Abstract
PDD² (proportional + derivative + second derivative) compensator has been standardly used for position control of the pneumatic stage. This compensator is based on the integral characteristics of a pneumatic system composed of pipes, servo valves, and pneumatic cylinders. At this time, since the output of this compensator is integrated through the pneumatic system, PID control of the position is possible. However, the positioning of the pneumatic stage is slower than that of the electromagnetic actuators such as a linear and a ball screw stages. Generally, when either the controlled object or the compensator has a slow response, the response of the control system becomes slow. In the previous studies, the pneumatic stage itself, which is the controlled object, was focused on. Local feedback applied to the pneumatic and mechanical systems realized high-speed positioning. However, the influence on the positioning response using PDD² compensator, which forms the framework of the position control, has not been considered. Therefore, this note focuses on the structure of PDD² compensator. Here, the characteristics of this compensator are reinterpreted. Specifically, it is shown that a slow response cannot be avoided intrinsically due to the structure of this compensator. Furthermore, modified PDD² compensator with improved slow response is proposed.

Keywords: Positioning, Pneumatic equipment, Motion control, PDD² compensator, PID compensator

1. Introduction

Integrated circuits (hereinafter called IC) have been densified and miniaturized every year, contributing to improvement in the performance of electronic devices. A photomask produced by an electron beam (hereinafter called EB) exposure apparatus enables mass production of such IC. By using this mask as the original circuit pattern, IC can be mass-produced by the semiconductor exposure apparatus. Therefore, a positioning error is not allowed in the drawing process of this mask, and high exposure precision is required for the positioning stage. In general, an electromagnetic actuator is adopted as an actuator of a precision positioning stage because of excellent linearity (Saravanakumar et al., 2017). However, in the case of this actuator, it is inevitable to generate heat and magnetism, which causes deterioration of the exposure precision of the EB. Therefore, it has been proposed to use a low heat generation and nonmagnetic pneumatic actuator (Teo et al., 2015) for precision positioning stage in the EB exposure apparatus. In fact, the vacuum air servo stage (SUMITOMO HEAVY, CA-230) has been commercialized as a precision positioning XY stage, and it is in operation at the industrial sites.

Generally, PID (proportional + integral + derivative) compensator has been used for position control of electromagnetic actuators such as a linear and a ball screw stages. This is because of excellent versatility of PID control. On the other hand, PDD² (proportional + derivative + second derivative) compensator (Miyajima et al., 2004) is adopted for pneumatic stage. This compensator is based on the integral characteristics of a pneumatic system composed of pipes, servo valves, and pneumatic cylinders. At this time, since the output of this compensator is integrated through the pneumatic system, PID control of the position is possible. However, the positioning of the
pneumatic stage is slower than that of the electromagnetic actuator. For this reason, it is proposed to speed up positioning by means of local feedback. Specifically, pressure feedback (Wakui and Tada, 2008) to compensate for the slowness of the pneumatic system due to compressibility of the air, and positive stage jerk feedback (Wali and Wakui, 2013) to compensate for that of the mechanical system due to the stage weight have been proposed, and their effects are confirmed. However, when either the pneumatic stage or PDD² compensator has a slow response, the response of the control system becomes slow. Therefore, it is necessary to examine the characteristics of PDD² compensator. This is because this compensator is the framework of the position control system. Nevertheless, the discussion on this compensator is not sufficient.

Therefore, this note focuses on the structure of PDD² compensator itself, which has been adopted as a standard in the positioning of the pneumatic stage. The characteristics of this compensator are reinterpreted. In particular, by performing plain equivalent transformation of the control system, it is shown that a slow response cannot be avoided intrinsically due to the structure of this compensator. Furthermore, modified PDD² compensator, which has been improved based on the problem derived from the equivalent transformation, is proposed.

