Effect of Dead Zone Compensation by Mass-Flow-Rate Twin-Drive System with Anti-Windup for Pressure Control System

Yui Takaki Shirato*a)  Member,  Wataru Ohnishi** Member
Hiroshi Fujimoto** Senior Member,  Yoichi Hori** Fellow
Koichi Sakata* Senior Member,  Atsushi Hara* Non-member

Manufacturing equipment often require high-speed and high-precision positioning with long strokes. This study aims to utilize pneumatic cylinders for such equipment owing to their several advantages. One of the challenges in pressure and position control is valve nonlinearity, such as a varying dead zone. While the conventional feedforward dead zone compensation method cannot address variations in valve input-output characteristics, the twin-drive system, a feedback compensation method, can address the variations using a fast-response flowmeter. However, the disadvantage of the twin-drive system is that it is likely to cause saturation and windup. To solve this problem, we propose an anti-windup method for the twin-drive system. Experimental results indicate the proposed method avoids windup and enables accurate tracking control in the difference mode (i.e., mass-flow input to the tank). Moreover, the experimental results reveal that the proposed twin-drive system with the anti-windup structure improves the pressure tracking performance and enhances the pressure control system’s linearity compared with those of the conventional feedforward compensation method.

Keywords: pneumatic cylinder, valve, mass-flow-rate control, dead zone compensation, twin-drive system, anti-windup

1. Introduction

Manufacturing equipment such as machine tools, wafer scanners, and flat-panel scanners requires high-precision and high-speed tracking position control with a long stroke (1)-(3). Because a linear motor with a long stroke may cause a massive heat generation and a lack of thrust that limits the performance (4)-(6), an attempt was made to replace the linear motor in the coarse stage with a pneumatic cylinder. A schematic of the pneumatic cylinder is illustrated in Fig. 1. A pneumatic cylinder has several advantages such as a high power-to-weight ratio, low cost, and low heat generation (6)-(10). A major challenge for application results from the valve dead zone (7)-(11). Dead zone compensation in the mass-flow-rate control system is required because the dead zone degrades the control performance of the pressure and position. The mass flow rate through the valves determines the pressure in the chambers, and the pressure in the chambers moves the stage.

The conventional approach of dead zone compensation is to employ an inverse model of the input-output characteristics of a valve (7)-(11)-(12). The merit of this feedforward (FF) approach is that there is no need for a fast-response flowmeter. However, this method cannot address the variation in the input-output characteristics of a valve.

To address the variation of the dead zone, some of the mass-flow-rate feedback (FB) approaches with a valve and a fast-response flow meter were introduced (14)-(15). These approaches improve the mass-flow-rate tracking performance, yet the errors may occur because the varying dead zone degrades the linearity of the control system (15). In particular, at low flow rates, the linearity becomes low owing to the strong influence of the dead zone, resulting in poor flow control performance.

To solve this nonlinearity problem, a twin-drive system was introduced in this study. The twin-drive system is a control method that uses two actuators and transforms the con-
control variables into sum and difference modes and is known to improve the performance against nonlinearity. The twin-drive system can avoid low-flow-rate operating points for the air supply and exhaust valves by providing an offset to the flow rate reference value, thus rendering it possible to use a region of high valve linearity. However, the twin-drive system is likely to cause saturation. The twin-drive system is composed of the sum mode and the difference mode. Although the difference mode results in the total mass flow rate being input to the system, the sum mode controls the mass-flow-rate offset of each valve. The sum-mode reference must be high to avoid the effect of the dead zone. A high sum-mode command is also required to output a large amount of mass-flow-rate difference. However, a high sum-mode reference may cause saturation, because it provides large valve-input voltages to each valve. To avoid the windup resulting from saturation, an anti-windup (AWU) structure is required.

Although the twin-drive system essentially requires an AWU structure, the AWU structure for the single-input single-output system cannot be straightforwardly applied to a twin-drive system. The twin-drive system has two controllers, and the controller outputs are not directly input to the plants. In this article, an AWU structure is proposed that limits the sum-mode controller output by converting the allowable voltage range.

