This paper focuses on the response deterioration of the force balance control system including the temperature control system due to the difference between heating and cooling speed. Our conventional method uses the limit error feedback method to suppress the windup of the temperature controller. The proposed method realizes the quick force balance control system using the equilibrium point movement controller. The experimental results show that the convergence time of the proposed method is faster than that of our conventional method, and the same response is obtained at different operating points.

**Keywords:** injection molding machine, non-linear, equilibrium point, thermal expansion, force control, mode conversion

1. Introduction

Portable electronic devices, such as smartphones, are becoming increasingly ubiquitous. The plastic parts of these devices should be manufactured with high accuracy, for weight and cost reduction. Figure 1 shows a typical injection molding machine for making such components; the machine is expected to fabricate molding products with high accuracy\(^{(1)-(4)}\). Accurate thickness of plastic molding products is necessary for optical components such as camera lens or light-guiding plates\(^{(5)-(6)}\).

Figure 2 shows a part of the mechanical structure of the molding machine. The force produced by the clamping of the mold contact surface affects the thickness accuracy of the corresponding plastic mold. For accurate molds, it is necessary to adjust the force balance. The clamping force applied to the mold contact surface is distributed across four metal bars, fastening both the molds. These metal bars are called tie bars. The force balance of each tie bar is related to the force balance of the mold contact surface.

The tie bar temperature control system\(^{(11)-(13)}\) \(^{(19)}\) slightly adjusts the tie bar’s length in response to thermal stress. In addition, the force balance of each tie bar is adjusted as well. Each tie bar has a heater, and the mold contact balance is adjusted by thermal expansion. This method, however, has two drawbacks.

First, the force-heater system is coupled, making the design and analysis difficult. In the field of bilateral/multilateral control, the Hadamard matrix is used to transform a system into its modal space\(^{(17)-(18)}\). Uncoupling is achieved by designing controllers in the modal space. Thus, in the tie bar temperature control system, the four temperatures and forces are transformed into the modal space using the Hadamard matrix.

Another drawback is that the system does not have a cooling device, and exhibits nonlinearity owing to the different rates of heating and cooling. A cooling device requires more space than a heater. The system studied in the present paper assumes a complete injection-molding machine. A typical injection-molding machine does not have sufficient space for a cooling device and it is difficult to attach. The response rates associated with heating and cooling are different and
this in turn triggers nonlinearity in the corresponding control system. The temperature control system is incorporated into the force balance control system. In the control system, a windup occurs by slow natural cooling in the inner loop. In the field of motor control, the limit error feedback method is used to suppress windups, depending on the current limit. This method compensates for the windups caused by the current control limit in the inner loop. The tie bar temperature control system has an anti-windup control feature based on the limit error feedback method. However, this method is slow because it depends on natural cooling that has a slow response speed.

This paper proposes a force balance controller that does not use cooling in the transient state. The proposed method achieves the quick force balance control system that does not depend on the cooling rate in order to control the molding product’s thickness.

2. Injection Molding Machine with Heaters

The clamping device in the injection-molding machine is shown in Fig. 2. Two molds in the clamping device are pressed to maintain pressure on the resin. When the clamping device presses the molds, the pressing force is distributed across the four metal bars, which are called tie bars. The force on each of the tie bars affects the force on the mold surface. The tie bar’s lengths change slightly with temperature; this is mediated by the heaters that are wound around each tie bar. Changing the tie bars’ lengths changes the force on the mold contact surface as well. The injection-molding machine controls the force balance of the mold contact surface via the heaters around the tie bars.

The actual machines that are used in our experiments have strain gauges, band heaters, and thermocouples. The band heater and thermocouple are integrated. The strain gauges are installed away from the heaters to avoid the influence of heater and thermocouple on the clamping force. The clamping device separates the heater model and tie bar model for the purposes of modeling.

2.1 Heater Model The heater model \( P_f \) captures the relationship between the current \( I \) and temperature \( T_h \) of a heater. The thermal network method is widely used in the field of bilateral temperature control. The thermal propagation system constructed in this study is shown in Fig. 3. The plant parameters quantify the thermal resistance \( R_h \) from the heat source to the heater, the thermal resistance \( R_o \) from the outside air to the heater, and the heat capacity \( C_T \) near the heater. Variable \( U \) is defined as input of sign function. The difference between the heater temperature and the outside air temperature is added to the heating of the heater, resulting in the heat flow related to the heater temperature. The heater does not feature cooling. The sign function in the block diagram cuts the cooling command input. The function of the heater model is shown as

\[
T_h = \begin{cases} 
\frac{R_o + R_h T_h}{R_o + R_h} C_T S + R_o T_h (0 \leq I) \\
\frac{R_o T_h}{R_o + R_h} (I < 0)
\end{cases}
\]  

The sign function is zero when the argument is negative; consequently, the heater’s temperature is allowed to drop until it reaches the outside air temperature. The cooling behavior is modeled as first-order lag.

