High-Precision Control of Magnetic Levitation System


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Abstract—In this paper, we address two position control schemes; the lead-lag control and the sliding mode control for a stage system, which is levitated and driven by electric magnetic actuators. This consists of a levitating object (called platen) with 4 permanent magnetic linear synchronous motors in parallel. Each motor generates vertical force for suspension against gravity and propulsion force horizontally as well. This stage can generate six degrees of freedom motion by the vertical and horizontal forces. Dynamic equations of the stage system are derived simply. The sliding mode control algorithm is more effective than the lead-lag control algorithm to reduce effects from movements and disturbances of other axes.

1. INTRODUCTION

Recently, the necessity for high precise position control mechanisms for highly integrated and accurate products as industrial technology is gradually increased. We can easily find that the high precision positioning systems play an important role in the field of modern fabrication process. This mechanism generally can be applied to high precise machining, alignment device for optics, and a stepper for semi-conductor manufacturing application. In particular, sub-micro meter level positioning mechanism is an essential NT(Nano Technology) technology and supposed to be an important key to various applications. Such devices could support micro- or even nano- positioning accuracy, high bandwidths of operation and sufficient stiffness. Piezoelectric actuators provide the necessary stiffness and positioning accuracy but have some restriction with its traveling range. The combination of linear motor and air-bearings is a general strategy to realize long stroke movement with high velocities. But to achieve a large and accurate travel in multiple degrees of freedom using linear motor with non-contact bearing, it needs complex system configuration.

In this paper, there is proposed a position control scheme, which is valid for a high precise control mechanism. A high precise control mechanism is fabricated here and has a potential for a stepper for semi-conductor manufacturing or complicated non-spherical lens manufacturing platform. There are so many researches for a magnetic levitation system to cope with the deficits.

The magnetic levitation system has merits of adjusting stroke range for an application and non-contacting with magnetic force. Because the non-contacting actuating system has no linkages for actuating force transmission, it can make the dynamic equations of a stage system simple. The magnetic levitation system can generate six degrees of freedom motion by the vertical and horizontal forces. Several important coordinate systems and vectors for describing the magnetic levitation stage are shown in Fig. 2. The actuator resembles a synchronous linear motor that consists of windings on stator and permanent magnet on platen but in former case, there is no mechanical contact guide. The platen of the magnetic levitated stage system can travel in a range of 50mm x 50mm. The real picture of magnetic levitation stage is shown in Fig. 3.

Newton equation can be used for describing translational motion, Euler equation for rotational motion. The platen can be assumed as a rigid body. Rigid body motion consists of translational and rotational motion and can be described as following

\[ m_p \ddot{x} + m_p g = \sum_{i=1}^{4} f_i \]  

(1a)
\[ I_c \ddot{\omega} + \omega \times (I_c \omega) = \sum_{i=1}^{4} \mathbf{r}_i \times \mathbf{f}_i \]  
\hspace{1cm} (1b)

All variables in Eq.(1) are described in inertial frame unless special statement. Eq.(1) can be packed as a simple matrix vector form as following

\[
\begin{bmatrix}
    m_p & E & 0 \\
    0 & I_c & \omega \\
    \end{bmatrix} \begin{bmatrix}
    \dot{x} \\
    \dot{\omega} \\
    \end{bmatrix} + \begin{bmatrix}
    m_p \mathbf{g} \\
    \end{bmatrix} = \begin{bmatrix}
    \sum \mathbf{f}_i \\
    \end{bmatrix} \times \mathbf{r}_i \\
\]  
\hspace{1cm} (2)

Where, the gravitational force does not enter moment equation since it is a distributed force. \(m_p\) denotes mass of the platen, \(\mathbf{g}\) denotes gravitational acceleration, \(E\) denotes a proper dimensional identity matrix, \(I_c\) denotes moment of inertial about mass center, \(\mathbf{x}, \omega\) denotes linear and angular acceleration of the platen, \(\mathbf{r}_i\) denotes a position vector pointing permanent magnet center about moving frame, \(\mathbf{f}_i\) denotes actuating force. All the actuators can produce vertical propulsion while some motors can produce only \(x\)-axis or \(y\)-axis.

2.2 The Linear Driver

The linear driver consists of 12 independent circuits with one input and one output channel to drive four actuators with three phases. The real picture of linear driver is shown in Fig. 4. The PI control circuit using OP-Amp is applied to control a current linearly and rapidly. The range of input is linear values from -10 [V] to 10 [V] and the range of output is also linear values from -2 [A] to 2 [A].

2.3 The Control System

The control system consists of a PC board, a DSP board (TMS 320C6701), a 8 channel A/D board, a 16 channel D/A board and three laser interferometer boards. The former manages the entire experimental setup and analyze the experimental results, the later consists of four DSPs to achieve high sampling rate and takes a role of computing control algorithm, kinematics of the platen. The configuration of control system is shown in Fig. 5. The VME bus is applied to transfer 32 bit data between each board in real time. The control period is 100 [µs].

