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슬라이딩모드제어기를 적용한 자기부상 스테이지의 위치제어

전정우*, 이주훈*, 황돈하*, 강동식*, 김성신**
*한국전기연구원, **부산대학교

Positioning Control of Magnetic Levitation Stage Using Sliding Mode Controller

Jeong-Woo Jeon*, Joo-Hoon Lee*, Don-Ha Hwang*, Dong-Sik Kang*, Sung-Shin Kim**
*Korea Electrotechnology Research Institute, **Pusan National University

Abstract - In this paper, we address two position control scheme; 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. The sliding mode control algorithm is more effective than the lead-lag control algorithm to reduce effects from movements and disturbances of other axis.

1. 서 론

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 mechanisms 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.

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.

Tusda achieved sub-micrometer accuracy with a 5-D.O.F. magnetic levitated system, Busch developed a 2-D.O.F. mechanism for semi-conductor device verification prove, Kim [1] developed a 6-D.O.F magnetic levitation mechanism with four permanent-magnet linear motors and achieved sub-micro meter accuracy.

In this paper, there are carried out position control experiments with a 6-D.O.F magnetic levitation system for the position control mechanism with four motors, which are the same as Kim's result [1]. In section 2, we introduce the structure of the magnetic levitation system, describe its simple dynamic equations and comment the properties of the dynamic equations which are an important role for constructing a controller. There are introduced two specific control schemes the lead-lag control and the sliding mode control and described each property in section 3[2]. According to experiments, we present various experimental results of each control scheme and discuss its properties in section 4.

2. Magnetic Levitation System

The magnetic levitation system which is shown in Fig.1 is composed of four parts: a magnetic levitation stage, a linear driver, a high performance controller and a precision measure.

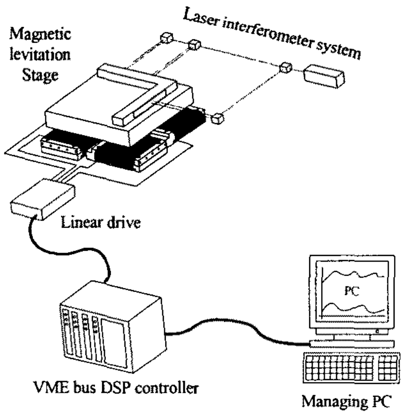

Fig. 1. The configuration of magnetic levitation system

2.1 Magnetic Levitation Stage

The magnetic levitation stage consists of movable platen and four actuators arranged in parallel, which have 2-D.O.F with vertical and lateral direction. Several important coordinate systems and vectors for describing the magnetic levitation stage are shown in Fig. 2. There is no mechanical contact guide. The platen of the magnetic levitated stage system can travel in a range of $50mm \times 50mm$. 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

$$m_p\ddot{\mathbf{x}} + m_p\mathbf{g} = \sum_{i=1}^{4}\mathbf{f}_i \tag{1a}$$

$$\mathbf{I}_c\dot{\boldsymbol{\omega}} + \boldsymbol{\omega}\times(\mathbf{I}_c\boldsymbol{\omega}) = \sum_{i=1}^{4}\mathbf{r}_i\times\mathbf{f}_i \tag{1b}$$

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

$$\begin{bmatrix} m_p\mathbf{E} & \mathbf{0} \\ \mathbf{0} & \mathbf{I}_c \end{bmatrix} \cdot \begin{Bmatrix} \ddot{\mathbf{x}} \\ \dot{\boldsymbol{\omega}} \end{Bmatrix} + \begin{Bmatrix} m_p\mathbf{g} \\ \boldsymbol{\omega}\times(\mathbf{I}_c\boldsymbol{\omega}) \end{Bmatrix} = \begin{Bmatrix} \sum\mathbf{f}_i \\ \sum\mathbf{r}_i\times\mathbf{f}_i \end{Bmatrix} \tag{2}$$

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, $\mathbf{I}_c$ denotes moment of inertial about mass center, $\ddot{\mathbf{x}}, \dot{\boldsymbol{\omega}}$ 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 Control Algorithm

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. 4. Where, **p** denotes measured position vector (6 components x,y,z,θx,θy,θz); **pr** denotes reference position vector (6); **Fm** denotes modal forces vector; output of the controller (6); **Fd** 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); **Ia** denotes actual current vector (12); **Fa** denotes actual forces vector: decomposed (12) or modal (6); **Ctrl** denotes Lead-lag-integration controller or sliding mode controller; **FD** denotes Force Decomposition based on platen's geometry; **FCT** denotes Force to Current Transformation; **LA** denotes Linear Driver; **S** denotes Stators; **Pl** denotes Platen. Since **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, θx, θy, θz)and then the sliding mode controller is applied instead of former controller only two axes(x, y).

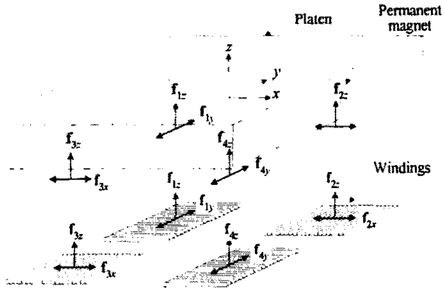

Fig. 2. The magnetic levitation stage using four linear synchronous motors.