2.2 Tie Bar Model The tie bar model \( P_f \) captures, for each heater, the relationship between the heater temperature \( T_h \) and forces \( F \) applied to the four tie bars during clamping. When the heater temperature changes, the tie bar’s temperature away from the heater changes gradually. Temperature change in any of the heaters incurs a force change in all the tie bars. The tie bar model couples the heaters’ temperatures and forces applied to the tie bars. Therefore, the tie bar model \( P_f \) is described by a \( 4 \times 4 \) matrix-like transfer function. The tie bar model is defined as

\[
F = P_f(s) T_h
\]

\[
\begin{bmatrix}
F_1 \\
F_2 \\
F_3 \\
F_4
\end{bmatrix} = \begin{bmatrix}
P_{f(1,1)} & P_{f(1,2)} & P_{f(1,3)} & P_{f(1,4)} \\
P_{f(2,1)} & P_{f(2,2)} & P_{f(2,3)} & P_{f(2,4)} \\
P_{f(3,1)} & P_{f(3,2)} & P_{f(3,3)} & P_{f(3,4)} \\
P_{f(4,1)} & P_{f(4,2)} & P_{f(4,3)} & P_{f(4,4)}
\end{bmatrix} \begin{bmatrix}
T_{h1} \\
T_{h2} \\
T_{h3} \\
T_{h4}
\end{bmatrix} + \begin{bmatrix}
\text{offset} \\
\text{error}
\end{bmatrix}
\]

The subscripts, 1 to 4, number the tie bars.

3. Force Balance Control using Tie Bar Heaters

The plant model takes the heater current as an input and outputs the heater temperature and force applied to the tie bar. The control system for the tie bar temperature control is shown in Fig. 4. The model’s variables capture the force balance command \( F_b \), force balance response \( F_b \), heater temperature command in modal space \( T_{h1} \), heater temperature command \( T_{h2} \), offset of the temperature error \( T_e \), and gain of the anti-windup controller \( K_f \). The blocks depict the force balance controller \( C_f \), transformation matrix \( M \), temperature controller \( C_T \), heater model \( P_f \), and tie bar model \( P_f \). The variable \( K_p \) in \( C_f \) is the proportional gain of the force balance control. The variable \( K_i \) in \( C_f \) is the integral gain of the force balance control. The force control system is the main loop including the temperature control system. This control system is transformed into the modal space for uncoupling. The anti-windup controller is used for considering its nonlinearities.

3.1 Plant Representation in Modal Space This section explains uncoupling by transformation into the modal space. The temperature control system is sufficiently faster than the force control system. The transfer function of the temperature control system becomes approximately 1. Therefore, only the tie bar model is considered for uncoupling.

The tie bar model is described by a \( 4 \times 4 \) matrix-like transfer function, with 16 arguments. The clamping device is designed to be symmetric with respect to up and down, left and right directions. The 16 variables of the tie bar model \( P_f \) are
The amount of force change in the heated tie bar itself in the vertical and diagonal directions exhibit the same coupling. Similarly, the tie bars categorized into four groups. The shape of each tie bar is the same. The change in the tie bar force owing to its own thermal expansion is the same across all the tie bars as well. When the tie bars are heated, the tie bars in the horizontal direction exhibit the same coupling. Similarly, the tie bars in the vertical and diagonal directions exhibit the same coupling. The amount of force change in the heated tie bar itself is defined as \( A_1 \), horizontal coupling is defined as \( A_2 \), vertical coupling is defined as \( A_3 \), and diagonal coupling is defined as \( A_4 \). The tie bar model is converted as described by

\[
P_f(s) = \begin{bmatrix} A_1 & A_2 & A_3 & A_4 \\ A_2 & A_1 & A_4 & A_3 \\ A_3 & A_4 & A_1 & A_2 \\ A_4 & A_3 & A_2 & A_1 \end{bmatrix}
\]