2. Experimental setup and control system
2.1 Pneumatic stage and experimental apparatuses

Figure 1 shows the pneumatic stage. This stage is driven by a differential pressure of air generated between the chambers in the pneumatic cylinders. Figure 2 shows the experimental setup. Compressed air created by an air compressor is decompressed and smoothed through a regulator, and supplied to the servo valves (LINATOR, EWS 3/4). In order to independently control the left and right pressure in the chamber of the pneumatic cylinder (Airpel, M16D300.0S), the valves are installed on each of the left and right sides. As a result, the differential pressure corresponding to the positioning command is generated between both the chambers, and the stage is driven from the high to the low pressure side. The stage position is detected with a linear variable differential transformer (SHINKO ELECTRIC, LT2-120R). The acquired position signal is inputted to the digital signal processor to calculate manipulated variable of each valve based on the control law described in the next section.

2.2 Control system of pneumatic stage
2.2.1 Control configuration

Figure 3 shows the control system configuration of the pneumatic stage. In this figure, this stage is constituted by a series connection of pneumatic and mechanical systems. In addition, the former means a differential pressure generating part, and the latter means a stage part driven by the differential pressure. As a position control method, PDD² compensator is implemented by taking into account the integral characteristics of the pneumatic system.

PDD² compensator consists of proportional, derivative, and second derivative terms for the position signal. At this time, the output of this compensator can be regarded as being integrated through the pneumatic system. Therefore, proportional, derivative, and second derivative terms for the position correspond to integral, proportional, and differential terms for the position, respectively. Thus, the output of the pneumatic system is equivalent to the...
manipulated variable of PID compensator. As a result, the stage is driven by PID control method; that is, the control system of Fig. 3 corresponds with that of Fig. 4, which means a general PID control system used for an electromagnetic actuator. Therefore, PDD² compensator is an implicit configuration in the positioning field using the pneumatic stage and the pneumatic cylinder. Incidentally, the pneumatic system shows practically first-order lag characteristics. Therefore, PI compensator is placed behind PDD² compensator. The time constant of PI compensator matches that of the pneumatic system. Thereby, the pneumatic system is shaped from the first-order lag characteristics to perfect integral characteristics through the pole-zero cancellation.

### 2.2.2 Parallel type PDD² compensator

Figure 5 shows the specific control system of pneumatic stage including PDD² compensator. The symbols used in this figure are shown in Table 1. In addition, stage is modeled as a series connection of the pneumatic and the mechanical systems. The former is the first-order lag system, and the latter is the second-order lag system. Moreover, Fig. 5(a) is a control system using parallel type PDD² compensator, which is adopted as a standard in the position control system. In contrast, Fig. 5(b) is series type. In Figs. 5(a) and (b), pseudo derivative is used instead of perfect derivative to avoid setpoint kick and excitation of high frequency dynamics. Furthermore, measured value derivative is adopted rather than error derivative.

In order to intuitively understand the role of PDD² compensator in the positioning of the pneumatic stage, the transfer function $\frac{K_{pos,x}}{r}$ is derived. In this subsection, Fig. 5(a) is discussed. Here, the following is assumed.

\[
T_{pi} = T_{air}
\]  
\[
\frac{T_{d}s}{1 + T_{d}s} \approx T_{d}s
\]

At this time, the transfer function $\frac{K_{pos,x}}{r}$ is given as

\[
\frac{K_{pos,x}}{r} = \frac{K_pK_{air}A_{q}K_{pos}}{T_{pi}s\left(Ms^2 + (D + \Delta D)s + (K + \Delta K)\right) + K_pK_{air}A_{q}K_{pos}}
\]

where the electrical viscosity $\Delta D$ and the electrical stiffness $\Delta K$ are defined as follows.

\[
\Delta D = \frac{K_{dd} \cdot K_{air}A_{q}K_{pos}T_{d}}{T_{pi}}
\]
\[
\Delta K = \frac{K_{d} \cdot K_{air}A_{q}K_{pos}T_{d}}{T_{pi}}
\]

Refer to Eqs. (3)~(5), $\Delta D$ includes the second derivative gain $K_{dd}$ of PDD² compensator and $\Delta K$ includes the derivative gain $K_{d}$. Therefore, in parallel type PDD² compensator, it is possible to operate the viscosity and stiffness terms by second derivative and derivative terms respectively. In the positioning response, the former makes for suppression of overshoot, and the latter makes for shortening of response time. Thereby, a desired positioning response is realized.