This article is structured as follows:

C1 In Section 4.2, an AWU method for twin-drive system is proposed.

C2 In Section 6.2, the experimental validation of the proposed AWU method in the mass-flow-rate control system is discussed. The proposed AWU method avoids windup and renders accurate tracking control possible in the difference mode even when the mass-flow-rate sum has a high value.

C3 The effect of the mass-flow-rate control system in the pressure control system was experimentally validated, as described in Section 6.3. The results indicate that the proposed system improves the pressure following ability and enhances the linearity compared with the conventional mass-flow-rate FF control system.

2. Problem formulation

The problem addressed in this study is to present a dead zone compensation method that enhances the pressure control performance. The requirements of the dead zone compensation method are as follows:

R1 The flow rate can be controlled even at low flow rates near the dead zone.

R2 The mass-flow-rate control system can avoid windup owing to the high sum-mode reference.

R3 The pressure tracking performance improves in the low-frequency region.

R4 The pressure bandwidth improves.

R1 is necessary to compensate for the valve nonlinearity. R2 is required for the twin-drive system because the system requires a high sum-mode reference that is likely to cause saturation. R3 is required for high-precision flow rate control, and R4 is desired for high-speed control.

A block diagram of the mass-flow-rate FF control system is illustrated in Fig. 2. Inv represents the inverse model of the valve that compensates for the dead zone. The inverse model outputs the reference voltage according to the mass-flow-rate input. It is designed based on the steady-state input-output characteristics of a valve. The model was designed in two steps to address the pressure dependency. The first step is from the mass-flow-rate input to the valve orifice area with pressure dependency, and the second step is from the valve orifice area to the voltage reference. Case block outputs \( m_{\text{sup,in}} \) and \( m_{\text{exh,in}} \) using (1) and (2).

\[
\begin{align*}
\dot{m}_{\text{sup,in}} &= \begin{cases} 
\dot{m}_{\text{dif,ref}} & (\dot{m}_{\text{dif,ref}} > 0) \\
0 & (\dot{m}_{\text{dif,ref}} \leq 0)
\end{cases} \\
\dot{m}_{\text{exh,in}} &= \begin{cases} 
0 & (\dot{m}_{\text{dif,ref}} > 0) \\
-\dot{m}_{\text{dif,ref}} & (\dot{m}_{\text{dif,ref}} \leq 0)
\end{cases}
\end{align*}
\]

4. Proposed mass-flow-rate twin-drive system with AWU

4.1 Twin-drive system without AWU

To satisfy requirement R1, the twin-drive system is introduced, which renders it possible to track to a reference near the dead zone because it can supply or exhaust a small amount of mass flow.
rate with a high mass flow rate of each valve. In addition, it can control two valves without interference between the supply air and the exhaust air. It converts the mass flow rate of each valve into the differences in the mode sum and the mode with the Hadamard matrix (17).

The symbols of the mass-flow-rate twin-drive system are listed in Table 2. Figure 3 shows a block diagram of the mass-flow-rate twin-drive system. The twin-drive system controls the sum mode and the difference mode. The modes of each value are obtained using (3). The difference mode controls the supplied/exhausted mass flow rate to/from a tank. Because the effect of the dead zone is canceled out by the two valves, the difference mode has a small amount of nonlinearity. Therefore, the flow tracking control performance must improve. However, the sum mode controls the mass flow rate of each valve. The following accuracy is low because the dead zone remains in the sum mode. The coordinate transformation block in Fig. 3 converts $t_{df}$ and $t_{sum}$ to $v_{ref, sup}$ and $v_{ref, exh}$, respectively, based on (4).

$$\begin{pmatrix} m_{sum} \\ m_{dif} \end{pmatrix} = \frac{1}{2} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} m_{sup} \\ m_{exh} \end{pmatrix}$$ (3)

$$\begin{pmatrix} v_{sup, org} \\ v_{exh, org} \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} v_{sum} \\ v_{dif} \end{pmatrix}$$ (4)

