Double Electrostatic Suspension System*

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Abstract
Multiple electrostatic suspension suspends multiple floaters with a single power amplifier. The controllability of double parallel suspension was previously analyzed and the conditions to be controllable were shown. To ensure the analytical results, single-DOF suspension systems were fabricated, and a double parallel electrostatic suspension system consisted of these systems. The feasibility of double parallel electrostatic suspension was demonstrated experimentally. Dynamic characteristics of double parallel electrostatic suspension were studied based on step responses and frequency responses.

Key words: Electrostatic Suspension, Multiple Suspension, Motion Control, Mechatronics

1. Introduction
Electrostatic suspension is one of the noncontact suspensions. Noncontact suspension technique is required in many industrial fields such as semiconductor manufacturing. In such field, contamination generated by mechanical contact should be avoided strictly in order to reduce production loss. Contact makes deflection of the wafer. This problem becomes more critical when wafers become larger. Glass plates for flat panel display become also larger.

Magnetic suspension and air bearing are useful and principal methods of noncontact suspension. However, magnetic suspension is limited to objects of ferromagnetic and diamagnetic materials. Air bearings are categorized into air cushion, ultrasonic and Bernoulli chuck. Ultrasonic is used to suspend only small targets (1) because of weak force. Bernoulli chuck (2) and air cushion (3)(4) have more strong force. However, they need compression gas, and special mechanism when they are used in vacuum. Electrostatic suspension has several advantages over these methods. It is easy to be miniaturized. It works even in the vacuum (5)(6) and also ferromagnetic field. Therefore, we focus on electrostatic suspension.

In order to achieve electrostatic suspension, voltage control system is necessary. The voltage applied to electrodes reaches several kilo volts in suspending wafers (7). The required voltage is determined by the suspension gap and the weight of the wafer. On the other hand, the applicable voltage is limited by the electrical breakdown strength. In practical use, voltage amplifier with high-voltage output increases total cost because such amplifiers are used for specific purposes. Several researches considered this problem. One of them is ON-OFF control (7). As another method, we have suggested voltage control using variable capacitor (8).

Recently we have proposed new concept that aims to reduce the cost of electrostatic suspension system. This concept is called multiple electrostatic suspension (9)(12). Normally, a sensor and an amplifier are needed for each actuator to suspend an object stably. However,
in the proposed system, a single amplifier can control several actuators simultaneously. The concept of multiple suspension system comes from multiple magnetic suspension\cite{13,14}. Magnetic suspension and electrostatic suspension have similar mathematical models. Their mathematical models are also similar to those of multiple inversed pendulums. When this system is installed, it will reduce the number of amplifiers so that the cost will be reduced.

To ensure the feasibility of the proposed system, we fabricated apparatuses of single-degree-of-freedom electrostatic suspension, and made up a double parallel electrostatic suspension system with two apparatuses.

In this paper, the basic concept and the property of controllability are discussed in Section 2. In Sections 3 and 4, control system and experimental setup of multiple electrostatic suspension system are explained. The realization of double parallel electrostatic suspension and its dynamics characteristics are presented in Section 5.

2. Theoretical Analysis

2.1 Basic model

In the basic model of electrostatic suspension system, only vertical motion is considered for simplicity as shown in Fig. 1. Electrodes and the object to be suspend, which is called a floator, constitute a capacitance

\[ C_a = \frac{\varepsilon S}{2D}, \]

where \( \varepsilon \) is permittivity, \( S \) is the area of electrode and \( D \) is the gap between the electrodes and the floator. In this state, electrostatic force \( f_e \) is given by

\[ f_e = \frac{\varepsilon SV^2}{8D^2}, \]

where \( V \) is applied voltage. The steady-state values of the gap and the voltage are defined by \( D_0 \) and \( V_0 \), respectively. At the steady state,

\[ mg = \frac{\varepsilon SV_0^2}{8D_0^2} \]

is satisfied. From Eqs. (2) and (3), the linearized equation of motion is obtained as
\begin{equation}
mx'' = \frac{\varepsilon SY_0^2}{4D_0} x + \frac{\varepsilon SV_0}{4D_0} v = k_x x + k_v v,
\end{equation}

