【Technical Note】

Positioning control of a pneumatic stage under different pipe length: Performance improvement of PDD² control and suppression of flow disturbance

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Abstract

In this study, we consider the positioning of a pneumatic stage in order to compensate effects of different length of pipes, which connect servo valves and cylinders. Since, in industrial scenes, it is difficult to use pipes of the same length due to the structure of industries, the length of each pipe is often different. In this case, the characteristic of the pneumatic system, which consists of the pipes, servo valves, and chambers, changes in accordance with the pipe length. It leads to two issues: The first one is that the performance of proportional-derivative-double derivative (PDD²) control, which is effective for the control of pneumatic actuators, is degraded. To overcome this issue, the parameter of a pre-compensator for the PDD² control is tuned. The suitable value of this tuned parameter increases with the length of the pipes. The second one is that the effects of flow disturbance increase due to the different pipe length. When the length of the pipes is not same, it is probable that the magnitude of flow disturbance transmitted to each pipe is different. For this reason, multiple flow disturbance observers (FDOBs) are implemented in a control system. Experimental results show that the repeatability of the positioning is improved by using the FDOBs.

Key words : Pneumatic stage, Pipe length, Flow disturbance observer, PDD² control, Positioning

1. Introduction

High-precision positing stage is used to manufacture small products such as semiconductor devices. As an actuator of the stage, electromagnetic type is often adopted. However, the drawbacks of this actuator are heat generation and magnetic leakage, which affect the performance of electron beam lithography equipment. For this reason, a pneumatic stage, which overcomes the above drawbacks, has been attracted. As a control method of pneumatic actuators, proportional-derivative-double derivative (PDD²) control (Kagawa, et al., 2000) is known. In our previous work (Wali and Wakui, 2012), we utilized this control scheme for the positioning of the pneumatic stage. The advantage of the PDD² control is that, by adjusting parameters of a PDD² controller, the desired damping and stiffness of a control system can be easily obtained.

Since the pneumatic stage can be actuated by supplying compressed air into both ends of cylinders, it is necessary to prepare multiple pipes, which connect the cylinders and servo valves. However, in industrial scenes, since many machines are usually installed around the pneumatic stage, each length of the pipes is often different. Due to this reason, it is difficult to use the pipes of the same length. When the pipe length is changed, the characteristic of a pneumatic system, which consists of the servo valves, pipes, and cylinders, is also changed. In this case, the parameter of a pre-compensator, which is used for the positioning with the PDD² control, has to be retuned. When this parameter is not suitably decided, it leads to the performance degradation of the PDD² control. However, effects of different pipe length on control performance were not sufficiently investigated in related works on the pneumatic actuators (e.g., Taheri, et al., 2014; Liu and Jiang, 2007; Kagawa, et al., 2000). Moreover, due to air compressibility, flow disturbance (Wali and Wakui, 2012) affects the repeatability of the positioning. Under the different pipe length, the effects of this

disturbance further increase.

Therefore, the objective of this study is to improve the performance of PDD² control and suppress the flow disturbance under the condition that each length of pipes is different. To deal with the performance degradation of the PDD² control, we focus on the tuning of the pre-compensator. In our approach, the pneumatic system is divided into two subsystems. Each subsystem corresponds to a one-side pipe, servo valve, and chamber of cylinders. Since the pneumatic system is divided, two pre-compensators for the subsystems are utilized. Due to this method, the number of the parameters of pre-compensators is increased. Consequently, the parameters can be precisely tuned, resulting in the performance improvement of the PDD² control. Furthermore, in order to suppress the flow disturbance, we employ a flow disturbance observer (FDOB) (Wali and Wakui, 2012). However, in Wali and Wakui (2012), the length of pipes was same. In this study, we explain the implementation method of the FDOB appropriate for the case of different pipe length. The effectiveness of our approach is demonstrated by experiments.

2. Positioning of a pneumatic stage

2.1 Pneumatic stage

Figure 1 shows the photograph of the pneumatic stage that is considered in this study. An experimental setup for the stage positioning is illustrated in Fig. 2. The actuators of this stage are air cylinders (Airpot, M16D300.0S), whose maximum stroke is 10 cm. Air is supplied by a compressor and its flow rate is kept constant by using regulators. The amount of the supplied air is adjusted by opening and closing servo valves (Kolvenbach, EWS3/4). The pneumatic stage can move due to pressure difference between the left and right chamber of cylinders. The position of the stage is detected by a linear variable differential transformer (LVDT, SHINKO ELECTRIC, LT2-120R), and the inner pressure of the cylinders is measured by two pressure sensors (Setra, Model 204). The input voltage to the servo valves is determined by a controller, which is implemented in a DSP.