The references of the valve input voltages $v_{ref, sup}$ and $v_{ref, exh}$ are expressed as (5) because a constant bias $v_{off, set}$ is added to $v_{sup, org}$ and $v_{exh, org}$ to make the valve input voltage larger than the valve dead zone.

$$v_{ref, sup} = v_{sup, org} + v_{off, set}$$

$$v_{ref, exh} = v_{exh, org} + v_{off, set}$$

Because the actual valve input voltages $v_{sup}$ and $v_{exh}$ are limited by (6)(7), the control system without an AWU mechanism may result in a saturation.

$$v_{sup} = \begin{cases} v_{min, sup} & (v_{ref, sup} \leq v_{min, sup}) \\ v_{ref, sup} & (v_{min, sup} \leq v_{ref, sup} \leq v_{max, sup}) \\ v_{max, sup} & (v_{max, sup} \leq v_{ref, sup}) \end{cases}$$

$$v_{exh} = \begin{cases} v_{min, exh} & (v_{ref, exh} \leq v_{min, exh}) \\ v_{ref, exh} & (v_{min, exh} \leq v_{ref, exh} \leq v_{max, exh}) \\ v_{max, exh} & (v_{max, exh} \leq v_{ref, exh}) \end{cases}$$

A block diagram of the sum-mode controller is shown in Fig. 4. The sum-mode controller $C_{fb, sum}$ can be implemented using (8).

$$C_{fb, sum} = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}}$$ (8)

The experimental results indicate that the twin-drive system satisfies R1(Fig. 7, 8 in a previous report (20)). The sum reference was set to a low value to avoid saturation.

### 4.2 Proposed method: twin-drive system with AWU

In this section, an AWU method for a twin-drive system that satisfies R2 is presented.

The disadvantage of the twin-drive system is that the difference mode value may not be able to follow the reference because of the constraints shown in (6) and (7). The gray area in Fig. 5 displays the constraints where valves cannot output the mass flow rate corresponding to the sum and difference reference. These are the dead zone, output limitation, and saturation. First, tracking is difficult with a low mass flow rate near the dead zone. Second, the system cannot output a large mass-flow-rate difference with a low mass flow rate. Third, a high mass flow rate is likely to cause saturation. While the pressure FB controller determines the difference-mode reference, the experimenter sets the sum-mode reference value. Without an AWU structure, the sum-mode reference is set to a low value to avoid saturation, due to which the system cannot output a large mass-flow-rate difference. However, the sum-mode reference can be set to a high value with an AWU structure. Because the AWU structure stops the following in the case of saturation, the system can avoid windup.

Moreover, the AWU structure for the single-input single-output system cannot be applied to a twin-drive system. The twin-drive system has two controllers, and the controller outputs are not directly input to the plants.

Here, an AWU structure in only the sum mode is proposed because a high sum-mode reference is likely to cause saturation. The sum mode does not require accurate tracking because it determines the mass flow rate. The AWU structure stops following in the sum mode in the case of saturation. The proposed method cannot achieve tracking in the difference mode when valves cannot output a sufficient mass flow rate to output a difference reference owing to the limitation of valve-input voltages. The proposed structure limits the controller output by converting the allowable input-voltage.
range.

The block diagram of a sum-mode controller with AWU is shown in Fig. 6. The sum-mode controller designed by referring to the general design method of the AWU controller \(^{(18)}\). The AWU controller comprises \(C_{fb, sum}\), \(C_{fb, dif}\), and AWU block. \(C_{fb, sum}\) and \(C_{fb, dif}\) are expressed as (9). Here, \(b_0, b_1, b_2, a_1, a_2\) are constant values in (8).

\[
\begin{align*}
C_{fb, sum} &= b_0 \\
C_{fb, dif} &= \frac{C_{fb, sum} - 1}{\left(a_1 - b_1/b_0\right)z^{-1} + \left(a_2 - b_2/b_0\right)z^{-2} + b_1/b_0z^{-1} + b_2/b_0z^{-2}}
\end{align*}
\]

The AWU block limits the sum-mode controller output by converting the allowable input-voltage range. Figure 7(a) shows the area where the valve-input voltages meet the allowable voltage range. In contrast, Fig. 7(b) indicates the area

5. Pressure control system with conventional or proposed mass-flow-rate control system

In this section, the pressure control system with the conventional or proposed mass-flow-rate control system is described to demonstrate the effect of the proposed method in the pressure control system.