---

Fig. 3 Control system configuration of pneumatic stage. PDD² compensator is implemented for position control system of pneumatic stage.

Fig. 4 Control system configuration of linear stage. PID compensator is implemented for position control system of linear stage.
(a) With parallel type PDD\textsuperscript{2} compensator. (b) With series type PDD\textsuperscript{2} compensator.

Fig. 5 Control system of pneumatic stage including PDD\textsuperscript{2} compensator. The pneumatic system is not completely integral characteristics. Then, Pre-PI is installed to shape the pneumatic system to integrator.

### Table 1 Parameters of Fig. 5.

| Symbol | Description | Unit | Symbol | Description | Unit |
|--------|-------------|------|--------|-------------|------|
| r      | Reference   | V    | T\textsubscript{d} | Time constant of pseudo differentiator | s |
| v      | Output of PDD\textsuperscript{2} compensator | V | T\textsubscript{pi} | Time constant of Pre-PI compensator | s |
| w      | Input voltage to servo valves | V | K\textsubscript{air} | Gain of pneumatic system | Pa/V |
| p      | Differential pressure in pneumatic cylinder | Pa | T\textsubscript{air} | Time constant of pneumatic system | s |
| x      | Position of pneumatic stage | m | A\textsubscript{0} | Piston area | m\textsuperscript{2} |
| K\textsubscript{p} | Proportional gain of PDD\textsuperscript{2} compensator | V/V | M | Stage mass | kg |
| K\textsubscript{d} | Derivative gain of PDD\textsuperscript{2} compensator | V/V | D | Viscous damping coefficient of stage | N \cdot s/m |
| K\textsubscript{dd} | Second derivative gain of PDD\textsuperscript{2} compensator | V/V | K | Spring constant of stage | N/m |
| K\textsubscript{v} | Velocity loop gain of PDD\textsuperscript{2} compensator | V/V | K\textsubscript{pos} | Detection sensitivity of linear variable differential transformer | V/m |
| K\textsubscript{a} | Acceleration loop gain of PDD\textsuperscript{2} compensator | V/V |

#### 2.2.3 Series type PDD\textsuperscript{2} compensator

Regarding Fig. 5(b), the transfer function \( K_{pos}x/r \) is given as

\[
K_{pos}x = \frac{K_a K_v K_p' K_{air} A_0 K_{pos}}{T_{pi} s \left( M s^2 + ( D + \Delta D') s + (K + \Delta K') \right) + K_a K_v K_p' K_{air} A_0 K_{pos}}
\]

where the electrical viscosity \( \Delta D' \) and the electrical stiffness \( \Delta K' \) are defined as follows.

\[
\Delta D' = \frac{K_a \cdot K_{air} A_0 K_{pos} T_d^2}{T_{pi}}
\]

\[
\Delta K' = \frac{K_a K_v \cdot K_{air} A_0 K_{pos} T_d}{T_{pi}}
\]

Equations (6)–(8) mean that the viscosity and stiffness terms can be operated in the same way as the control system in Fig. 5(b). However, the acceleration loop gain \( K_a \) is included as the parameters \( \Delta D' \) and \( \Delta K' \). Therefore, \( \Delta D' \) cannot be changed independently from \( \Delta K' \), and the degree-of-freedom of parameter adjustment decreases.