Fig. 1 Photograph of the pneumatic stage.

Fig. 2 Experiment setup.

Figure 3 shows a simplified schematic diagram of the servo valves and the cylinder. Parameters are summarized in Table 1. When the stage is moved, the flow rate occurs and the pressure in the cylinder changes. From the result presented in Wali (2014), the pressure changes p_L and p_R [Pa] in the left and right chambers are expressed as

$$p_L = \frac{G_{qL} w_L}{c_L + \beta_L V_{0L} s} - \frac{A_0 x s}{c_L + \beta_L V_{0L} s}, \quad p_R = -\frac{G_{qR} w_R}{c_R + \beta_R V_{0R} s} - \frac{A_0 x s}{c_R + \beta_R V_{0R} s}. \quad (1)$$

The first terms of the right-hand side in Eq. (1) represent the pressure change due to the open or close of the servo valves. The second terms of the right-hand side in Eq. (1) represent the pressure change due to the change of volume in the chamber. Under the condition of same pipe length, Wali (2014) assumes $w := w_L = w_R$, $V_0 := V_{0L} = V_{0R}$, $\beta := \beta_L = \beta_R$, and $c := c_L = c_R$. Then, the difference of pressure p [Pa] between the left and right chambers can be written as

$$p = p_L - p_R = \left(\frac{K_{air}}{1 + T_{air} s} \right) w, \quad (2)$$

where

$$K_{air} = \frac{G_{qL} + G_{qR}}{c}, \quad T_{air} = \frac{\beta V_0}{c}. \quad (3)$$

Equation (2) shows that the pneumatic system can be considered as a first order lag system.

Fig. 3 Simplified diagram of the servo valves and cylinder.

2.2 PDD² control for a pneumatic stage

Figure 4 illustrates the block diagram of the PDD² control system. Parameters are listed in Table 2. This control scheme determines the input voltage by means of the information on the tracking error $r-x$, the position first derivative $\dot{x}$, and the position second derivative $\ddot{x}$. In experiments, the pseudo differentiator $T_d s / (1 + T_d s)$ is used instead of differentiator s so as to calculate the first and second derivatives. When the pneumatic system is an integrator $1/s$, the stiffness and damping of the control system can be adjusted by D control and D² control shown in Fig. 4 (Kagawa, et al., 2000; Wali and Wakui, 2012). However, the pneumatic system (2) is modelled as a first order lag system. For this reason, a PI compensator is adopted as a pre-compensator for the PDD² control (see Pre-PI block shown in Fig. 4). When the time constant T_{pi} of the PI compensator is set to the time constant T_{air} of the pneumatic system (2), we obtain

$$p = \left(\frac{K_{air}}{1 + T_{air}s} \right) \left(\frac{1 + T_{pi}s}{T_{pi}s} \right) u = \frac{K_{air}}{T_{air}s} u. \quad (4)$$

From Eq. (4), it is found that the augmented system, which consists of the PI compensator and the pneumatic system, becomes an integrator due to pole-zero cancellation. Thus, the PDD² control can be utilized for the positioning of the pneumatic stage.

Fig. 4 PDD² control system for a pneumatic stage.

2.3 Positioning under different pipe length

In order to investigate effects of the pipe length on the repeatability of positioning, we conduct an experiment. In this experiment, the length of the right-side and left-side pipes is 0.5 m and 2.0 m, respectively. The gains of the PDD² control and the time constant of the PI compensator are chosen as $K_p=0.6$, $K_d=3.0$, $K_{dd}=1.0$, and $T_{pi}=10$ s.

Table 2 Parameters in Fig. 4.

Symbol	Description and unit	Symbol	Description and unit
M	Mass of the stage [kg]	K_{dd}	Damping gain of the PDD ² control [V/V]
D	Viscous damping coefficient of the stage [N·s/m]	K_{pos}	Detection sensitivity of the LVDT [V/m]
K	Spring constant of the stage [N/m]	T_d	Time constant of the pseudo differentiator [s]
T_{air}	Time constant of the pneumatic system [s]	r	Reference [V]
T_{pi}	Time constant of the PI compensator [s]	u	Output of the PDD ² controller [V]
K_{air}	Gain of the pneumatic system [N/V]	w	Input voltage to the servo valves [V]
K_p	Proportional gain of the PDD ² control [V/V]	p	Difference of pressure between the left and right chambers [Pa]
K_d	Stiffness gain of the PDD ² control [V/V]	x	Position of the stage [m]

