \tag{6}$$

where k_p is a proportional gain, k_i is an integral gain.

In the experiments, the following first-order transfer function of the reference model $P_n(s)$ and the transfer function of the filter $Q(s)$ are used.

$$P_n(s) = \frac{2}{s+2}, \tag{7}$$

$$Q(s) = \frac{10\pi}{s+10\pi}. \tag{8}$$

Note that it is reasonable to use the first-order transfer functions because the cylinder has an integrator in the transfer function from $u(t)$ to $y(t)$ and then the disturbance observer is designed for the velocity feedback system. The time constants of $P_n(s)$ and $Q(s)$ are chosen by considering the dynamics of the cylinder which is examined by pre-experiment.

The initial position of the slide stage is seted on the center of the cylinder. In the proposed control, the designed parameters of PI gains k_p = 45 V/m, k_i = 15 V/(m·s) are used. The time delay L is chosen to 0.15 s by pre-experiment of step response of the cylinder. The supply pressure for the system is 400 kPa and the sampling period of the experiment is 0.001 s.

The transfer function of the system can be expressed as

$$\frac{Y(s)}{R(s)} = \frac{3s+1}{s^3+2s^2+3s+1} \cdot e^{-0.15s}, \tag{9}$$

and then the bode diagram is shown in Fig. 9.

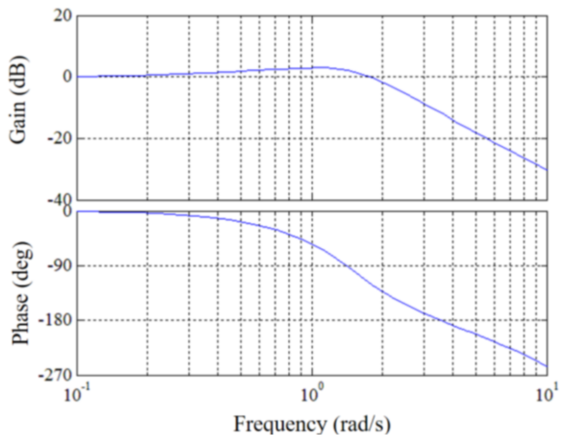

Figure 9. Bode diagram of whole system.

The reference trajectory is designed from Fig. 9 taking consideration of the dynamics of the system.

B. Experimental Result of Model Matching

It is important that the system is matched the reference model by using disturbance observer to improve its control performance. Then, in this section, experiment of model matching is carried out. As mentioned in Chap. III, when input frequency is less than the cutoff frequency of $Q(s)$, the transfer function of the system can be equivalent to the reference model $P_n(s)$. In the experiment, it is confirmed that the system matches $P_n(s)$ by input $u'(t)$ as sine wave. Fig. 10 shows the experimental result of model matching. From Fig. 10, it is seen that the output signal of the system matches the model and then the disturbance observer works well.

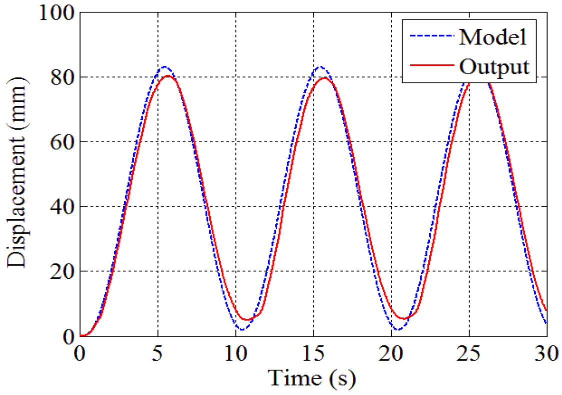

Figure 10. Experimental result of model matching.

However, there remains error between model and system outputs. This error may be caused by the low-pass filter for measured velocity from the encoder which is designed to decease observed noise of the encoder.

C. Experimental Result of Displacement Control

As the model matching can work well in the previous section, the experiment of the displacement control by the proposed controller is carried out. Fig. 11 shows experimental result of the proposed control with reference frequency of 0.1 Hz. Note that the figure includes the experimental result of the conventional PI control and the reference is based on (9) which considers the dynamics of the whole system. Compared with the result of the PI control, it is shown that the control performance of the proposed control is improved. Fig. 12 shows the experimental result of the proposed control with reference frequency of 0.3 Hz. Notice that the amplitude of the reference signal and the PI gains are same as previous. Although the experimental result of the PI control is degraded by changing of frequency of the reference signal, the result of the proposed control is kept comparable accuracy with previous one. In particular, the proposed control is effective for the time delay of the system.

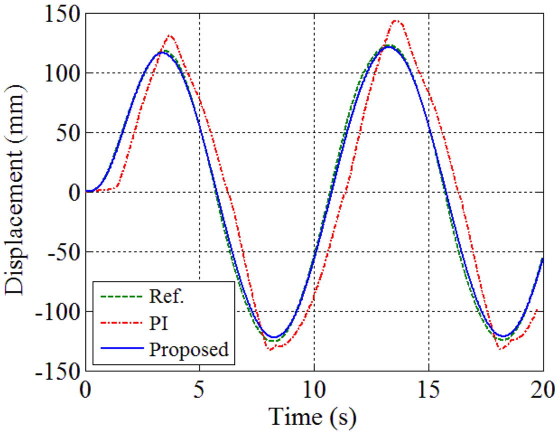

Figure 11. Experiment result of displacement control with reference frequency of 0.1 Hz.

