Decoupling Control Method for High-Precision Stages using Multiple Actuators considering the Misalignment among the Actuation Point, Center of Gravity, and Center of Rotation

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Abstract: High-precision stages are widely used in the semiconductor and flat panel industries. Because six degrees of freedom have to be controlled in these stages, coupling forces can degrade their control performance and stability. This paper proposes a decoupling control method from the scanning motion $\mathbf{x}$ to the pithing motion $\theta_y$ using multiple actuators. The method proposed in this paper consists of three steps: 1) a detailed modeling of the scanning motion $\mathbf{x}$ and the pithing motion $\theta_y$, 2) a changeable actuation point stage, and 3) an integrated design of mechanism and control. The validity of the proposed method is demonstrated by experiments.

Keywords: multiple actuator, decoupling control, integrated design of mechanism and control, high-precision stage

1. Introduction

High-precision scan stages play an important role in the manufacturing processes for semiconductors and liquid crystal displays (12). In these applications, high-precision stages have to control six degrees of freedom (DOFs: $x, y, z, \theta_x, \theta_y$, and $\theta_z$) (3). For this purpose, a dual stage that consists of a short-stroke 6-DOF fine stage and a long-stroke coarse stage is widely used (45). Our research group designed a dual stage, which is shown in Fig. 1. In such multi-input multi-output (MIMO) systems, the coupling force degrades the control performance.

This paper focuses on the scanning motion $\mathbf{x}$ and the pithing motion $\theta_y$. If the center of gravity (CoG) of the fine stage, the center of rotation (CoR) of the fine stage, the actuation point of the translational force $f_x$, and the measurement point of the translational position $x$ are not at the same points, coupling between the scanning motion $\mathbf{x}$ and the pithing motion $\theta_y$ occurs. It is difficult to match these four points because of mechanical constraints such as spatial limitation and shifting of the CoG due to load mass variation.

This paper proposes a detailed model of the scanning motion $\mathbf{x}$ and the pithing motion $\theta_y$ considering the misalignment among the CoG, the CoR, the actuation point, and the measurement point. In general, a precise model is important for the design of high-performance feedforward (FF)/feedback (FB) controllers (467). Next, on the basis of the detailed model, this paper proposes a block diagram that clearly shows the relationship between the misalignment and the zeros of the transfer functions. A 6-DOF high precision stage that has two VCMs (voice coil motors) in the $x$ direction is then designed. With a thrust distribution ratio $a$ (see (21) and (22)), the height of the virtual actuation point can be determined arbitrarily.

Fig. 1. Photograph of the 6-DOF high-precision stage

Fig. 2. Side view of the fine stage. By changing the thrust distribution ratio $a$ (see (21) and (22)), the height of the virtual actuation point can be determined arbitrarily

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\[ x_{g2} = x_{g1} + L_{g2} \sin(\theta_y), \quad \cdots \cdots \cdots \cdots \cdots (1) \]

mechanism and control (10) (11) is proposed for decoupling control between the scanning motion \( x \) and the pitching motion \( \theta_y \).

This method focuses on the relationship between the numerator of the transfer functions (zeros) and kinematic parameters such as the positions of the CoG, the CoR, the actuation point, and the measurement point. Finally, a method to improve the performance considering the height of the actuation point and the bandwidth of the feedback (FB) controller is proposed. The effectiveness of the proposed method is demonstrated experimentally.

2. Modeling

2.1 Experimental Setup

Our research group designed the dual stage shown in Fig. 1. The actuator and sensor arrangement of the fine stage is shown in Fig. 3. As shown in Fig. 2 and Fig. 3(a), the fine stage has two VCMs in the \( x \) direction.

The fine stage is supported by a 6-DOF air bearing "gravity canceller" (12). The picture and schematic of the gravity canceller are shown in Fig. 4. The gravity canceller compensates for the gravitational force experienced by the fine stage and supports its 6-DOF without friction. The gravity canceller is composed of three parts: the air gyro, the planar air bearing and the air bearing actuator that supports the \( (\theta_x, \theta_y, \theta_z), (x, y) \) and \( (z) \)-directional motion, respectively. As shown in Fig. 4, the air gyro is shaped like a hemisphere. The fine stage slides on the hemispheric surface of the air gyro with an air gap of a few micrometers. In this paper, the center of the hemisphere is called the CoR. In other words, the radius of the curvature of the air gyro determines the height of the CoR.