The time constant T_d of the pseudo differentiator is 0.008 s, and the detection sensitivity K_{pos} of the LVDT is 83.3 V/m. Figure 5 shows the experimental result on five times positioning. Since we measured the output voltage of the LVDT, the unit of the vertical axis in Fig. 5 is voltage. From this figure, we can find that the repeatability of the positioning is low in the case where the length of pipes is different (see overshoots in close-up of Fig. 5). The cause of this result is the flow disturbance. Even in the case of the same pipe length, the flow disturbance occurs due to the air compressibility. On the other hand, the result in Fig. 5 indicates that in the case of the different pipe length, the effects of the flow disturbance become large. It leads to the low repeatability of the positioning.

Moreover, in order to evaluate effects of the different pipe length on the performance of the PDD² control, we conduct another experiment on positioning. In this experiment, the overshoot of the control system is measured under the condition that the gain K_{dd} of the PDD² control is increased. This is because the value of gain K_{dd} affects the damping of the control system (see subsection 2.2). The other gains (i.e., K_p and K_d) are also increased so that large overshoot can be observed. The values of the gains K_p and K_d are 0.7 and 4.0, respectively. The other conditions of this experiment are the same as those of the above positioning experiment. Figure 6 shows the step response of the control system. From this figure, we can see that when the values of the gain K_{dd} are 5.0, 10, and 15, overshoots in the case of the different pipe length are larger than those in the case of the same pipe length. The reason is that when the length of each pipe becomes different, the time constant T_{air} of the pneumatic system (2) changes. For this reason, the pole-zero cancellation of the PI compensator and the pneumatic system does not occur. Consequently, the damping effects of the PDD² control are not obtained, resulting in the increase of overshoots. Therefore, the difference of pipe length leads to the performance degradation of the PDD² control.

Fig. 5 Effects of the difference of the pipe length on repeatability.

Fig. 6 Effects of the difference of the pipe length on the performance of the PDD² control.

3. Performance improvement of PDD² control

3.1 PDD² control system considering different pipe length

As mentioned in subsection 2.3, since the time constant T_{air} of the pneumatic system changes due to the different pipe length, the pole-zero cancellation cannot be achieved. For this reason, it is necessary to retune the PI compensator. In this subsection, we explain the method appropriate for tuning of the PI compensator. Our approach divides the

pneumatic system into two subsystems. Each subsystem corresponds to the left or right side pipe, servo valve, and chamber (see Fig. 3). Hereinafter, we refer to the subsystems as left and right pneumatic systems. The pressure changes p_L and p_R in the left and right chambers are defined as Eq. (1). In the right-hand side of Eq. (1), the first terms (i.e., $(G_{qL}w_L)/(c_L+\beta_L V_{0LS})$ and $(-G_{qR}w_R)/(c_R+\beta_R V_{0RS})$) indicate the pressure change generated by opening and closing servo valves. On the other hand, the second terms (i.e., $(A_0x_s)/(c_L+\beta_L V_{0LS})$ and $(A_0x_s)/(c_R+\beta_R V_{0RS})$) indicate the pressure change due to volume change in the chamber. Now, for simplicity, we assume that the effects of the volume change are sufficiently small. Then, the second terms of the right-hand side in Eq. (1) can be approximated to zero. For this reason, the pressure changes p_L and p_R are expressed as

$$p_L = \left(\frac{K_{airL}}{1 + T_{airL}s} \right) w_L, \quad p_R = \left(\frac{K_{airR}}{1 + T_{airR}s} \right) w_R, \quad (5)$$

where

$$K_{airL} = \frac{G_{qL}}{c_L}, \quad T_{airL} = \frac{\beta_L V_{0L}}{c_L}, \quad K_{airR} = -\frac{G_{qR}}{c_R}, \quad T_{airR} = \frac{\beta_R V_{0R}}{c_R}. \quad (6)$$

By considering Eq. (5), we tune the PI compensator. Figure 7 shows the PDD² control system appropriate for the tuning of the PI compensators. The parameters in this figure are summarized in Table 3. From the experimental results in Figs. 5 and 6, the time constant of the pneumatic system (2) is changed due to different pipe length. It is probable that, when the pipe length is different, each pole of the left and right pneumatic systems (5) is also different. Due to this reason, our approach employs two PI compensators (see Pre-PI (left) and Pre-PI (right) blocks shown in Fig. 7). Since the time constants T_{airL} and T_{airR} of the two PI compensators can be tuned separately, the pole-zero cancellation between the PI compensators and the pneumatic systems (5) is achieved under the different pipe length.