The symbols used in the pressure control system are listed in Table 3. Here, \(G_1\) is a constant value that converts the pressure derivative to the mass flow rate.

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_{fb, dif})</td>
<td>pressure FB controller (PI controller)</td>
</tr>
<tr>
<td>(v_{of, dif})</td>
<td>pressure reference of tank</td>
</tr>
<tr>
<td>(v_{of, dif})</td>
<td>pressure derivative reference</td>
</tr>
<tr>
<td>(G_1)</td>
<td>gain (constant value)</td>
</tr>
<tr>
<td>(n_{dif, ref})</td>
<td>mass-flow-rate difference reference</td>
</tr>
<tr>
<td>(m)</td>
<td>mass-flow-rate difference</td>
</tr>
<tr>
<td>(p)</td>
<td>pressure of tank</td>
</tr>
</tbody>
</table>
Effect of Mass-Flow-Rate Feedback Control in Pressure (Yui Takaki Shirato et al.)

Figure 8 illustrates a block diagram of the pressure control system. The mass-flow-rate FF control (Section 3) or the mass-flow-rate twin-drive system with AWU (Section 4.2) is applied as the mass-flow-rate control system.

6. Experimental validation

6.1 Experimental setup

6.1.1 Hardware setup of mass-flow-rate FF control system

The experimental setup of the mass-flow-rate FF control system is shown in Fig. 9. Because the unused port of the 5-port valve (FESTO, MPYE5-1/8-LF-010-B) was plugged in, it was used as a 3-port valve. A valve supplies air to a tank when the voltage is under the nominal value and exhausts air from the tank when it exceeds the nominal value. The supplied air passes from the pressure regulator to the tank, and the exhausted air passes from the tank to the ambient air. Flowmeters (Keyence, FD-A100, FD-V40A) measure the supplied and exhausted mass flow rate of air. The mass-flow-rate difference between the supplied mass flow rate and the exhausted mass flow rate results in the pressure derivative of the tank.

6.1.2 Hardware setup of mass-flow-rate twin-drive system

The experimental setup of the mass-flow-rate twin-drive system is illustrated in Fig. 10. The twin-drive system essentially requires two valves because it controls the mass-flow-rate difference mode and the mass-flow-rate sum mode. The supply valve constantly flows air from the pressure regulator to the tank, and the exhaust valve flows air from the tank to the ambient air. Flowmeters (Keyence, FD-A100, FD-V40A) measure the mass flow rate of air passing through valves. The mass-flow-rate difference between the supplied mass flow rate and the exhaust mass flow rate determines the pressure in the tank.

6.2 Experimental results of AWU for the twin-drive system

The experimental results indicated that the twin-drive system with the proposed AWU structure (Section 4.2) can satisfy R2 (19). The conditions of the experiment were as follows. A high sum-mode reference was provided because it was likely to cause saturation. Although it was not possible to apply the same pressure in the tank at 0 s because there was no pressure FB control, it was set at the value where two values could form the mass-flow-rate difference. In the case where the pressure of the tank is too high or too low, a supply valve or an exhaust valve cannot output a mass flow rate of 5 L/min with voltage limitations.