2.2 Lagrange’s Equations

In this section, Lagrange’s equations are formulated on the basis of the model shown in Fig. 5 and Table 1. First, the relationship between \( x_{g1} \), \( x_{g2} \), and \( \theta_y \) is expressed by

\[ x_{g2} = x_{g1} + L_{g2} \sin(\theta_y), \quad \cdots \cdots \cdots \cdots \cdots (1) \]
Lagrange's equations are given by
\[ \frac{\partial f_i(s)}{\partial \dot{q}_i} - \frac{\partial L}{\partial q_i} + \frac{\partial B}{\partial q_i} = \frac{\partial W}{\partial \dot{q}_i} \quad (i = 1, 2), \]
where \( q_1 \) and \( q_2 \) denote the generalized coordinates, \( q_1 = \theta_y \) and \( q_2 = \theta_y \), respectively. Finally, according to (1)–(8), the following equations (9) and (10) are obtained:
\[ \begin{align*}
\dot{x}_m(s) & = \frac{[J_{\theta y} + L_f s M_{m/c_1} - (L_{f x} - L_{q_2})(L_{q_2} - L_m)M_{m/c_2}]^2 + (C_{\theta y} + L_f s M_{c_1}) s + K_{\theta y} + L_f s M_{c_1} s - L_{q_2} M_{c_2} g}{D(s)} \\
\theta(x)(s) & = \frac{[L_f s M_{c_1} + (L_{f c_1} - L_{q_2}) M_{c_2}]^2 + L_{f c_1} s + L_{f c_1} s + L_{f c_1} s}{D(s)} \\
x_m(s) & = \frac{[L_m M_{c_1} + (L_{m} - L_{q_2}) M_{c_2}]^2 + L_m c_1 s + L_{m c_1} s}{D(s)} \\
\theta(x)(s) & = \frac{(M_{c_1} + M_{c_2}) s^2 + C_{c_1} s + K_{c_1}}{D(s)} \\
D(s) & = [(M_{c_1} + M_{c_2}) J_{\theta y} + M_{c_1} M_{c_2} L_{q_2}^2 s^2 + [(M_{c_1} + M_{c_2}) C_{\theta y} + (J_{\theta y} + M_{c_2} L_{q_2}^2) C_{c_1}] s^2 + [C_{\theta y} K_{c_1} + C_{c_1}(K_{\theta y} - L_{q_2} M_{c_2} g)] s + K_{c_1}(K_{\theta y} - L_{q_2} M_{c_2} g)] \quad (19)
\end{align*} \]

The kinetic energy \( T \), the potential energy \( U \), the dissipation function \( B \), and the work \( W \) are defined as follows:
\[ \begin{align*}
T & = \frac{1}{2} M_{c_1} \dot{x}_1^2 + \frac{1}{2} M_{c_2} \dot{x}_2^2 + \frac{1}{2} J_{\theta y} \dot{\theta}_y^2, \quad (3) \\
U & = \frac{1}{2} K_{c_1} \dot{x}_1^2 + \frac{1}{2} K_{c_2} \dot{\theta}_y^2 + L_{q_2} M_{c_2} g \cos(\theta_y), \quad (4) \\
B & = \frac{1}{2} C_{c_1} \dot{x}_1^2 + C_{c_2} \dot{\theta}_y^2, \quad (5) \\
W & = f_x \left[ \dot{x}_1 + L_{f x} \sin(\theta_y) \right] + \tau_y \dot{\theta}_y. \quad (6)
\end{align*} \]

According to (3) and (4), the Lagrangian \( L = T - U \) is given by
\[ L = \frac{1}{2} M_{c_1} \dot{x}_1^2 + \frac{1}{2} M_{c_2} \left( \dot{x}_1 + L_{q_2} \cos(\theta_y) \dot{\theta}_y \right)^2 + \frac{1}{2} J_{\theta y} \dot{\theta}_y^2 - \frac{1}{2} K_{c_1} \dot{x}_1^2 - \frac{1}{2} K_{c_2} \dot{\theta}_y^2 - L_{q_2} M_{c_2} g \cos(\theta_y). \quad (7) \]

The height of the actuation point can be changed by the thrust distribution ratio \( a \) (see (21) and (22)).