Let us assume that the pseudo differentiators used for the PDD² control shown in Fig. 4 can be approximated as differentiators, i.e., $T_d s/(1+T_d s) \approx T_d s$. Then, by choosing the time constants of the PI compensators as $T_{piL}=T_{airL}$ and $T_{piR}=T_{airR}$, the transfer function from the reference r to the position x can be expressed as

$$\frac{x}{r} = \frac{A_0 K_p (K_{airL} T_{airR} + K_{airR} T_{airL})}{T_{airL} T_{airR} T_d s^2 \left\{ M T_d^2 s^2 + \left(D + \frac{A_0 K_{pos} K_{dd} (K_{airL} T_{airR} + K_{airR} T_{airL})}{T_{airL} T_{airR}} \right) T_d s + \left(K + \frac{A_0 K_{pos} K_d (K_{airL} T_{airR} + K_{airR} T_{airL})}{T_{airL} T_{airR}} \right) \right\} + A_0 K_{pos} K_p (K_{airL} T_{airR} + K_{airR} T_{airL})}. \quad (7)$$

From Eq. (7), it is found that the stiffness term, i.e., $K+A_0 K_{pos} K_d (K_{airL} T_{airR}+K_{airR} T_{airL})/(T_{airL} T_{airR})$, includes the gain K_d of D control. In contrast, the damping term, i.e., $(D+A_0 K_{pos} K_{dd} (K_{airL} T_{airR}+K_{airR} T_{airL})/(T_{airL} T_{airR})) T_d$, includes the gain K_{dd} of D² control. This indicates that the stiffness and damping of the control system can be adjusted by selecting the gains K_d and K_{dd} adequately. Thus, even if the pipe length is different, the performance of the PDD² control can be improved by means of our method.

Fig. 7 PDD² control system under different pipe length.

3.2 Tuning of time constant for pole-zero cancellation

In this subsection, we consider how to tune the time constants T_{piL} and T_{piR} of the PI compensators. The values of these time constants are determined in accordance with the overshoot of the control system so as to obtain the desired performance of the PDD² control. We first conduct experiments on the positioning under the condition of the same pipe length. Since each length of the left and right pipes is same, the time constants T_{piL} and T_{piR} are set to the same value. Figure 8 shows the experimental results. In the experiments, the length of both pipes is set to 0.5 m. The time constants of the PI compensators are chosen as $T_{piL}=T_{piR}=5.0, 6.0$, and 10 s. The other conditions of the experiments are the same as those in subsection 2.3. From Fig. 8, we can find that the overshoots in the case of $T_{piL}=T_{piR}=6.0$ s are smaller than those in the other cases (see time responses in the cases of $K_{dd}=1.0$ and 5.0). The results indicate that when the time constants T_{piL} and T_{piR} are set to 6.0 s, the pole-zero cancellation of the PI compensators and the pneumatic systems (5) occurs. Due to the pole-zero cancellation, the performance of the PDD² control can be obtained, resulting in the reduction of the overshoot. Hence, under the condition of the same pipe length, the time constants of the PI compensators are chosen as $T_{piL}=T_{piR}=6.0$ s.

Then, we change the length of the left-side pipe from 0.5 to 2.0 m and conduct experiments on the tuning of the time constant. Since the left pipe length is changed, only the time constant T_{piL} is tuned, and the time constant T_{piR} is fixed to 6.0 s. The other conditions are the same as those of the above experiments. The experimental result is shown in Fig. 9. From this figure, we can see that the overshoots in the case of $T_{piL}=7.0$ s and $T_{piR}=6.0$ s are smaller than that in the case of $T_{piL}=T_{piR}=6.0$ s. In other words, under the different pipe length, the performance of the PDD² control is improved by increasing the time constant T_{piL} of the PI compensator. The time constant T_{airL} of the left pneumatic system (5) changes in accordance with the initial volume V_{0L} of the left pipe and chamber (see Eq. (6)). When the length of the left pipe becomes large, the initial volume V_{0L} increases. Due to this reason, the time constant T_{airL} of the left pneumatic system (5) also increases. As a result, when the time constant T_{piL} is larger than that in the case of the same pipe length, the pole-zero cancellation occurs and the overshoots decrease. Therefore, the time constants of the PI compensators should be tuned in accordance with the pipe length.