- limitation of input voltage: 5 - 7.5 V
- sum-mode reference: 60 L/min
- difference-mode reference: 5 L/min 1 Hz sine wave
- pressure of a regulator: 0.15 MPa
- pressure of ambient air: 0 MPa
- pressure of tank at 0 s: 0.102 MPa (without AWU), 0.125 MPa (with AWU)
- offset voltage \( v_{\text{off, set}} \): 0 V

The experimental results of the mass-flow-rate control by the twin-drive system without AWU (see Section 4.1) are shown in Fig. 9. Although the mass-flow-rate difference that determines the mass flow rate of each valve does not require accurate tracking, there is no issue when the mass-flow-rate sum in Fig. 11(b) does not follow the reference. Figure 11(c) shows that the voltage reference to the supply valve exceeds the limitation value that is, the system cannot address the saturation. Because the mass-flow-rate sum that decides the mass flow rate of each valve does not require accurate tracking, there is no issue when the mass-flow-rate sum in Fig. 11(b) does not follow the reference. Figure 11(c) shows that the voltage reference to the supply valve exceeds the limitation value that is, the system cannot address the saturation.

The experimental results of the mass-flow-rate control by the twin-drive system with the proposed AWU (see Section 4.2) are shown in Fig. 12 (identical to Fig. 11 in a previous report (19)). Figure 12(a) shows that the mass-flow-rate difference follows the reference. There is no issue when the mass-flow-rate sum does not follow the reference in Fig. 12(b). Figure 12(c) shows that the voltage references are limited by 7.5 V. In short, the proposed AWU for the twin-drive system can address the saturation and follow the difference mode.

6.3 Experimental results of pressure control system

In this section, the effect of the proposed method on the pressure control system is demonstrated.

The proportional-integral (PI) controller of the pressure control system was designed by pole placement, and the poles of the closed-loop system were at 1 Hz. Because the pneumatic driving system contains the time delay of air propagation, a high gain FB cannot maintain stability. The FB
controller of the proposed mass-flow-rate control system was designed using pole placement. The closed-loop poles were set at 50 Hz considering the time delay.

6.3.1 Time-domain results In this section, the time-domain experimental result with the proposed method that satisfies R3 is presented.

The conditions of the experiment are shown below.
- pressure reference: sine wave (amplitude: 0.001 MPa, frequency: 1 Hz)
- pressure of a regulator: 0.15 MPa
- pressure of a tank at 0 s: 0.125 MPa
- pressure of ambient air: 0 MPa
- limitation of input voltage (in the case of conventional system): 3 - 8.2 V
- limitation of input voltage (in the case of proposed system): 5 - 8 V
- reference of sum mode (in the case of proposed system): 60 L/min
- voltage $v_{off set}$ (in the case of proposed system): 2.5 V

Figure 13 illustrates the experimental results of the pressure PI control system with the conventional mass-flow-rate control system. Figure 13(a) shows that the pressure has large peaks. The pressure at 0 s (0.125 MPa) is illustrated as 0 MPa in this figure. As illustrated in Fig.13(b), the mass flow rate has an offset because of the modeling error and changes discontinuously. Figure 13(c) shows the reference for the valve input voltage change discontinuously. This is because the conventional system has an inverse model of a valve for dead zone compensation. The voltage reference to the valve was within the allowable voltage range that is, there was no saturation.

Figure 14 illustrates the experimental results of the pressure PI control system with the proposed mass-flow-rate control system. Figure 14(a) shows that the proposed system improves the tracking control performance of the pressure compared with the conventional system hence, R3 is satisfied. As illustrated in Fig.14(b), the mass-flow-rate difference follows the reference. The twin-drive system with the FB controllers achieves this, and the proposed AWU system avoids windup. Figure 14(c) shows that the voltage references changed continuously. Because the twin-drive system renders the output of a small mass-flow-rate difference possible with a high mass flow rate of each valve, the voltage reference is not affected by the dead zone.

