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

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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. Because a linear motor with a long stroke may cause a massive heat generation and a lack of thrust that limits the performance, 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. A major challenge for application results from the valve dead zone. 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. The merit of this feedforward (FF) approach is that there is no need for a fast-response flow meter. 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. 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. 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\(^{(16)}\). 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\(^{(19)}\). 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\(^{(19)}\). Case block outputs \(m_{\text{sup, in}}\) and \(m_{\text{exh, in}}\) using (1) and (2).

\[
\begin{align*}
\dot{m}_{\text{sup, in}} &= \begin{cases} 
\dot{m}_{\text{dif, ref}} & (\dot{m}_{\text{dif, ref}} > 0) \\
0 & (\dot{m}_{\text{dif, ref}} \leq 0)
\end{cases} \quad (1) \\
\dot{m}_{\text{exh, in}} &= \begin{cases} 
0 & (\dot{m}_{\text{dif, ref}} > 0) \\
-\dot{m}_{\text{dif, ref}} & (\dot{m}_{\text{dif, ref}} \leq 0)
\end{cases} \quad (2)
\end{align*}
\]

### Table 1. List of symbols of mass-flow-rate FF control

| Symbol | Definition |
|--------|------------|
| Inv    | inverse model of a valve |
| \(m_{\text{dif, ref}}\) | reference of mass-flow-rate difference |
| \(m_{\text{sup, in}}\) | mass-flow-rate input to an inverse model of a supply port |
| \(m_{\text{exh, in}}\) | mass-flow-rate input to an inverse model of an exhaust port |
| \(m_{\text{sup}}\) | mass flow rate of a supply port |
| \(m_{\text{exh}}\) | mass flow rate of an exhaust port |
| \(m_{\text{dif}}\) | mass-flow-rate difference |
| \(v_{\text{ref}}\) | voltage reference to a valve |
| \(v\) | input voltage of a valve |

### 3. Conventional mass-flow-rate FF control system\(^{(13)}\)

Because the conventional flow meter causes a long time delay to measure the mass flow rate, the dead zone was compensated with an inverse model without FB control. Here, a conventional control system with an inverse model for dead zone compensation is introduced\(^{(13)}\). This system is called the "mass-flow-rate FF control system" in this article, and it is distinct from the FB approach.

The symbols of mass-flow-rate FF control are listed in Table 1.

### 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 difference mode and the sum 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

| Symbols | Definition                                                                 |
|---------|---------------------------------------------------------------------------|
| \( C_{fb,sum} \) | FB controller of sum mode                                                 |
| \( C_{ff,sum} \) | FB controller of difference mode                                          |
| \( \dot{m}_{ref} \) | mass-flow-rate reference of difference mode                               |
| \( \dot{m}_{df} \) | mass flow rate of difference mode                                         |
| \( \dot{m}_{sum} \) | mass-flow-rate reference of sum mode                                      |
| \( \dot{m}_{sup} \) | mass flow rate of supply valve                                            |
| \( \dot{m}_{exh} \) | mass flow rate of exhaust valve                                           |
| \( v_{ref} \) | control output voltage of mode                                            |
| \( v_{ref, sup} \) | control output voltage of sum mode                                        |
| \( v_{ref, exh} \) | control output voltage of difference mode                                 |
| \( v_{ff, sum} \) | voltage reference to sum valve                                            |
| \( v_{ff, exh} \) | voltage reference to exhaust valve                                        |
| \( v_{sup} \) | input voltage to supply valve                                             |
| \( v_{exh} \) | input voltage to exhaust valve                                            |
| \( v_{min, sup} \) | minimum voltage of supply valve                                           |
| \( v_{min, exh} \) | minimum voltage of exhaust valve                                          |
| \( v_{max, sup} \) | maximum voltage of supply valve                                           |
| \( v_{max, exh} \) | maximum voltage of exhaust valve                                          |
| \( v_{sup, org} \) | sum of \( v_{sum} \) and \( v_{diff} \)                                   |
| \( v_{exh, org} \) | difference of \( v_{sum} \) and \( v_{diff} \)                           |
| \( v_{offset} \) | voltage to avoid the dead zone                                            |

| Symbols | Definition                                                                 |
|---------|---------------------------------------------------------------------------|
| \( C_{fb,sum} \) | part of FB controller of sum mode                                         |
| \( C_{ff,sum} \) | part of FB controller of sum mode                                         |
| \( v_{sum,min} \) | lower limit of \( v_{sum} \)                                             |
| \( v_{sum,max} \) | upper limit of \( v_{sum} \)                                             |