Refer to Eqs. (3) and (6), in order to equalize Fig. 5(a) to 5(b), each gain must satisfy the following Eqs. (9)–(11). These equations can be also obtained from the equivalent transformation of Fig. 5(b). Although the result is

\[
K_p = K_a K_v K_p'
\]

\[
K_d = K_a K_v
\]

\[
K_{dd} = K_a
\]
omitted, even in the case of converting from Fig. 5(b) to 5(a), the conditional expression can be derived by the modification of Eqs. (9)~(11). Hereinafter, it is assumed that PDD² compensator refers to parallel type PDD² compensator.

3. Reinterpretation of PDD² compensator
3.1 Reinterpretation by plain equivalent transformation

In the previous chapter, it was mentioned that PDD² compensator is a special compensator used for position control with the pneumatic stage. Control methods for high speed and high precision driving of this stage have been studied in various ways. On the other hand, this compensator has been adopted invariably. Therefore, it cannot be said that the discussion on this compensator, which forms the framework of the position control, is sufficient. Thus, this note discusses the properties of PDD² compensator itself. In this section, reinterpretation from a new viewpoint is performed by the plain equivalent transformation for the block diagram.

Figure 6 shows the result of equivalent transformation for the block diagram of Fig. 5(a). In Fig. 6, the pneumatic system is incorporated into PDD² compensator. However, it is assumed that Eq. (1) is satisfied. From this figure, proportional, derivative, and second derivative terms for the position constituting PDD² compensator are respectively integrated, and correspond to I, P, and D control. On the other hand, in order to avoid the setpoint kick due to differential operation, it can be seen that the position sensor output is directly differentiated in P and D control unit. Therefore, strictly speaking, the position is I-PD (proportional-derivative preceded integral) control. Hereinafter, PDD² compensator capable of I-PD control of position will be referred to as P-DD² compensator in consideration of its structure.

3.2 Reinterpretation by transfer function

In the previous section, it is shown that P-DD² compensator performs I-PD control of position. Generally, using this control, the overshoot is small, while the response is slow. In this section, reinterpretation from viewpoint of the transfer function is performed. Specifically, it is considered that I-PD control is a cause of the slow response.

Figure 7 shows the transformed block diagram of Fig. 6. This transformation is based on the transfer function
shown in Eq. (3). In this figure, the path of the minor loop having derivative and second derivative terms for the position is changed. Here, it is assumed that Eqs. (1) and (2) are satisfied. From this figure, it can be seen that only I control is performed for the shaped mechanical system with improved dynamic characteristics by supplying appropriate stiffness and viscosity. In other words, P and D control units of I-PD control contribute to the improvement of the dynamic characteristics, and the position control is performed by only I control, that is, the integral operation. Hence, even if a high-speed positioning is realized by local feedback such as pressure feedback and stage jerk feedback, the slow response cannot be avoided intrinsically due to the characteristics of P-DD² compensator itself.

4. Improvement of PDD² compensator

4.1 Implementation of PI-D control

In the control system shown in Fig. 3, high-speed positioning of the pneumatic stage is fundamentally difficult. Therefore, in this section, the modified P-DD² compensator is proposed, which enables PI-D (derivative preceded proportional-integral) control of the stage position.

Figure 8 shows PDD² compensator capable of PI-D control of the stage position (hereinafter referred to as PD-D² compensator). In this figure, the input signal to D compensation unit constituting this compensator is changed from the position sensor output to the error. For this reason, the setpoint kick occurs at input voltage to servo valves $w$ due to error derivative.

Here, the structure of the control system with PD-D² compensator is visually confirmed using the block diagram. Figure 9 shows the result of equivalent transformation for the block diagram of Fig. 8. In Fig. 9, the pneumatic system is incorporated into PD-D² compensator under the same procedure and conditions as in Fig. 6. From Fig. 9, proportional, derivative, and second derivative terms for the position constituting this compensator are respectively integrated and correspond to I, P, and D control. In addition, D control unit directly differentiates the position sensor output in order to avoid the setpoint kick due to differential operation. Therefore, the stage position is PI-D control.