Equation (3) reveals non-zero non-diagonal elements that indicate coupling between the forces and heaters. Therefore, conversion into the modal space is used for alleviating such coupling. The transformation matrix for such a modal-space transformation is a 4 \( \times \) 4 matrix, known as the Hadamard matrix. The Hadamard matrix \( M \) is given by

\[
M = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}
\]

After the plant model is converted into the modal space, it is described by

\[
M^{-1} P_f(s) M = \begin{bmatrix} P_f(1) & 0 & 0 & 0 \\ 0 & P_f(1) & 0 & 0 \\ 0 & 0 & P_f(2) & 0 \\ 0 & 0 & 0 & P_f(3) \end{bmatrix}
\]

The variables are the total force balance \( F_t \), vertical force balance \( F_v \), horizontal force balance \( F_h \), and distortion force balance \( F_d \). The variables \( F_1 \) to \( F_4 \) are elements of \( F \). Each state in the modal space is controlled independently by designing a control system in this modal space.

### 3.2 Anti-Windup Control for Cooling Command

This section describes nonlinearity suppression using anti-windup. The underlying problem is excessive integration owing to the slow cooling rate. In the approach described in this paper, excessive integration is suppressed by feeding back the cooling amount to the integrator of the force balance controller.

The cooling system uses only slow natural cooling. Even if the cooling command is given, the system does not cool fast naturally, resulting in a slow convergence as the integrator integrates excessively. By feeding back the cooling amount to the integrator, excessive cooling commands are suppressed. However, if the cooling amount is feedback to the integrator as such, the entire cooling amount is canceled, and natural cooling does not take place. Therefore, feedback is activated only when the cooling amount exceeds a constant amount \( T_c \), and the cooling command value is constant. Both natural cooling and anti-windup are realized by the modal conversion of the value obtained by adding a constant to the temperature error and feedback to the integrator of the force balance controller.

The force balance error \( F_{be} \), heater temperature response \( T_h \), and constant value \( T_c \) are defined as the input to the anti-windup system. When the temperature error \( T_e \) is below \( -T_c \), the system suppresses windup. The temperature error \( T_e \) when \( T_e \) is below \( T_c \) is given by

\[
T_e = M^{-1} \left[ \frac{1}{s} (K_1 F_{be} - K_1 M (T_c + T_e)) - K_1 F_{be} \right] - T_h
\]

\[
= -M^{-1} \frac{1}{s} K_1 F_{be} - M^{-1} \frac{1}{s} K_1 M T_e
\]

\[
- M^{-1} \frac{1}{s} K_1 M T_c - M^{-1} K_1 F_{be} - T_h \cdot \cdot \cdot \cdot \cdot (7)
\]
The modal conversion of $F_{be}$ defines $F_e$ by

$$F_{be} = MF_e = \begin{bmatrix} F_{bet(1)} & F_{bet(2)} & F_{bet(3)} & F_{bet(4)} \end{bmatrix}^T$$

Therefore, the temperature error $T_e$ is given by

$$\frac{1}{s}K_iT_e + T_e = -\frac{1}{s}K_pF_e - \frac{1}{s}sK_iT_e - K_pF_e - T_h$$

$$T_e = -\frac{K_p}{s + K_i}F_e - \frac{K_i}{s + K_i}T_e - \frac{s}{s + K_i}T_h$$

Equation (9) shows that when the cooling command is relayed, the temperature error converges to $-(K_i/K_p)F_e - T_c$. The bandwidth is designed by $K_i$. When the cooling command is relayed, the temperature command always attains a slightly lower value than the response. Both natural cooling and anti-windup are implemented in this system. In this paper, this control system is defined as our conventional method.

### 3.3 Numerical Simulation Results
This section describes the simulation of the force balance control with anti-windup. The goal of the force balance controller with anti-windup is to suppress excessive integration caused by slow natural cooling.

If the heater temperature is the same as the outside temperature, natural cooling does not occur. The heater temperature has to rise above the outside temperature before the controller starts to use natural cooling. In this simulation, the outside temperature is set to 30°C, and initial temperature for each heater is 80°C. The simulation results for the force balance $F_b$ and heater's temperature $T_b$ are shown in Fig. 5. In these simulations, the vertical force balance $F_v$ is increased to 15 kN. The values of the other parameters are: $K_p = 3.6$, $K_i = 0.012$, $K_l = 0.1$, and $T_c = [3 \ 3 \ 3 \ 3]^T$. The more stable gains are determined by trial and error.