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).

\[
C_{fb,sum} = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}}
\]

The experimental results indicate that the twin-drive system satisfied 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

\[
v_{ref, sup} = v_{sup, org} + v_{offset}
v_{ref, exh} = v_{exh, org} + v_{offset}
\]

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.

\[
v_{sup} = \begin{cases} v_{min, sup} & \text{if } v_{ref, sup} \leq v_{min, sup} \\ v_{ref, sup} & \text{if } v_{min, sup} \leq v_{ref, sup} \leq v_{max, sup} \\ v_{max, sup} & \text{if } v_{max, sup} \leq v_{ref, sup} \end{cases}
\]

\[
v_{exh} = \begin{cases} v_{min, exh} & \text{if } v_{ref, exh} \leq v_{min, exh} \\ v_{ref, exh} & \text{if } v_{min, exh} \leq v_{ref, exh} \leq v_{max, exh} \\ v_{max, exh} & \text{if } v_{max, exh} \leq v_{ref, exh} \end{cases}
\]

The symbols 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 \( v_{df} \) and \( v_{sum} \) to \( v_{ref, sup} \) and \( v_{ref, exh} \) respectively, based on (4).

\[
\begin{bmatrix} \dot{m}_{sum} \\ \dot{m}_{df} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} \dot{m}_{sup} \\ \dot{m}_{exh} \end{bmatrix} \quad (3)
\]

\[
\begin{bmatrix} v_{sup, org} \\ v_{exh, org} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} v_{sum} \\ v_{df} \end{bmatrix} \quad (4)
\]

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

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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 \(C_{fb,sum}^m\) and AWU block. \(C_{fb1,sum}^m\) and \(C_{fb2,sum}^m\) are expressed as (9). Here, \(b_0\), \(b_1\), \(b_2\), \(a_1\), \(a_2\) are constant values in (8).

\[
C_{fb1,sum}^m = b_0 \\
C_{fb2,sum}^m = \frac{C_{fb,sum}^m}{C_{fb,sum}} - 1 = \frac{(a_1 - b_1/b_0)z^{-1} + (a_2 - b_2/b_0)z^{-2}}{1 + b_1/b_0z^{-1} + b_2/b_0z^{-2}} \quad (9)
\]

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 where the control outputs meet (10). Equation (10) is obtained by (4), (6), and (7). The previous \(v_{diff}\) to calculate the limitation on \(v_{sum}\). When \(v_{diff}\) is smaller than the minimum value or larger than the maximum value of \(v_{diff}\), \(v_{sum}\) is set to a constant value.

\[
\begin{align*}
\frac{v_{min,sup}}{v_{max,sup}} & \leq v_{sum} + v_{diff} \leq \frac{v_{max,sup}}{v_{min,sup}} \\
\frac{v_{min,exh}}{v_{max,exh}} & \leq v_{sum} - v_{diff} \leq \frac{v_{max,exh}}{v_{min,exh}}
\end{align*} \quad (10)
\]

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.

| Symbols | Definition |
|---------|------------|
| \(C_{fb}^m\) | pressure FB controller (PI controller) |
| \(v_{ref}\) | pressure reference of tank |
| \(v_{dsf}\) | pressure derivative reference |
| \(G_1\) | gain (constant value) |
| \(v_{diff,ref}\) | mass-flow-rate difference reference |
| \(m\) | mass-flow-rate difference |
| \(p\) | pressure of tank |
Experimental results of AWU for the twin-drive system without AWU (see Section 4.1) are shown in Fig. 11 (identical to Fig. 9 in an earlier report\textsuperscript{(19)}). Although the mass-flow-rate difference that determines the pressure must follow the reference, the mass-flow-rate difference in Fig. 11(a) does not follow the reference because of 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 AWU (see Section 4.2) are shown in Fig. 12 (identical to Fig. 11 in a previous report\textsuperscript{(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 mass-flow-rate sum 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 $v_{off, set}$: 0 V

The experimental results of the mass-flow-rate FF control by the twin-drive 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 $v_{sum}$ 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
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.

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Fig. 15. Complementary sensitivity function of pressure PI control system with the conventional/proposed mass-flow-rate control system
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