where $k_x$ is force to displacement factor, and $k_v$ is force to voltage factor. The state equation becomes

\begin{equation}
\dot{x} = Ax + bv,
\end{equation}

\begin{equation}
\frac{d}{dt} \begin{bmatrix} x \\ \dot{x} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \end{bmatrix} + \begin{bmatrix} 0 \\ b \end{bmatrix} v.
\end{equation}

where

\begin{equation}
a_{21} = \frac{k_x}{m} \left( \frac{\varepsilon SY_0^2}{4mD_0} \right),
\end{equation}

\begin{equation}
b = \frac{k_v}{m} \left( \frac{\varepsilon SV_0}{4mD_0} \right).
\end{equation}

Note that damping force acting in the floator is neglected at this stage to simplify the analysis. As well known, this state model is controllable so that it can be stabilized by state feedback (PD control).

2.2 Double parallel electrostatic suspension with parallel connection

Multiple electrostatic suspension system can be classified according to the connection of electrodes: series or parallel. An essential difference in controllability between them was shown analytically. Figure 2 shows a schematic view of a double parallel electrostatic suspension system with parallel connection. The electrodes are connected to the amplifier in parallel. In this work, the multiplicity is fixed to two for simplicity of calculation and basic theoretical analysis. The superscript of each parameter shows the parameter belongs to the specified suspension system e.g. $m^{(1)}$ is the mass of the floator of suspension system (1). The equations of motion of the double parallel suspension system with parallel connection are
\[ m^{(1)} x^{(1)} = k^{(1)} x^{(1)} + k^{(1)} v, \]  
\[ m^{(2)} x^{(2)} = k^{(2)} x^{(2)} + k^{(2)} v. \]  

The same control voltage is applied to each suspension system. The state equation is given by
\[ \dot{x}_p = A_p x_p + b_p v, \]  
where
\[ x_p = \begin{bmatrix} x^{(1)} & \dot{x}^{(1)} & x^{(2)} & \dot{x}^{(2)} \end{bmatrix}^T, \]  
\[ A_p = \begin{bmatrix} A^{(1)} & 0 \\ 0 & A^{(2)} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ a^{(1)}_{21} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & a^{(2)}_{21} & 0 \end{bmatrix}, \]  
\[ b_p = \begin{bmatrix} b^{(1)} \\ b^{(2)} \end{bmatrix} = \begin{bmatrix} 0 & b^{(1)} & 0 & b^{(2)} \end{bmatrix}^T. \]  

This equation is similar to that of current-controlled double parallel multiple magnetic suspension system\(^{(13)}\).

2.3 Double parallel electrostatic suspension with series connection

Figure 3 shows a schematic view of the double parallel electrostatic suspension system with series connection. The electrodes are connected to amplifier in series. The equation of motion is
\[ m^{(k)} \ddot{x}^{(k)} = k^{(k)} x^{(k)} + k^{(k)}_v v^{(k)} \]  
\[ (k = 1 \text{ or } 2), \]  
where \( v^{(k)} \) is voltage applied to suspension system \((k)\). In contrast with the parallel-connected system, the voltage applied to each suspension system is different from output voltage of the amplifier \( V_a = V_{a0} + v_a \). Each voltage is presented as the sum of bias and deviation from it as
\[ V^{(1)} = V^{(1)}_0 + v^{(1)} \]

![Fig. 3 Schematic view of the double series electrostatic suspension system with series connection.](image-url)
\[ V^{(2)} = V_0^{(2)} + v^{(2)} \]

\[
V^{(1)} = \frac{C^{(1)}}{C^{(1)} + C^{(2)}} V_a
\]

\[ = V_0^{(1)} + r^{(1)}r^{(2)} V_a \left( \frac{x^{(1)}}{D_0^{(1)}} - \frac{x^{(2)}}{D_0^{(2)}} \right) + r^{(2)} V_a, \quad (16) \]

\[ V^{(2)} = \frac{C^{(1)}}{C^{(1)} + C^{(2)}} V_a \]

\[ = V_0^{(2)} + r^{(1)}r^{(2)} V_a \left( \frac{x^{(1)}}{D_0^{(1)}} - \frac{x^{(2)}}{D_0^{(2)}} \right) + r^{(1)} V_a, \quad (17) \]

where

\[ r^{(k)} = \frac{C^{(k)}}{C^{(1)} + C^{(2)}} \quad (k = 1 \text{ or } 2). \quad (18) \]