2.4 The Precision Measurement System

The precision measurement system consists of laser interferometer system and capacitance probe system. The configuration of laser interferometer system is shown in Fig. 6. The laser interferometer system consists of three modules to measure displacements of X, Y and Yaw directions. The measurement resolution of laser interferometer system is 0.3 [nm]. The measurement signal from this system is transferred to interferometer board in VME system.
Also, to measure displacements of Z, pitch and roll directions, three capacitance probe is applied. This probe is installed on stator parts. The measurement signal from the capacitance probe system is amplified and then transferred to A/D board.

3. CONTROL ALGORITHMS

The magnetic levitation system can levitate and thrust the platen simultaneously with 6-D.O.F. using four linear motors in parallel. Each linear motor can produce vertical and horizontal force and is a 2-D.O.F actuator. The block diagram of control scheme is shown in Fig. 7. Where, \( p \) denotes measured position vector (6 components – \( x,y,z,\theta_x,\theta_y,\theta_z \)); \( p_r \) denotes reference position vector (6); \( F_m \) denotes modal forces vector; output of the controller (6); \( F_d \) denotes decomposed forces vector; output of the controller (8 components, 2 per motor); \( I \) denotes current vector (12 components, 3 for each motor with a 60° phase difference); \( I_a \) denotes actual current vector (12); \( F_a \) denotes actual forces vector: decomposed (12) or modal (6); \( \text{Ctrl} \) denotes Lead-lag-integration controller or sliding mode controller; \( \text{FD} \) denotes Force Decomposition based on platen’s geometry; \( \text{FCT} \) denotes Force to Current Transformation; \( \text{LA} \) denotes Linear Driver; \( S \) denotes Stators; \( \text{Pl} \) denotes Platen.

Since \( \text{FD} \) is used, it is simple for controller to apply each axis independently. Firstly, the lead-lag controller is applied for six axes (\( x, y, z, \theta_x, \theta_y, \theta_z \)) and then the sliding mode controller is applied instead of former controller only two axes (\( x, y \)).

3.1 The Lead-Lag Controller

The modal of \( x \) axis is simple as the following Eq. (3).

\[
m_p \ddot{x} + k x = f_x \text{ or } u_x
\]

Where, \( m_p \) denotes mass of platen; \( k \) denotes damping of platen, the lead-lag controller for \( x \) axis,

\[
G_x(z) = K_x \left( \frac{z - A_x}{z - B_x} \right) = \frac{C_x}{z - 1}
\]

Where, \( K_x \) denotes gain; \( A_x, B_x, C_x \) denotes parameters for controller.

The same method can be used to calculate the lead-lag controller for five axes (\( y, z, \theta_x, \theta_y, \theta_z \)).

3.2 The Sliding Mode Controller[5]

Define the errors as

\[
e(t) = x - x_r, \quad \dot{e}(t) = \dot{x} - \dot{x}_r
\]

Where, \( x \) and \( x_r \) denote current variable and desired variable, respectively.

Here, we introduce switching surface

\[
s(t) = \dot{e}(t) + \lambda e(t), \quad (\lambda > 0)
\]

The control problem is to derive control input \( u_x \) which guarantees \( s(t) \to 0 \) and preserve states \( x, x_r \) on the sliding surface. To derive such a control input, we can consider Lyapunov function candidates

\[
V = \frac{1}{2} s^2
\]

Time differentiation of Eq. (7) is

\[
\dot{V} = s \dot{s}
\]

Using Eq. (6)

\[
\dot{V} = s(\ddot{x} + \lambda \dot{x})
\]

Using Eq. (5)

\[
\dot{V} = s(\ddot{\lambda} + \lambda \dot{\lambda})
\]

Using Eq. (3)

\[
\dot{u}_x = -b_x^{-1}(-\ddot{x}_r + \lambda \dot{x}_r + K x \text{ sgn}(s))
\]

Where, \( K_x \geq 0 \)

\[
\dot{V} = s(-K_x \text{ sgn}(s))
\]

Therefore, \( s(t) \to 0 \) was achieved from Eq. (7) and Eq. (12) as
\[ t \to \infty \]. We can see that \( z(t) \to 0 \) means stabilization of error variable because it makes stable error equation \( \dot{e} = -\lambda e \) under the condition of the new control input Eq. (12).