After the cooling command is relayed, the temperature converges to a value that is smaller than the response suggesting that the anti-windup controller is functioning properly.

This result further shows that the force balance response is affected by slow natural cooling, which is the cooling method utilized by the control system. The drawback of the conventional method is that the heater requires heating before exerting control. In addition, the response rate is slow because it is necessary to wait for slow natural cooling.

### 4. Quick Force Balance Control
The anti-windup control of the conventional method alleviates the nonlinearity-dependent deterioration of the force balance controller. However, the response speed of the control system is slow because the inner loop contains nonlinear elements. The proposed method shifts the control equilibrium point using total balance, which is one of the four force balances.

#### 4.1 Equilibrium Point Movement Controller
This section explains the improvement in control performance due to the control equilibrium point shift. As it uses natural cooling, the tie bar temperature control encounters problem. The natural cooling is slow, and heating is necessary before starting the control system because its temperature does not drop below the outside temperature. In this study, relative cooling is realized, by heating other tie bars instead of cooling the bar of interest.

Attention should be paid to the total balance in the force balance system. The total balance is the sum of the pressing forces on the molds; therefore, it does not affect the thickness balance of the molding parts. Several injection-molding machines feature mechanisms for adjusting the overall force. Therefore, the influence of the total balance on the thickness balance of the molded product is small. When the total balance command increases, the control system cools all the tie bars to reduce the distance between both the molds. When the total balance command decreases, the control system heats all the tie bars to increase the distance between the molds. When the cooling command is relayed, the control equilibrium point is shifted to heat all the tie bars by lowering the total balance, thereby canceling the cooling command. The control system heats the other tie bars instead of cooling the bar of interest and thus creates relative cooling; this is realized using the total balance as a control equilibrium point.

The block diagram that shows the control equilibrium point shift is shown in Fig. 6. The relevant variables are the natural cooling temperature $T_a$ and gain of the equilibrium point shift controller $K_a$. The sign function in Fig. 6 passes only the cooling command. Only the cooling command is extracted from the temperature error using the sign function. The cooling commands of all the tie bars are summed and multiplied by the gain $K_a$ and then accumulated. The control equilibrium point is shifted by imparting certain amount of cooling to the total balance. If the control equilibrium point is continuously lowered, the heater temperature will continue to rise toward the maximal temperature. Therefore, if the strong cooling command is not generated, a constant value is continuously input; thus, the overall temperature slowly decreases. The equilibrium point shift compensates for the excess integration; therefore, the anti-windup mechanism introduced in the previous section is not necessary.

#### 4.2 Analysis of Force Balance
The temperature error $T_e$ for $T_e < 0$ is given by

![Fig. 5. Simulation results of conventional method](image_url)
Quick Force Balance Control for Injection Molding Machine (Yuki Matsui et al.)

Equilibrium Point Movement Controller

\[
F_b^* = \begin{bmatrix} F_{b1}^* \\ F_{b2}^* \\ F_{b3}^* \\ F_{b4}^* \\ F_{b5}^* \end{bmatrix}
\]

\[
\begin{bmatrix} 1 \\ -K_p \\ -K_p \end{bmatrix}
\]

\[
T_b = T_{na} + \text{Sign Function (through only existing amount)}
\]

\[
\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}
\]

\[
M = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix}
\]

\[
T_b^* = \begin{bmatrix} T_{b1}^* \\ T_{b2}^* \\ T_{b3}^* \\ T_{b4}^* \end{bmatrix}
\]

\[
P_{Fb} = \begin{bmatrix} P_{Fb1} \\ P_{Fb2} \end{bmatrix}
\]

\[
F = \begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix}
\]

\[
F_b = \begin{bmatrix} F_{b1} \\ F_{b2} \end{bmatrix}
\]

Fig. 6. Block diagram of the proposed quick force balance control

\[
T_e = M^{-1} \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} T_{be} \\ T_{hb} \end{bmatrix} + C_f \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}
\]

\[
T_e = M^{-1} C_f F_b - M^{-1} C_f \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}
\]

\[
\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} K_p \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}
\]

\[
\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} K_p \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}
\]

\[
\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} K_p \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}
\]