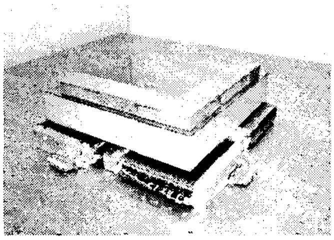

Fig. 3. The real picture of magnetic levitation stage.

2.2.1 Lead-Lag Controller

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

$$m_p\ddot{x} + kx = f_x \ or\ u_x \tag{3}$$

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

$$G_x(z) = K_x\left(\frac{z - A_x}{z - B_x}\right)\left(\frac{z - C_x}{z - 1}\right) \tag{4}$$

Where, K_x denotes gain; A_x, B_x, C_x denotes

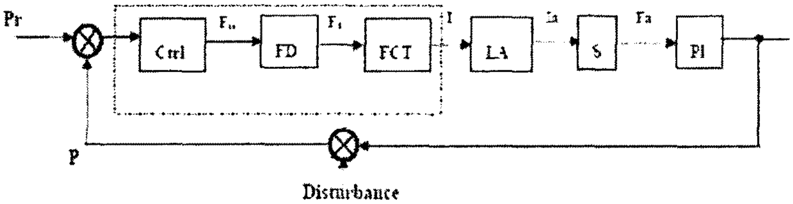

Fig 4. Control Scheme

parameters for controller. The same method can be used to calculate the lead-lag controller for five axes(y, z, x,y,z).

2.2.2 Sliding Mode Controller

Define the errors as

$$e(t) = x - x_r,\ \dot{e}(t) = \dot{x} - \dot{x}_r \tag{5}$$

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

$$u_x = -b_x^{-1}(-\ddot{x}_r + \lambda\dot{e} + K_s sat(s)) \tag{6}$$

Therefore, we will introduce a saturation function

$$sat(s) = \begin{cases} \dfrac{s}{\phi} & ,if\ \|s\| \le \phi \\ \operatorname{sgn}(s) & ,if\ \|s\| > \phi \end{cases} \tag{7}$$

Where, $0 < \phi \le 1$

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

2.3 Experimental Results

We fabricate a magnetic levitated stage system, which consists of four linear motors. The experimental setup is shown in Fig. 5.

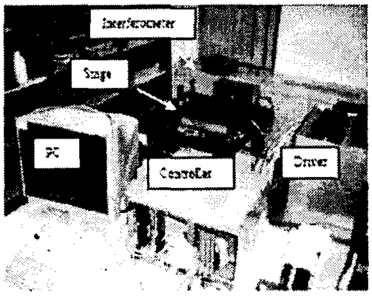

Fig. 5. The experimental setup

2.3.1 Results of Lead-Lag Controller

Firstly, the lead-lag controller is applied for six axes (x, y, z, θx, θy, θz). Initial values of x and y are 0.3 [μm] and 0.5 [μm]. Target values of x and y are 5,000 [μm] and 0 [μm]. The experimental results are shown in Fig.6. The time periods between initial and target of x and y axes are about 0.5238 [sec] and 1.0654 [sec].

2.3.2 Results of 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 at the slope of $\lambda = 5$ are shown in Fig. 7. The time periods between initial and target of x and y axes are about 0.7908 [sec] and 0.5350 [sec]. It is almost similar with the time period of the lead-lag controller.

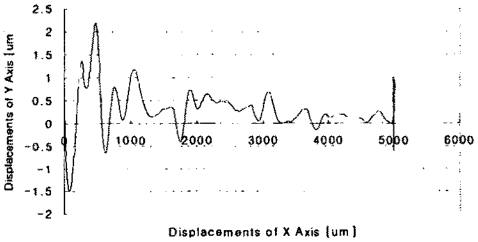

Fig. 6. The displacements of x vs. y axis [μm] at applying the lead-lag controller

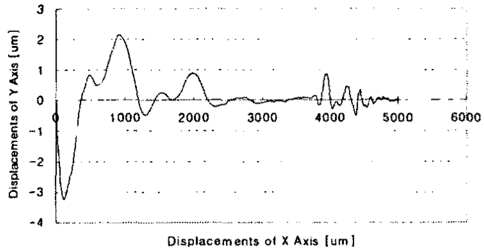

Fig. 7. The displacements of x vs. y axis [μm] at applying the sliding mode controller ($\lambda = 5$)

Table 1. The summary of experimental results

Time Period [sec]	lead lag	The sliding surface slope of λ				
		1	2	3	4	5
t_x	0.5238	2.4240	1.5076	1.1334	0.9228	0.7908
t_y	1.0654	0.2354	0.4250	0.5362	0.4976	0.5350

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.

3. Conclusions

In this paper, we construct a conventional lead-lag controller and sliding mode controller for precise position control of the magnetic levitationstage 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. The sliding mode control algorithm is more effective than the lead-lag control algorithm to reduce effects from movements and disturbances of other axis.

[참 고 문 헌]

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