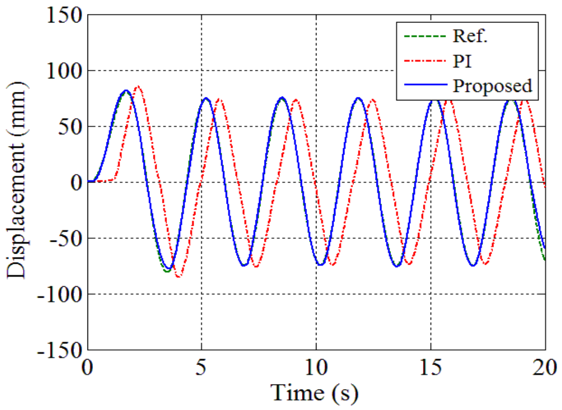

Figure 12. Experiment result of displacement control with reference frequency of 0.3 Hz.

On the other hand, experiments are carried out to confirm the effectiveness of Smith compensator for time delay. The experiments apply the proposed control scheme without Smith compensator and then the experimental results are compared with the proposed control scheme as shown above. Figs. 13, 14 show experimental results of the proposed control without Smith compensator with reference frequency of 0.1 and 0.3 Hz.

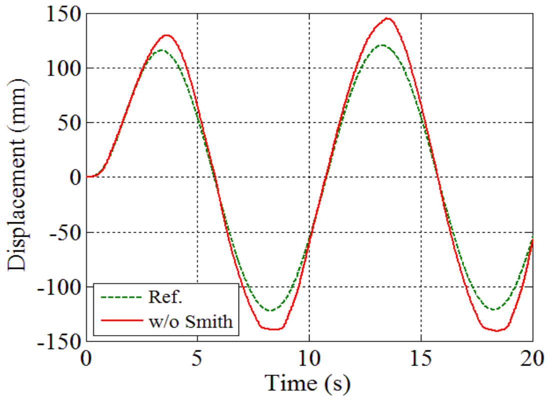

Figure 13. Experiment result of displacement control without Smith compensator (reference frequency: 0.1 Hz)

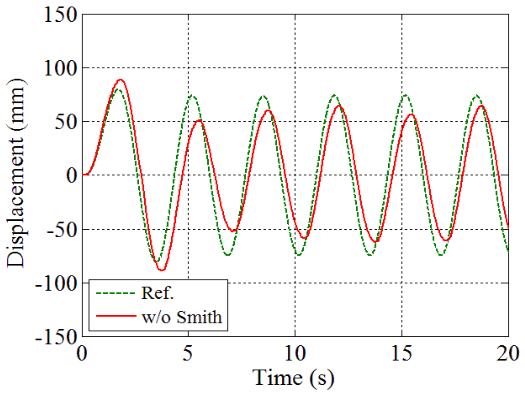

Figure 14. Experiment result of displacement control without Smith compensator (reference frequency: 0.3 Hz)

Table I shows quantitative evaluation of three control schemes. For reference frequency of 0.1 Hz, the mean absolute error of the proposed control can be reduced by 85.7% compared with the error of the PI control. Similarly, the error of the proposed control can be reduced by 96.4% for 0.3 Hz. On the other hand, compared with PI control scheme with disturbance observer, which is equivalent to the proposed control scheme without Smith compensator, the proposed control scheme can reduce the error by 72.2% (0.1 Hz), 91.1% (0.3 Hz), respectively. Therefore, it is shown that the time delay cannot be compensated adequately by PI control scheme with disturbance observer and the effectiveness of the proposed control scheme is verified.

TABLE I. COMPARATIVE ANALYSIS OF MEAN ABSOLUTE ERROR

		Frequency of reference signal	
		0.1 Hz	0.3 Hz
Control scheme	PI control	22.3 mm	47.8 mm
	PI control with disturbance observer	11.5 mm	19.0 mm
	Proposed control	3.2 mm	1.7 mm

V. CONCLUSIONS

In this paper, the improvement of the control performance of the flexible cylinder is considered. The control performance of the cylinder is low by relatively large frictional force and time delay. As the control scheme of the flexible cylinder, PI control with disturbance observer which compensates frictional force of the cylinder and Smith compensator which compensates time delay of the cylinder is proposed.

The control performance of the cylinder with the proposed control is confirmed by experimental results of the displacement control. The reference frequency of 0.1 and 0.3 Hz is given into the system. As a result, the mean absolute error of displacement can be reduced by 85.7% for the reference of 0.1 Hz. On the other hand, the mean absolute error of displacement can be reduced by 96.4% for the reference of 0.3 Hz compared to only PI control. The effectiveness of Smith compensator is confirmed by the comparative result of the proposed control scheme and PI control scheme with only the disturbance observer. As a result, mean absolute error can be reduced 72.2% for reference frequency of 0.1 Hz and 91.1% for reference frequency of 0.3 Hz. Thus, it is confirmed that the system with the proposed control scheme has high control performance regardless of reference input frequency.

As future work, the robustness of the system is examined by experiments under loaded conditions. Moreover, the flexible cylinder is applied to rehabilitation devices and then the control performance of whole system is evaluated in practice.

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