Fig. 8 Tuning of the time constants T_{piL} and T_{piR} (Same pipe length).

Fig. 9 Tuning of the time constant T_{piL} (Different pipe length).

4. Suppression of flow disturbance

4.1 Implementation of a flow disturbance observer under different pipe length

In this subsection, we consider the implementation method of the FDOB so as to compensate effects of the flow disturbance under the different pipe length. Figure 10 shows the control system with the FDOB and Table 4 lists parameters given in this figure. The flow disturbance is transmitted through the right and left side pipes connected to the cylinder. Moreover, as mentioned in subsection 2.3, the effects of the flow disturbance change in accordance with the difference of pipe length. For these reasons, it is probable that the magnitude of each flow disturbance added to the left and right pneumatic systems is different under different pipe length. To suppress the flow disturbance, we employ multiple FDOBs. In this approach, the FDOBs estimate the flow disturbances d_L and d_R by using the input voltages w_L and w_R to servo valves and the pressure changes p_L and p_R in chambers. The estimates $\hat{d}_L$ and $\hat{d}_R$ of the flow disturbances are added to the outputs of the PI compensators. The inverse systems for the left and right pneumatic systems (5) are improper. For this reason, in order to make the inverse systems proper, a low pass filter (LPF), $1/(1+T_{lpf}s)$

s), is utilized. Moreover, a second-order LPF, $1/(1+T_1s)^2$, is applied so as to reduce effects of pressure sensor noise. Although the LPF in the input and output sides is different, we use the second-order LPF due to the above practical reason. The input-output relation of the left pneumatic system and the FDOB shown in Fig. 10 is expressed as follows:

$$p_L = \frac{P(s)P_n(s)}{P_n(s) + Q(s)\{K_{obl}K_{L2}R(s)P(s) - K_{obl}K_{L1}P_n(s)\}} w'_L + \frac{P(s)P_n(s)\{1 - K_{L1}K_{obl}Q(s)\}}{P_n(s) + Q(s)\{K_{obl}K_{L2}R(s)P(s) - K_{obl}K_{L1}P_n(s)\}} d_L, \quad (8)$$

where

$$P(s) = \frac{K_{airL}}{1 + T_{airL}s}, \quad P_n(s) = \frac{K_{airL(n)}}{1 + T_{airL(n)}s}, \quad Q(s) = \frac{1}{1 + T_{lpf}s}, \quad R(s) = \frac{1}{(1 + T_1s)^2}. \quad (9)$$

In low frequency region, the LPFs are approximately expressed as $Q(s) \approx 1$ and $R(s) \approx 1$. Then, Eq. (8) is rewritten as

$$p_L \approx \frac{P(s)P_n(s)}{P_n(s) + \{K_{obl}K_{L2}P(s) - K_{obl}K_{L1}P_n(s)\}} w'_L + \frac{P(s)P_n(s)\{1 - K_{L1}K_{obl}\}}{P_n(s) + \{K_{obl}K_{L2}P(s) - K_{obl}K_{L1}P_n(s)\}} d_L. \quad (10)$$

By choosing $K_{L1}=1.0$, $K_{L2}=1.0$, and $K_{obl}=1.0$, Eq. (10) can be expressed as

$$p_L \approx P_n(s)w'_L = \frac{K_{airL(n)}}{1 + T_{airL(n)}s} w'_L. \quad (11)$$

From Eq. (11), it is found that the second term in the right-hand side of Eq. (10), which includes the flow disturbance d_L , becomes zero. Due to this reason, by using our approach, the effects of the flow disturbance d_L can be compensated. Similarly, it is possible to suppress the flow disturbance d_R by means of the FDOB for the right pneumatic system (see blue broken line in Fig. 10). The detail is omitted due to the page length limitation of this note.

Table 4 Parameters in Fig. 10.

Symbol	Description and unit
K_{L1}, K_{R1}	Gain of the low pass filter [V/V]
K_{L2}, K_{R2}	Gain of the inverse system of the nominal model [V/V]
K_{obl}, K_{obR}	Gain of the FDOB [V/V]
$K_{airL(n)}, K_{airR(n)}$	Nominal gain of the pneumatic system [V/V]
$T_{airL(n)}, T_{airR(n)}$	Nominal time constant of the pneumatic system [s]
T_{lpf}, T_1	Time constant of the low pass filter [s]
w'_L, w'_R	Outputs of the PI compensator [V]
d_L, d_R	Flow disturbance [V]
$\hat{d}_L, \hat{d}_R$	Flow disturbance estimate [V]

Fig. 10 Control system with FDOBs under different pipe length.