These equations show that voltage applied to each suspension system depends on each capacitance formed by suspension system. The state equation is given by

\[ \dot{x}_p = A_s x_p + b_s v_a, \quad (19) \]

where

\[
A_s = \begin{bmatrix}
0 & 1 & 0 & 0 \\
-\sigma^{(1)}b^{(1)} & 0 & \gamma^{(1)}b^{(1)} & 0 \\
0 & 0 & 1 & 0 \\
\gamma^{(2)}b^{(2)} & 0 & -\sigma^{(2)}b^{(2)} & 0
\end{bmatrix}, \quad (20)
\]

\[
b_s = \begin{bmatrix} 0 & r^{(2)}b^{(1)} & 0 & r^{(1)}b^{(2)} \end{bmatrix}^T, \quad (21)
\]

\[
\sigma^{(k)} = \frac{r^{(k)}V^{(k)}_0}{D_0^{(k)}}, \quad (k = 1 \text{ or } 2), \quad (22)
\]

\[
\gamma^{(1)} = \frac{r^{(1)}V^{(1)}_0}{D_0^{(2)}}, \quad (23)
\]

\[
\gamma^{(2)} = \frac{r^{(2)}V^{(2)}_0}{D_0^{(1)}}, \quad (24)
\]

The most different point from the parallel-connected system is that cross-coupling terms exist in matrix \( A_s \).

2.4 Controllability

The controllability of single-input system is determined by the determinant of the controllability matrix. First, the controllability matrix of double parallel electrostatic suspension with parallel connection is given by
\[
M_C^p = \begin{bmatrix}
0 & b^{(1)} & 0 & a_{21}^{(1)} b^{(1)} \\
b^{(1)} & 0 & a_{21}^{(1)} b^{(1)} & 0 \\
0 & b^{(2)} & 0 & a_{21}^{(2)} b^{(2)} \\
b^{(2)} & 0 & a_{21}^{(2)} b^{(2)} & 0
\end{bmatrix}.
\] (25)

Its determinant becomes
\[
\det M_C^p = \{b^{(1)} b^{(1)} (a_{21}^{(1)} - a_{21}^{(2)})\}^2.
\] (26)

The condition to be controllable is
\[
a_{21}^{(1)} \neq a_{21}^{(2)}.
\] (27)

From Eqs (7) and (27), the condition becomes
\[
\frac{\varepsilon_0^{(1)} V_0^{(1)} x^2}{4m^{(1)} D_0^{(1)}} \neq \frac{\varepsilon_0^{(2)} V_0^{(2)} x^2}{4m^{(2)} D_0^{(2)}}.
\] (28)

Since Eq. (3) is satisfied by each suspension system, the condition (28) becomes
\[
D_0^{(1)} \neq D_0^{(2)}.
\] (29)

It indicates that different levitation gaps are important to achieve the double parallel electrostatic suspension with parallel connection.

On the other hand, the controllability matrix of series-connected system is given by
\[
M_C^s = \begin{bmatrix}
0 & M_C^s_{11} & 0 & M_C^s_{12} \\
M_C^s_{11} & 0 & M_C^s_{12} & 0 \\
0 & M_C^s_{31} & 0 & M_C^s_{32} \\
M_C^s_{31} & 0 & M_C^s_{32} & 0
\end{bmatrix},
\] (30)

where
\[
M_C^s_{11} = \rho^{(2)} b^{(1)},
\] (31)
\[
M_C^s_{12} = \rho^{(1)} \rho^{(1)} b^{(1)} b^{(2)} + \rho^{(2)} b^{(1)} (a_{21}^{(1)} - b^{(1)} \sigma^{(1)}),
\] (32)
\[
M_C^s_{31} = \rho^{(1)} b^{(2)},
\] (33)
\[
M_C^s_{32} = b^{(1)} b^{(2)} \rho^{(2)} + \rho^{(1)} b^{(2)} (a_{21}^{(2)} - b^{(2)} \sigma^{(2)}).
\] (34)