When PD-D² compensator shown in Fig. 8 is applied, the transfer function $K_{posx}/r$ is given as

$$\frac{K_{posx}}{r} = \frac{K_p K_{air} A_0 K_{pos} \left( \frac{K_d T_d}{K_p} s + 1 \right)}{T_{ps}^{pd} \left(Ms^2 + (D + \Delta D)s + (K + \Delta K) \right) + K_p K_{air} A_0 K_{pos}}$$  \hspace{1cm} (12)

where Eqs. (1) and (2) are satisfied. Moreover, the electrical viscosity $\Delta D$ and the electrical stiffness $\Delta K$ are shown in Eqs. (4) and (5). Equation (12) is multiplied the right side of Eq. (3) by the polynomial $(K_d T_d/K_p + 1)$. In addition, comparing the transfer functions of Eqs. (3) and (12), PD-D² compensator can also operate the viscosity and stiffness terms as before because both denominators are perfectly identical. On the other hand, the difference between Eqs. (3) and (12) is found in the numerator. In particular, Eq. (12) has the zero.

The effect of the zero can be interpreted through the equivalent transformation of Fig. 8. Figure 10 shows the result of equivalent transformation in accordance with Eq. (12). Here, it is assumed that Eqs. (1) and (2) are satisfied.
Fig. 10  Equivalent transformation for Fig. 8 using Eq. (12). In this control system, FF-like control is implemented in addition to I control for the shaped mechanical system. Therefore, the response of the system with PD-D\textsuperscript{2} compensator is faster than that with P-DD\textsuperscript{2} compensator.

From this figure, feedforward (hereinafter called FF) like control is performed for the shaped mechanical system with improved dynamic characteristics by supplying appropriate stiffness and viscosity in addition to I control. As a result, responsiveness to the reference increases.

### 4.2 Comparison between P-DD\textsuperscript{2} compensator and PD-D\textsuperscript{2} compensator

In this section, the control system with P-DD\textsuperscript{2} compensator shown in Fig. 3 and that with PD-D\textsuperscript{2} compensator shown in Fig. 8 are experimentally compared. Specifically, the difference between the two is examined through both the frequency response and positioning experiment.

Figure 11 shows the simulated frequency responses in the closed-loop based on Eqs. (3) and (12). Table 2 shows the parameters used in the simulation. For the sake of convenience, the estimated values obtained in the previous study (Santo and Wakui, 2013) (Takei and Wakui, 2016) (Takei and Wakui, 2017) are substituted for the unknown parameters \( T_{\text{air}}, K_{\text{air}}, D, \) and \( K. \) From the upper part of this figure, application of PD-D\textsuperscript{2} compensator has wide bandwidth compared to that of P-DD\textsuperscript{2} compensator. This is due to the presence or absence of the zero. Furthermore, the control system with P-DD\textsuperscript{2} compensator attenuates with the slope \(-60 \text{ dB/dec}\) after the break frequency while that with PD-D\textsuperscript{2} compensator attenuates at the slope \(-40 \text{ dB/dec}\). Therefore, the former is superior to the latter in terms of responsiveness at high frequency region. Incidentally, the simulation is selected instead of actual experiment in order to prevent wear of the cylinder sliding part and shorten the time required for frequency sweeping in the low frequency region.