### 2.4 Transformation to Measurable Coordinate

The generalized coordinate \( x_{q_1} \) cannot be measured. Thus, \( x_{q_1} \) is converted to \( x_m \) by
\[ \begin{align*}
x_m(s) & = x_{q_1}(s) + L_{m} \frac{\theta_y(s)}{f_x(s)} \\
x_m(s) & = x_{q_2}(s) + L_{m} \frac{\theta_y(s)}{f_x(s)} \quad (13)
\end{align*} \]

### 2.5 Transfer Functions

According to (11)–(14), transfer functions (15)–(19) are obtained. In this paper, (15)–(19) are also expressed as
\[ G(s) = \begin{bmatrix} g_{11}(s) \\ g_{12}(s) \\ g_{21}(s) \\ g_{22}(s) \end{bmatrix} \begin{bmatrix} x_m(s) \\ x_m(s) \\ \theta_y(s) \\ \theta_y(s) \end{bmatrix} = \begin{bmatrix} x_{q_1}(s) \end{bmatrix} \begin{bmatrix} f_x(s) \\ f_x(s) \end{bmatrix} \quad (20) \]

According to (15)–(19), \( G(s) \) can also be modeled as the block diagram shown in Fig. 6. This block diagram clearly shows the coupling structure.

### 3. Proposal of a Changeable Actuation Point Stage

Owing to the spatial limitation of the fine stage, the VCM for the \( x \) direction cannot be placed at the desired actuation point. In this section, a fine stage structure that can shift the virtual actuation point by means of the thrust distribution of multiple actuators is proposed. This is based on a simple idea shown in Fig. 2. The two VCMs generate force \( f_{x_1} \) and \( f_{x_2} \) in the \( x \) direction by the thrust distribution law,
\[ f_{x_1} = a f_x, \quad f_{x_2} = (1 - a) f_x, \quad (21) \]
where \( a \) denotes the thrust distribution ratio. Here, the height of the virtual actuation point \( L_{fx} \) is defined as

\[
L_{fx} = aL_{f1} + (1-a)L_{f2},
\]

(22)

where \( L_{f1} \) and \( L_{f2} \) denote the heights of the actuation point of \( f_1 \) and \( f_2 \) from the CoR.

Although this structure doubles the amount of wiring, and the mass of the fine stage increases slightly, this structure has the following advantages. By changing the thrust distribution ratio \( a \), the height of the virtual actuation point \( L_{fx} \) can be placed at a desired point such as the position of the CoG and the CoR. Moreover, during the operation, the CoG shifts owing to load mass variation. Because the transfer functions (15)–(19) depend on the height of the CoG \( L_g2 \), the coupling characteristics change dynamically. Even in this case, this structure can reduce coupling forces if the virtual actuation point is placed at the optimal position.

4. Integrated Design of Mechanism and Control

The coupling path of \( G(s) \) is shown in Fig. 7, which clearly shows the relationship between the numerators of \( G(s) \) and the position of the actuation point \( L_{fx} \).

4.1 Equivalence between the Precompensator \( k_{21} \) and the Actuation Point \( L_{fx} \)

Figure 8 shows the MIMO system with a precompensator \( K(s) \). Here, the control object \( Q(s) \) in Fig. 8 is obtained by

\[
Q(s) = G(s)K(s), \quad \text{------ (23)}
\]

where \( Q(s) \), \( K(s) \), and \( G(s) \) are defined as

\[
Q(s) = \begin{bmatrix} q_{11}(s) & q_{12}(s) \\ q_{21}(s) & q_{22}(s) \end{bmatrix}, \quad K(s) = \begin{bmatrix} k_{11}(s) & k_{12}(s) \\ k_{21}(s) & k_{22}(s) \end{bmatrix}, \quad G(s) = \begin{bmatrix} g_{11}(s) & g_{12}(s) \\ g_{21}(s) & g_{22}(s) \end{bmatrix} \quad \text{------ (24)}
\]

Substituting (25) for Fig. 8, Fig. 9 is obtained. In this case, the control object \( Q(s) \) can be represented by Fig. 10. Here, the precompensator \( k_{21} \) and the position of the actuation point \( L_{fx} \) are connected in parallel. Hence, there is a linear relationship between the precompensator \( k_{21} \) and the actuation point \( L_{fx} \); varying \( k_{21} \) results in variation in \( L_{fx} \).
4.2 Decoupling $g_{21}(s)$ Using the Changeable Actuation Point $L_{fx}$

Figure 7 shows that by changing the actuation point $L_{fx}$, the coupling transfer function $g_{21}(s)$ can be suppressed without any impact on $g_{12}(s)$ and $g_{22}(s)$. In this section, “CoR-driven method” and “CoG-driven method” are proposed.