Its determinant becomes
\[
\det M_C^s = \left\{(\rho^{(1)} \rho^{(2)} b^{(1)} b^{(2)} (a_{21}^{(1)} - b^{(1)} \frac{V_0^{(1)}}{D_0^{(1)}}) - (a_{21}^{(2)} - b^{(2)} \frac{V_0^{(2)}}{D_0^{(2)}}))^2\right\}.
\] (35)
From Eqs. (11) and (12), we can obtain

\[
D_0^{(k)} V_{ba}^{(k)} = b^{(k)} \frac{P_0^{(k)}}{D_0^{(k)}} (k = 1 \text{ or } 2).
\]  

(36)

Because of Eq. (36), Eq. (35) becomes zero. It means that the serial connected system is uncontrollable. Thus, we carried out experiments on parallel-connected system.

3. Experimental Setup

3.1 Apparatus

Figure 4 and 5 show a fabricated single-DOF seesaw-type electrostatic suspension system. It mainly consists of electrodes, a force target, a displacement sensor for detecting the gap between the electrodes and the force target, a cross spring made of phosphor bronze, and a seesaw suspended by the cross spring. In order to avoid the interference of the other degrees-of-freedom motions and to minimizing friction, the cross spring is used to guide the motion of the seesaw into a single-DOF rotation. The effects of stiffness and damping due to the cross spring will be discussed in the next section.

We can adjust the combination of the weight (gravitational force) to be suspended and the inertia of the seesaw flexibly by additional mass (counter balancer) as shown in Fig. 5. In this system, the equilibrium condition corresponding to Eq. (3) can be obtained by the balance of momentum. Therefore, the condition to be controllable system is given by just Eq. (27) and not Eq. (29) generally. The rotational motion of the seesaw can be treated as translation by linearization such as \( x = l \theta \) in the specified range, where \( l \) is length of the seesaw arm. The range is determined as \( \theta \theta \approx \tan \theta \) with an error of less than 5% so that the linear range of displacement in the apparatus is about ±2 mm.

In this apparatus, the coefficients of matrixes \( A \) and \( b \) become

![Fig. 4 Photo of single-DOF seesaw-type electrostatic suspension system.](image1)

![Fig. 5 Schematic view of single-DOF seesaw-type electrostatic suspension system.](image2)
\[ a_{21}^{(k)} = l^2 \frac{k_{s}^{(k)} - k_c}{f^{(k)}}, \quad (37) \]

\[ b^{(k)} = l^2 \frac{k_{s}^{(k)}}{f^{(k)}}, \quad (38) \]

where \( f^{(k)} \) is the Inertia of each seesaw, \( k_s^{(k)} \) is the negative stiffness generated by electrostatic force as given by Eq. (4), \( k_c \) is the positive stiffness of the cross spring.

### 3.2 Characteristics of the seesaw mechanism

The coefficients \( a_{21} \) and \( b \) are identified experimentally. When the fabricated suspension system is individually stabilized under PD control, the closed system can be assumed the ideal second-order system as

\[ G(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}, \quad (39) \]

where \( \zeta \) is damping factor, \( \omega_n \) is resonant frequency. In this state, a squared resonant frequency is given by

\[ \omega_n^2 = b_{pd} - a_{21}. \quad (40) \]

Therefore, the coefficients can be estimated from the squared resonant frequency against the proportional feedback gain \( p_{pd} \). Figure 6 and 7 show the experimental results. The coefficients were estimated by the least squared method. In this study, the value of \( a_{21}^{(1)} \) is approximately 20 times that of \( a_{21}^{(2)} \). This condition was determined by trial and error to stabilize the system.

The cross spring has a positive stiffness \( k_c \) of \( 5.3 \times 10^3 \) N/m. On the other hand, \( k_s^{(1)} \) and \( k_s^{(2)} \) are \( 2.7 \times 10^4 \) N/m and \( 1.9 \times 10^3 \) N/m, respectively. The positive stiffness is smaller than the absolute value of each negative stiffness. Therefore, the two suspension systems are maintained to be unstable even if the seesaw mechanism is used.