Figure 12 shows the results of positioning using the control system of Figs. 5(a) and 8. In the positioning experiment, after 2 seconds, the stage is driven from the center (0 mm) to the right (12 mm). Here, \( K_p=0.3, K_d=1.0, K_{\text{air}}=7.0. \) Application of PD-D\textsuperscript{2} compensator speeds up the rise time compared to that of P-DD\textsuperscript{2} compensator. This
Table 2 Parameters used for simulation.

| Symbol | Value | Unit | Symbol | Value | Unit |
|--------|-------|------|--------|-------|------|
| $K_p$ | 1.0  | V/V  | $T_{air}$ | 5.0  | s    |
| $K_d$ | 10   | V/V  | $A_{hi}$ | $4\times1.98\times10^{-4}$ | m$^2$ |
| $K_{dd}$ | 20   | V/V  | $M$ | 15 | kg   |
| $T_d$ | 0.015 | s    | $D$ | 345 | N $\cdot$ s/m |
| $T_{pi}$ | 5.0 | s    | $K$ | 3100 | N/m |
| $K_{air}$ | $4.2\times10^4$ | Pa/V | $K_{pos}$ | $0.833\times10^4$ | V/m |

means that the slow response due to the structure of the compensator could be resolved as expected. From the viewpoint of high-speed driving, PD-$D^2$ compensator should be adopted instead of P-DD$^2$ compensator even if a pulse-like kick is inputted to the valves. In this experiment, care was taken not to saturate the input voltage of the valves by this kick.

5. Conclusions

In this note, the characteristics derived from the structure of P-DD$^2$ compensator, which is adopted as a standard in the pneumatic stage, are discussed. The conclusions are as follows.

1) Essence of P-DD$^2$ compensator can be regarded as I-PD control. In this control, only I control is performed for the shaped mechanical system with improved dynamic characteristics. Therefore, the response of the system is intrinsically slow.

2) PD-$D^2$ compensator with modified P-DD$^2$ compensator realizes PI-D control of the stage position. In this control, FF-like control is performed in addition to I control for the shaped mechanical system. Therefore, it is possible to accomplish the fast positioning.

3) From the results of frequency response by simulation, it was confirmed that the control system to which PD-$D^2$ compensator is applied has wide bandwidth as compared with that of P-DD$^2$ compensator. Furthermore, from the actual positioning results, it was confirmed that the control system to which PD-$D^2$ compensator is applied can speed up the response compared with that of P-DD$^2$.

References

Miyajima, T., Sakaki, K., Shibukawa, T., Fujita, T., Kawashima, K., and Kagawa, T., Development of pneumatic high-precision position controllable servo valve, Proceedings the 2004 IEEE International Conference on Control Applications, Vol.2 (2004), pp.1159-1164.

Santo, Y. and Wakui, S., Implementation of an easy dual disturbance observer for pneumatic stages, Transactions of the Japan Society of Mechanical Engineers, Series C, Vol.79, No.799 (2013), pp.738-742 (in Japanese).

Saravanakumar, D., Mohan, B., and Muthuramalingam, T., A review on recent research trends in servo pneumatic positioning systems, Precision Engineering, Vol.49 (2017), pp.481-492.

Takei, R. and Wakui, S., A study of implementation of model following control for a pneumatic stage, Transactions of the JSME (in Japanese), Vol.83, No.845 (2017), DOI: 10.1299/transjsme.16-00334.

Takei, R. and Wakui, S., Performance improvement of model following control for a pneumatic stage, Proceedings of the 2016 International Conference on Advanced Mechatronic Systems, (2016), pp.277-282.

Teo, T. J., Yang, G., and Chen, I.-M., A flexure-based electromagnetic nanopositioning actuator with predictable and re-configurable open-loop positioning resolution, Precision Engineering, Vol.40 (2015), pp.249-260.

Wakui, S. and Tada, R., Positioning control using pressure feedback and series compensator for pneumatic system, Journal of the Japan Society for Precision Engineering, Vol.74, No.7 (2008), pp.769-774 (in Japanese).

Wali, M. and Wakui, S., Positive stage jerk feedback combined with positive base plate jerk feedback to improve the positioning speed of a pneumatic stage, Journal of Advanced Mechanical Design, Systems, and Manufacturing, Vol. 7, No. 2 (2013), pp. 219-232.