To achieve precise mass-flow-rate and pressure tracking, $v_{off set}$ was set as 2.5 V. In the case where $v_{off set}$ was 0 V, the pressure had a small peak because the voltage reference was not smooth. In this case, the proposed AWU method could not limit the voltage reference using a precise maximum voltage range. Although the voltage reference was around the maximum voltage range, it was not the precise maximum voltage range. With $v_{off set}$ of 2.5 V, the sum-mode control output was limited by a constant value of 6.5 V because the difference-mode control output $v_{dif}$ was more than 1.5 V (see Fig. 7(b)). In this case, as the voltage reference could change smoothly. Thus, the pressure and the mass-flow-rate difference could achieve more precise tracking than when $v_{off set}$ was 0 V.

6.3.2 Frequency-domain data In this section, the frequency-domain data show that the proposed system achieves R4.

The conditions of the experiment were as follows. There was no saturation in either case.
- pressure reference: chirp sine (amplitude: 0.001 MPa, frequency: 0.1-50 Hz)
- pressure of a regulator: 0.15 MPa
- pressure of a tank at 0 s: 0.125 MPa
- pressure of ambient air: 0 MPa
- limitation of input voltage (in the case of conventional system): 3 - 8.2 V
- limitation of input voltage (in the case of proposed system): 5 - 8 V
- reference of sum mode (in the case of proposed system): 60 L/min
- voltage $v_{off set}$: 2.5 V

Figure 15(a) displays the coherence and Bode plot of the pressure PI control system with the conventional system. A coherence of 1 indicates that the system is linear, and a coherence of less than 1 implies the effect of noise or nonlinearity. The system maintains a coherence of approximately 1 at less
Effect of Mass-Flow-Rate Feedback Control in Pressure (Yui Takaki Shirato et al.)

than 1 Hz because of the pressure FB control. The conventional system cannot compensate for nonlinearity owing to the modeling error in the inverse model. The pressure bandwidth of the magnitude-frequency plot in Fig. 15(a) is less than 1 Hz. Figure 15(b) shows the coherence and Bode plot of the pressure PI control system with the proposed system. This system maintains a high coherence at less than 10 Hz.
The proposed system can compensate for the nonlinearity of the valve under the mass-flow-rate FB bandwidth. The magnitude-frequency plot in Fig. 15(b) indicates that the proposed method has a higher pressure bandwidth hence, R4 is satisfied.

7. Conclusion

The flow control of pneumatic valves is an important component of pneumatic control. Pneumatic valves have nonlinearities, such as dead zones, which can be compensated for twin-drive systems, however, they are prone to saturation of the control input. In this article, an AWU control method was proposed for a twin-drive system. Experimental results demonstrated that the proposed method can avoid saturation of the difference mode, which is important for pressure control, and it can achieve accurate flow control. In addition, in this study, the pressure control accuracy and pressure bandwidth were compared at low frequency using the conventional mass flow FF control method and the proposed mass flow twin-drive method with AWU. Moreover, the experimental results demonstrated that the proposed method can improve the pressure control bandwidth and linearity.

Acknowledgment

This research is supported by the Fluid Power Technology Promotion Foundation.

References


(19) Y. Shirato, W. Ohnishi, H. Fujimoto, Y. Hori, K. Sakata, and A. Hara, “Pro-
Yui Takaki Shirato (Member) received the B.E. and M.E. degrees from the University of Tokyo, Japan in 2021. Since April 2021, she has been with Nikon Corporation. Her research interest is high precision motion control of the pneumatic system.

Wataru Ohnishi (Member) received the B.E., M.S., and Ph.D. degrees from the University of Tokyo, Japan in 2013, 2015, and 2018, respectively. Presently, he is a research associate with the Department of Electrical Engineering and Information Systems, Graduate School of Engineering, the University of Tokyo. His research interest includes high-precision motion control. He is a member of the Institute of Electrical and Electronics Engineers.