The switching function has some problems. It makes chattering problem on sliding mode control.

\[
\text{sgn}(s) = \begin{cases} 
1, & \text{if } s > 0 \\
-1, & \text{if } s < 0 
\end{cases}
\]  

(14)

Therefore, we will introduce a saturation function

\[
\text{sat}(s) = \begin{cases} 
\frac{s}{\phi}, & \text{if } |s| \leq \phi \\
\text{sgn}(s), & \text{if } |s| > \phi 
\end{cases}
\]  

(15)

Where, \( 0 < \phi \leq 1 \)

Finally, the control input to achieve configuration control purpose can be obtained

\[
u_x = -b_x^{-1}(-\ddot{x} + \lambda \dot{e} + K_x \text{sat}(s))
\]  

(16)

The same method can be used to calculate the sliding mode controller for y axis.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

We fabricate a magnetic levitated stage system, which consists of four linear motors. The experimental setup is shown in Fig. 8.

![Fig. 8. The experimental setup](image)

4.1 The Experiments of the Lead-Lag Controller

Firstly, the lead-lag controller is applied for six axes \( (x, y, z, \theta_x, \theta_y, \theta_z) \). Initial values of \( x \) and \( y \) are 0.3 [\mu m] and 0.5 [\mu m]. Target values of \( x \) and \( y \) are 5,000 [\mu m] and 0 [\mu m]. The experimental results are shown in Fig. 9. The time periods between initial and target of \( x \) and \( y \) axes are about 0.5238 [sec] and 1.0654 [sec].

During the platen is moving to \( x \) axis, it is affected for movement of \( y \) axis because the platen is guided magnetically than mechanically. Also, a mechanical error is included in the stage system. We know that the time period of \( y \) axis is longer than that of \( x \) axis.

4.2 The Experiments of the Sliding Mode Controller

Secondly, the sliding mode controller is applied instead of former controller only two axes \((x, y)\). Initial value and target value are the same as former experiments of the lead-lag controller. The experimental results are shown in Fig. 10. The time periods between initial and target of \( x \) and \( y \) axes are about 2.4240 [sec] and 0.4512 [sec]. The time period of \( x \) axis on the sliding mode controller is longer than it on the lead-lag controller. But the time period of \( y \) axis on the sliding mode controller is shorter than it on the lead-lag controller. During the platen is moving to \( x \) axis, it is not affected for movement of \( y \) axis after convergence because the movement of \( x \) axis is not quickly. This is results at the sliding surface slope of \( \lambda = 1 \). If the slope is increased, the time period of \( x \) axis is shorter than before. The experimental results at the slope of \( \lambda = 3 \) are shown in Fig. 11. The time periods between initial and target of \( x \) and \( y \) axes are about 1.1334 [sec] and 0.5362 [sec]. The time period...
of $x$ axis at the slope of $\lambda = 3$ is shorter than it at the slope of $\lambda = 1$. But the time period of $y$ axis at the slope of $\lambda = 3$ is longer than before. During the platen is moving to $x$ axis, it is little effected for movement of $y$ axis after convergence because the movement of $x$ axis is more quickly than before. The experimental results at the slope of $\lambda = 5$ are shown in Fig. 12. The time periods between initial and target of $x$ and $y$ axes are about 0.7908 [sec] and 0.5350 [sec]. The time period of $x$ axis at the slope of $\lambda = 5$ is shorter than before. It is almost similar with the time period of the lead-lag controller. The time period of $y$ axis at the slope of $\lambda = 5$ is similar with before but it is shorter than it of the lead-lag controller. During the platen is moving to $x$ axis, it is also little effected for movement of $y$ axis after convergence.

The summary of experimental results is shown in Table 1. The sliding mode control algorithm is more effective than the lead-lag control algorithm to reduce effects from movements and disturbances of other axis.

![Fig. 10. The experimental results of the sliding mode controller ($\lambda = 1$)](image)

![Fig. 11. The experimental results of the sliding mode controller ($\lambda = 3$)](image)

![Fig. 12. The experimental results of the sliding mode controller ($\lambda = 5$)](image)
Table 1. The summary of experimental results

<table>
<thead>
<tr>
<th>Time Period [sec]</th>
<th>lead-lag</th>
<th>The sliding surface slope of $\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_x$</td>
<td>0.5238</td>
<td>2.4240 1.5076 1.1334 0.9228 0.7908</td>
</tr>
<tr>
<td>$t_y$</td>
<td>1.0654</td>
<td>0.2354 0.4250 0.5362 0.4976 0.5350</td>
</tr>
</tbody>
</table>

5. CONCLUSIONS

In this paper, we construct a conventional lead-lag controller and sliding mode controller for precise position control of the magnetic levitation stage system and analyze the two controllers. The magnetic levitation stage system is driven by four linear motors with 2-D.O.F. and had 6-D.O.F. totally.

We derive simple dynamic equations of the system, which is an important role for constructing controller.

We identify the control performances of the two controllers are the same theoretically, and compare the performances of them experimentally.

The sliding mode control algorithm is more effective than the lead-lag control algorithm to reduce effects from movements and disturbances of other axis.

REFERENCES