- CoR-driven method (Fig. 11)
  
  If $L_{fx}$ is set as 0, this means the actuation point is placed at the CoR, $L_{fx}(M_1s^2 + M_2s^2 + C_1s + K_1)$ becomes 0. Now, the coupling term is only $-L_{q2}M_2s^2/D(s)$. Then, the coupling gain of $g_{21}$ in low frequency range is suppressed.

- CoG-driven method (Fig. 12)
  
  If $L_{fx}$ is set as $L_{q2}$, this means the actuation point is placed at the CoG, $(L_{q2} - L_{fx})M_2s^2$ becomes 0. Now, the coupling term is only $L_{fx}(M_1s^2 + C_1s + K_1)/D(s)$. The coupling gain of $g_{21}$ in high frequency range is thus suppressed considering $M_1 ≪ M_2$ (see Table 1). The comparison between the CoR- and the CoG-driven method is shown in Fig. 13. It is clear from the figure that there is a trade-off between the CoR- and the CoG-driven method in low and high frequency ranges.

This observation suggests that it is better to select a virtual actuation point $L_{fx}$ that has a small coupling gain $g_{21}(s)$ at the frequency of the sensitivity function peak of the $\theta_y$ closed loop. This is because the output of $g_{21}(s)$ can be considered a disturbance of the $\theta_y$ closed loop as shown in Fig. 8.

5. Experiment

Measurements are performed by using the experimental stage shown in Fig. 1. The virtual actuation point $L_{fx}$ is set at $L_{fx} = 0$, $-0.033$, and $-0.051$ by using the thrust distribution law described in (21) and (22). The CoG of the experimental setup is designed as $L_{fx} = -0.051$. $L_{fx} = -0.051$ is then considered the CoG-driven method. Here, a precompensator is not used ($K(s) = I$, $I$ is the identity matrix).

5.1 Frequency Responses

The frequency responses are shown in Fig. 14. The model formulated in (15)–(19) is validated by the experiments in Fig. 14(c).

The frequency responses shown in Fig. 14(c) demonstrate that there is a trade-off between the CoR-driven and CoG-driven methods. Figures 14(a), (b), and (d) show that the variation in $L_{fx}$ does not have a significant effect on $g_{11}$, $g_{12}$ and $g_{22}$.

5.2 Step Responses

The block diagram of the step response experiment is shown in Fig. 15. The nominal plants of the feedback controllers $c_1$ and $c_2$ are defined by

$$g_{11n}(s) = \frac{1}{(M_1s^2 + M_2s^2 + C_1s + K_1)} \ldots \ldots \ldots (26)$$

$$g_{22n}(s) = \frac{1}{(M_2s^2 + C_1s + K_1)} \ldots \ldots \ldots (27)$$

where $g_{11n}$ is the nominal plant of $c_1$ and $g_{22n}$ is the nominal plant of $c_2$. The feedback controllers $c_1$ and $c_2$ are PID compensators designed by pole assignment (23) using (26) and (27). The bandwidths of the position loops are 10 Hz for $x_m$ and $\theta_y$, respectively.

As shown in Fig. 15, a 100 μm step reference is given for $x_m$ and a zero constant reference is given for $\theta_y$, respectively. The experimental result of $g_{11}'$ is shown in Fig. 16. The settling time of $L_{fx} = 0$ (CoR-driven) is better than that of other
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Fig. 14. Frequency responses of $G$ (experiment, $L_{fs} = 0$, $-0.033$, $-0.051$). The variation in $L_{fs}$ does not affect $g_{11}$, $g_{12}$, and $g_{22}$ significantly. The validity of the proposed model is demonstrated by Fig. 13 and Fig. 14(c).

6. Conclusion

This paper proposes a decoupling method using multiple actuators in the $x$ direction on the basis of a precise model of the scanning motion $x$ and the pitching motion $\theta_y$. This precise model considers the misalignment of the CoG, CoR, actuation point, and measurement point. According to this model, a new block diagram is illustrated. This block diagram clearly shows the relationship between the numerator of the transfer function matrix and the misalignment. The validity of the proposed model and the decoupling method that takes the height of the actuation point into consideration are demonstrated experimentally.

References


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