4.2 Evaluation of repeatability

In order to evaluate the performance of the FDOBs, we conduct a positioning experiment. In this experiment, the length of the left and right pipes is 2.0 and 0.5 m, respectively. The positioning is conducted by using the following two methods: pushing motion and pulling motion. In the former method, the compressed air is supplied to the long pipe, whereas, in the latter method, the compressed air is supplied to the short pipe. In the case of the pushing motion, the reference is chosen as $r=1.5$ V (18 mm). On the other hand, in the case of the pulling motion, the reference is $r=-1.5$ V (-18 mm). Since the time constants T_{piL} and T_{piR} of the PI compensator are set to 6.0 and 7.0 s, the nominal time constants $T_{airL(n)}$ and $T_{airR(n)}$ of the pneumatic systems are also set to 6.0 and 7.0 s. The time constants of LPFs are

$T_1=0.002$ s and $T_{lpf}=0.016$ s. The other parameters of the FDOB are chosen as $K_{L1}=1.0$, $K_{obl}=0.1$, $K_{L2}=0.15$, $K_{airL(n)}=1.0$, $K_{R1}=1.0$, $K_{obR}=0.1$, $K_{R2}=-0.05$, and $K_{airR(n)}=1.0$ by using a trial-and-error method. The other conditions in this experiment are the same as those in subsection 2.3. Since it is difficult to measure frequency response due to the friction of guideway and the damage to the stage, we evaluate the performance of the FDOB in time domain. Figure 11 shows ten times positioning results of the pushing motion. From this figure, we can find that by using the FDOB, the overshoot is reduced. Moreover, the results of the pulling motion are shown in Fig. 12. The obtained results are similar to those on the pushing motion. Figure 13 shows the standard deviations of the position x at 2.2, 2.3, 2.4, and 2.5 s in the pushing motion, and Fig. 14 shows the standard deviations at 5.0, 10, 15, and 20 s in the pulling motion. From these figures, we can find that the standard deviations in the case with the FDOB are smaller than those in the case without the FDOB. Moreover, even if the FDOBs are used, the transient waveforms are not significantly changed. Due to this, it is probable that the nominalization of plant is achieved. Therefore, under different pipe length, the effects of flow disturbance are reduced and the repeatability of positioning is improved by using the FDOBs.

Fig. 11 Positioning results (Pushing motion).

Fig. 12 Positioning results (Pulling motion).

Fig. 13 Standard deviation (Pushing motion).

Fig. 14 Standard deviation (Pulling motion).

5. Conclusion

In this note, we considered the positioning control of the pneumatic stage connected by pipes of the different length. Since the performance of the PDD² control is degraded due to the difference of the pipe length, the time constants of the PI compensator were tuned. When pipes are long, large time constants of PI compensators for the left and right pneumatic systems are selected so that the pole-zero cancellation can occur. Due to this selection, even if the pipe length is different, the PDD² control becomes effective for the positioning of the pneumatic stage. Moreover, to suppress the flow disturbance, the implementation method of the FDOBs was explained. From experimental results, we found that the repeatability of the positioning is improved by using the FDOBs. Since parameters of the FDOBs were tuned through trial-and-error process, our future work is to consider the tuning method of these parameters.

References

- Kagawa, T., Tokashiki, L.R. and Fujita, T., Accurate positioning of a pneumatic servo system with air bearings, Proceedings of Bath Workshop on Power Transmission and Motion Control (2000), pp.257-268.
- Liu, Y. -T. and Jiang, C. -C., Pneumatic actuating device with nanopositioning ability utilizing PZT impact force coupled with differential pressure, Precision Engineering, Vol.31, No.3 (2007), pp.293-303.
- Taheri, B., Case, D. and Richer, E., Force and stiffness backstepping-sliding mode controller for pneumatic cylinders, IEEE/ASME Transactions on Mechatronics, Vol.19, No.6 (2014), pp.1799-1809.
- Wali, M. and Wakui, S., Combination of the flow disturbance observer and base plate jerk feedback in a pneumatic positioning stage, Journal of System Design and Dynamics, Vol.6, No.1 (2012), pp.12-27.
- Wali, M., Positioning control of a pneumatically actuated stage -control of reaction force and flow disturbance and improvement of positioning speed-, Ph.D. dissertation, Tokyo University of Agriculture and Technology (2014).