Equation (17) captures the effect of \( T_{be} \) and \( T_{hb} \) cooling direction as \( T_e \) converges to zero; it shows that \( T_{be} \) converges to \( T_{hb} \). While the equilibrium point shift controller uses the total balance to suppress the cooling command, the temperature command converges at a point that is lower than the response by \( T_e \). In the proposed method, both cooling command suppression and natural cooling are possible. The other three balances, that are the second to fourth elements of each input and output vectors, are given by

\[
\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} K_p \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}
\]

\[
\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} K_p \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}
\]

\[
\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} K_p \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}
\]

Equation (19) indicates that the equilibrium point shift controller does not affect the three balances other than the total balance. Vertical, horizontal, and distortion force balances all converge to the command without using slow natural cooling. The proposed controller linearize the control system by using only heating.

4.3 Numerical Simulation Results

This section describes the results of the simulations of the force balance control with the equilibrium point shift controller. In the conventional method, the heater temperature has to rise above the outside temperature before the controller starts to use natural cooling. In the proposed method, as the cooling command is suppressed, overheating before starting the control becomes unnecessary. Parameter values are \( K_p = 3.6 \), \( K_i = 0.012 \), \( K_a \)
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Fig. 7. Simulation results of proposed method

= 0.05, and \( T_a = 0.1 \). The simulation results are shown in Fig. 7.

5. Experimental Results

5.1 Experimental Conditions Each tie bar features a heater, thermocouple, and strain gauge. In this paper, the injection-molding machine repeatedly clamps the mold every 10 s. In addition, the strain gauges measure the forces during the clamping times. Force balances and heater temperatures, when only the vertical force balance command reaches 15 kN, are shown for all experiments. In this paper, three validation experiments are performed.

First, the conventional method using the anti-windup control is confirmed for the vertical balance command response. In this experiment, the heaters’ temperatures are between 70 to 80 °C before starting control to enable natural cooling.

Second, the proposed method using the equilibrium point shift is validated for the vertical balance command response. In our experiment, the heaters’ temperatures are near room temperature when the control starts. The parameter values of the control gains (\( K_p \) and \( K_i \)) for the force balance controller are the same as in the first experiment.

The third experiment uses the same method and parameters as used in the second experiment. In addition, the initial state of the equilibrium point is changed by changing the initial temperature. The control parameter values for the three experiments from first to third are listed in Table 1. The bandwidth of the temperature control system needs to sufficiently faster than the force balance control system. Simulation analysis confirms that the rate between two systems needs to over 5 times. In this paper, the bandwidth is set to 10.3 times.

5.2 Experimental Results The command response for the conventional method using the anti-windup in Fig. 4 is shown in Fig. 8. The temperatures of heater 2 and heater 4 are raised by the heaters, and the temperatures of heater 1 and heater 3 decrease by natural cooling. The cooling command

Table 1. Parameters of the experiment

| Parameter                          | Value |
|------------------------------------|-------|
| Force balance proportional gain    | 3.6   |
| Force balance integral gain        | 0.012 |
| Offset of temperature error        | 3°C   |
| Anti-windup gain                   | 0.1   |
| Natural cooling coefficient        | 0.1°C |
| Equilibrium point movement gain    | 0.05  |

Fig. 8. Experimental results for force balance and heater temperature using conventional method

Fig. 9. Experimental results for force balance and heater temperature using proposed method

for heaters 1 and 3 is controlled at a point slightly below the response by the anti-windup. The command responses for the proposed method using the equilibrium point shift in Fig. 6 are shown in Figs. 9 and 10. The proposed method is not
required to wait for slow natural cooling because cooling is converted into heating by moving the equilibrium point. In addition, the heater temperature is not required to rise before the controller starts.

Figure 11 shows a comparison of the vertical balance responses of Figs. 8 and 9. In addition, Fig. 11 shows the convergence time reaching 90% of the command. The convergence time of the conventional method is 8.9 min and that of the proposed method is 5.6 min. The convergence time of the proposed method is reduced by 63% as compared to the conventional method. Figure 12 shows the comparison of the vertical balance responses of Figs. 9 and 10. Figure 12 shows that the proposed method has the same response even when the initial equilibrium point is different. This result indicates that the equilibrium point movement controller linearizes the control system by working on the linear region.

6. Conclusion

This paper realizes a quick force balance control method based on the equilibrium point movement method. This method uses only heating during the transient state. Natural cooling is realized after response stabilization. The convergence time of the proposed method is 63% of our conventional method, and experimental results show that the same response is obtained at different operating points.

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