The damping ratios are measured. When the gap is at 0.37 mm, the damping ratio is 0.13. In this state, the damping force generated by the air between electrodes and the force target is dominant. On the other hand, when the gap is 2.4 mm, the damping ratio is 0.0047. It indicates that the damping due to the cross spring is negligible in suspension experiment.

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Fig. 6 Proportional gain \( p_{pd} \) v.s. squared resonant frequency \( \omega_n^2 \) of suspension system (1).
The main purposes of using the seesaw mechanism are to restrict the motion of the seesaw into single-DOF rotation and to adjust the value of $a_{21}$ flexibly as mentioned above. The identified values of $a_{21}$ include the effect of the stiffness. The effect of the damping is negligible.

### 3.3 Control design

In order to stabilize the double parallel electrostatic suspension system with parallel connection, state feedback control was applied. The transfer function of each displacement to the command signal is obtained from Fig. 8 as

$$G^{(k)}(s) = \frac{\beta^{(k)}_2 s^2 + \beta^{(k)}_0}{s^4 + \alpha_{3} s^3 + \alpha_{2} s^2 + \alpha_{1} s + \alpha_{0}} \quad (k = 1, 2),$$  \hspace{1cm} (41)

where

$$\alpha_{3} = b^{(1)}_1 p_{v}^{(1)} + b^{(2)}_1 p_{v}^{(2)},$$  \hspace{1cm} (42)

$$\alpha_{2} = -a_{21}^{(1)} b^{(1)}_1 p_{d}^{(1)} - a_{21}^{(2)} b^{(2)}_1 p_{d}^{(2)},$$  \hspace{1cm} (43)

$$\alpha_{1} = -a_{21}^{(1)} b^{(1)}_1 b^{(2)}_1 p_{v}^{(1)} - a_{21}^{(2)} b^{(2)}_1 b^{(1)}_1 p_{v}^{(1)},$$  \hspace{1cm} (44)

$$\alpha_{0} = a_{21}^{(1)} a_{21}^{(2)} - a_{21}^{(1)} b^{(2)}_1 b^{(1)}_1 p_{d}^{(2)} - a_{21}^{(2)} b^{(2)}_1 b^{(1)}_1 p_{d}^{(1)},$$  \hspace{1cm} (45)

$$\beta^{(1)}_2 = -b^{(1)}_1,$$  \hspace{1cm} (46)

$$\beta^{(2)}_0 = b^{(1)}_1 a_{21}^{(1)}.$$  \hspace{1cm} (47)

![Fig. 7 Proportional gain $p_d$ v.s. squared resonant frequency $\omega_r^2$ of suspension system (2).](image)

![Fig. 8 Block diagram of double parallel electrostatic suspension system.](image)
\[ \beta_2^{(2)} = -b^{(2)}, \]  
\[ \beta_0^{(2)} = b^{(2)}a_2^{(1)}, \]  
(48)  
(49)

When double parallel magnetic suspension was achieved, the feedback gains related to one floator had opposite sign to those of the other \(^{(14)}\). Here, we will show such characteristics analytically. It is assumed that the characteristic polynomial of the closed-loop system is represented as

\[ s^2 + 2\zeta_1\omega_1 s + \omega_1^2)(s^2 + 2\zeta_2\omega_2 s + \omega_2^2). \]  
(50)

where \( \zeta_k > 0 \) for stability. The feedback gains are obtained as

\[ p_d^{(1)} = \frac{(a_2^{(1)} + \omega_2^2)(a_2^{(1)} + \omega_1^2) + 4a_1^{(1)}\zeta_1\omega_1\omega_2}{b^{(1)}(a_2^{(1)} - a_2^{(2)})}, \]  
(51)

\[ p_v^{(1)} = \frac{2(a_2^{(1)} + \omega_2^2)\zeta_1\omega_1 + 2(a_2^{(1)} + \omega_1^2)\zeta_2\omega_2}{b^{(1)}(a_2^{(1)} - a_2^{(2)})}, \]  
(52)

\[ p_d^{(2)} = \frac{-(a_2^{(2)} + \omega_2^2)(a_2^{(2)} + \omega_1^2) + 4a_1^{(2)}\zeta_1\omega_1\omega_2}{b^{(2)}(a_2^{(2)} - a_2^{(1)})}, \]  
(53)

\[ p_v^{(2)} = \frac{-2(a_2^{(2)} + \omega_2^2)\zeta_1\omega_1 + 2(a_2^{(2)} + \omega_1^2)\zeta_2\omega_2}{b^{(2)}(a_2^{(2)} - a_2^{(1)})}. \]  
(54)

The feedback gains of the system with smaller \( a_{21} \) are negative whereas those of the system with larger \( a_{21} \) are positive. “Negative” indicates that they have opposite sign to the conventional PD control.