Hiroshi Fujimoto (Senior Member) Hiroshi Fujimoto received a Ph.D. degree in the Department of Electrical Engineering from the University of Tokyo in 2001. In 2001, he joined the Department of Electrical Engineering, Nagaoka University of Technology, Niigata, Japan, as a research associate. From 2002 to 2003, he was a visiting scholar in the School of Mechanical Engineering, Purdue University, U.S.A. In 2004, he joined the Department of Electrical and Computer Engineering, Yokohama National University, Yokohama, Japan, as a lecturer and he became an associate professor in 2005. He is currently a professor at the University of Tokyo since 2010. He received the Best Paper Awards from the IEEE Transactions on Industrial Electronics in 2001 and 2013, Isao Takahashi Power Electronics Award in 2010, Best Author Prize of SICE in 2010, the Nagamori Grand Award in 2016, and the First Prize Paper Award IEEE Transactions on Power Electronics in 2016. His interests are in control engineering, motion control, nano-scale servo systems, electric vehicle control, motor drive, visual servoing, and wireless motors. He is a senior member of IEE of Japan and IEE. He is also a member of the Society of Instrument and Control Engineers, the Robotics Society of Japan, and the Society of Automotive Engineers of Japan.

Yoichi Hori (Fellow) Professor, Department of Electrical Engineering, Faculty of Science and Technology, Tokyo University of Science. Yoichi Hori received his B.S., M.S., and Ph.D. degrees in Electrical Engineering from the University of Tokyo, Tokyo, Japan, in 1978, 1980, and 1983, respectively. In 1983, he joined the Department of Electrical Engineering, The University of Tokyo, as a Research Associate. He later became an Assistant Professor, an Associate Professor and, in 2000, a Professor at the same university. In 2002, he moved to the Institute of Industrial Science as a Professor in the Information and System Division, and in 2008, to the Department of Advanced Energy, Graduate School of Frontier Sciences, the University of Tokyo. He retired in March 2021, and has been in current position since April. Professor Emeritus of the University of Tokyo. From 1991-1992, he was a Visiting Researcher at the University of California at Berkeley. His research fields are control theory and its industrial applications to motion control, mechatronics, robots, electric vehicles, etc. Recently, he has also been focusing on the research and promotion of wireless power transfer. He is a Life Fellow of IEEE (the Institute of Electrical and Electronics Engineers) and a past AdCom member of IES (Industrial Electronics Society). He has been the Treasurer of the IEEE Japan Council and Tokyo Section in a few years since 2001. He is now the Fellow members of IEEJ (the Institute of Electrical Engineers of Japan), JSASAE (the Society of Automotive Engineers of Japan), JSST (Japan Society of Simulation Technology), and so on. He was the President of the Industry Applications Society of the IEEJ, and WEVA (World Electric Vehicle Association), and the Director of Japan Automobile Research Institute (JARI). He is now the Vice-President of ISAE since June 2020, the President of Capacitors Forum, the Chairman of Motor Technology Symposium of JMA (Japan Management Association), and the Representative Director of NeV (Next Generation Vehicle Promotion Center), and so on. He is the winner of the Best Transactions Paper Award from the IEEE Transactions on Industrial Electronics in 1993, 2001 and 2013, of the 2000 Best Transactions Paper Award from IEEJ, and 2011 Achievement Award of IEEJ.

Koichi Sakata (Senior Member) received the B.S., M.S., and Ph.D. degrees in the Department of Physics, Electrical and Computer Engineering from Yokohama National University, Japan in 2006, 2008, and 2011, respectively. He was a research student at the University of Tokyo, Japan during April 2010 to March 2011. He was also a research fellow (DC2) of Japan Society for the Promotion of Science during April 2009 to March 2011. Since April 2011, he has been with Nikon Corporation. His interests are in motion control and nano-scale servo control. He works on the design of a motion control and high-precision servo control of large-scale stage. Dr. Sakata is a member of IEEE.

Atsushi Hara (Non-member) received the B.S. and M.S. degrees in mechanical engineering from Kyushu Institute of Technology, Kitakyushu, Japan, in 1998 and 2001, respectively. Since 2001, he has been with the Precision Equipment Company, Nikon Corporation, Yokohama, Japan. He is currently working on mechanical design and high-precision control for large-scale stages.