4. Experimental Results

4.1 Step responses

First, double parallel electrostatic suspension was achieved. The feedback gains were determined as shown in Table 1. The steady-state voltage is 1.2kV, and the target gaps \( D_0^{(1)} \) and \( D_0^{(2)} \) were set 0.17mm and 0.6mm, respectively. Under these conditions, double parallel electrostatic suspension was achieved. Next, to study transient behavior, a stepwise signal of \( \pm 10V \) was applied as disturbance. Figure 9 shows each gap of the floators and the control voltage. Transient response is rather vibratory. It is found that the system (1) with larger \( a_{21} \) responded to the fast change of control voltage just after the disturbance signal changed, while the system (2) with smaller \( a_{21} \) could not follow such fast change. For multiple suspension this difference of response speed is important for stabilization.

4.2 Frequency response

Frequency responses of parallel-connected suspension were measured. First, the effects of the feedback gain \( p_d^{(1)} \) was studied. Figure 10 shows the responses of (a) \( D^{(1)} \) and (b) \( D^{(2)} \) when the input signal was \( D_0^{(1)} \). The gain curves have two peaks approximately at 2Hz and
Table 1. Characteristic coefficients and feedback parameters.

<table>
<thead>
<tr>
<th></th>
<th>Suspension system (1)</th>
<th>Suspension system (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_1^{(1)}$</td>
<td>$1.9 \times 10^3$ [1/s$^2$]</td>
<td>$a_2^{(2)}$</td>
</tr>
<tr>
<td>$b^{(1)}$</td>
<td>$5.4 \times 10^{-2}$ [mm/Vs$^2$]</td>
<td>$b^{(2)}$</td>
</tr>
<tr>
<td>$p_0^{(1)}$</td>
<td>8250 [V/mm]</td>
<td>$p_0^{(2)}$</td>
</tr>
<tr>
<td>$p_c^{(1)}$</td>
<td>35 [Vs/mm]</td>
<td>$p_c^{(2)}$</td>
</tr>
</tbody>
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Fig. 9  Transient response of each floator and control voltage when the stepwise wave was inputted.

Fig. 10  Frequency response when the signal was inputted as command signal $D_0^{(1)}$ during change $p_0$. 
The peak at 6Hz increases when $p_d^{(1)}$ increases. Comparing (a) with (b) at the first peak, we found that the gain of $D^{(1)}$ is higher than $D^{(2)}$. On the other hand, at the second peak, the gain of $D^{(2)}$ is higher than that of $D^{(1)}$.

Next, the effects of the feedback gain $p_d^{(2)}$ was studied. Figure 11 shows the responses of (a) $D^{(1)}$ and (b) $D^{(2)}$ when the input signal was $D_0^{(2)}$. It was found that the peaks come close to each other when the feedback gains decrease.

5. Conclusions

The basic concept, configurations and properties of controllability of double parallel electrostatic suspension system were presented. To achieve double parallel electrostatic suspension, two single-DOF seesaw-type electrostatic suspension systems were fabricated. The seesaw mechanism enabled the flexible adjustment of the coefficient $a_{21}$ for this experiment. The value of $a_{21}^{(1)}$ was set to be approximately 20 times of that of $a_{21}^{(2)}$ in the experiment. Stable suspension was achieved in this condition. A step response and frequency responses of the double parallel electrostatic suspension system were measured. The effects of the feedback gains on the frequency responses were studied experimentally.

As a further work, influences of the difference of $a_{21}$ will be studied. It can be expected that the system is controlled more easily when the difference becomes large. However stabilization becomes difficult when the difference is too large. We expect the presence of the optimal value or optimal range of the difference.

Fig. 11  Frequency response when the signal was inputted as command signal $D_0^{(2)}$ during change $p_d$.
References