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Experiments of a Novel Magnetic Levitation Stage for Wide Area Movements

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Abstract – In this paper, a novel planar type magnetic levitation system without other assistant devices is proposed and it can move with 6 degree of freedom (X, Y, Z, θ_X, θ_Y, θ_Z) in wafer size as well as in nano scale positioning.The mover is composed with 2-D Halbach permanent magnet array and the stator is composed with 10 x 10 coil arrays.It was composed in laboratory and tested with short stroke (4 [mm]) and long stroke (160 [mm])movements. The errors of short movement test is [X, Y, Z, θ_X, θ_Y, θ_Z]≤ [±200nm, ±200nm, ±250nm, ±3urad, ±2urad, ±1urad]The errors of long stroke movement test is [X, Y, Z, θ_X, θ_Y, θ_Z]≤ [±200nm, ±200nm, ±250nm, ±1.5urad, ±2urad, ±0.5urad].

Keywords: Magnetic levitation, Mag-Lev, Magnetic levitation stage, Nano scale positioning

1. Introduction

Recently, the various types of magnetic levitation stage are researching for high precision positioning mechanism because an interesting about manufacturing of more and more small size in nano technology field is increasing [1-9]. Already, we introduced a novel magnetic levitation stage system which can move in wafer size as well as in nano scale positioning but only the possibility of nano scale positioning was shown [8]. This novel maglev stage system is composed with a permanent magnet array (PM array) for a mover part and a coil array for a stator part. The mover part can be moved with 6 degree of freedom(X, Y, Z, θ_X, θ_Y, θ_Z) within an area of the coil array by control of magnetic field of it. The stator part is composed with 10 x 10 coil array for movements of wafer size. We used three laser interferometer systems and three capacitance sensors for nano scale measurement and a high performance control system for control. Some advantages of this system are as followings:

- Simple Structures
- Fine Positioning with nano-meter scale as well as Coarse Positioning with mili-meter scale in one structure
- Easily Expansion of Working Area
- Usable top part of Structure
- Compatible in Vacuum

2. The Proposed Magnetic Levitation Stage for Wide Area Movement

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2.1 Conceptual design

The basic concept of magnetic levitation motor is shown in Fig. 1. It is composed with permanent magnet array (PM array) and coil module. The permanent magnet array is composed with several kind of magnet. Kim el al. researched 2-D structure of Halbach permanent magnet array [1]. The shape of magnetic field which is the bottom of the PM array is as shown in Fig. 2(a). The coil array is composed with twelve rectangular shaped coils. It has two pitches. The magnetic field of the coil array can be control by input current as shown in Fig. 2(b). These magnetic fields are the magnetic strength of N pole and S pole and these are estimated. The repulsive forces are generated between the same magnet poles of PM array and current

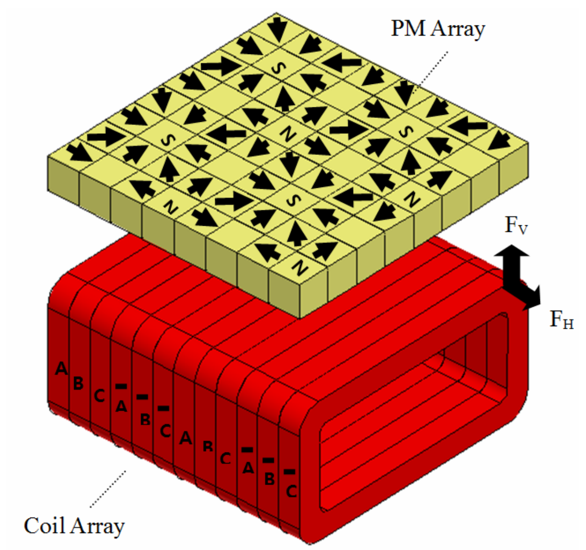


Fig. 1. The conceptual design of magnetic levitation module

distribution of coil array for reason of Lorentz Force. These forces are composed with the vertical force (F_V) and the horizontal force (F_H) in Fig. 1. The formulas of these forces for two pitches of the magnetic levitation motor are as the following [1]:

$$\begin{bmatrix} F_H \\ F_V \end{bmatrix} = \frac{1}{2}\mu_0 M_0 \eta_0 N_m G e^{-\frac{2\pi}{l}V_0} \begin{bmatrix} i_q \\ i_d \end{bmatrix} \tag{1}$$

$$G = \frac{\sqrt{2}\omega l^2}{\pi^2}(1 - e^{-\frac{2\pi}{l}\Gamma})(1 - e^{-\frac{2\pi}{l}\Delta}) \tag{2}$$

Here, $\mu_0 M_0$ is Magnet remanence and the value is 0.8 [T], η_0 is Turn density and the value is 2.3704e^{+6} [Turn/mm^2], N_m is Number of active magnet pitch and the value is 2, ω is PM array width and the value is 0.03 [m], l is coil array pitch and the value is 0.03 [m], Γ is PM array thickness and the value is 0.0075 [m], $\Delta$is coil array thickness and the value is 0.0054 [m], V_0 is Nominal gap and the value is 100 [um]. The horizontal and vertical forces of one pitch of our magnetic levitation motor are as the following:

$$\begin{bmatrix} F_H \\ F_V \end{bmatrix} = 4.0192 \begin{bmatrix} i_q \\ i_d \end{bmatrix} \tag{3}$$

If the values of input current (i_q, i_d) are 2 [A] for each, we obtain that the values of levitation force (F_V) and traction force (F_H) are 8.0384 [N].The DQ current values are transformed to 3 phase currents as the following equation:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \cos(\alpha - \frac{\pi}{3}) & -\sin(\alpha - \frac{\pi}{3}) \\ \cos(\alpha - \frac{2\pi}{3}) & -\sin(\alpha - \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{4}$$

where $\alpha = \frac{2\pi}{l}p$, l is pitch (0.03m), p is the current position on the suitable horizontal axis.

2.2 The principle structure

We proposed the principle structure of the novel magnetic levitation stage as shown in Fig. 3 [6]. It is composed of 16 coil arrays such as checkered matrix. The PM Array is located on the top of these coil arrays.

The area of the PM Array is similar with these coil arrays. Two kinds of magnetic force between the coil array and the PM array by each coil array are generated. Let the central position of coil matrix is [x_0, y_0, z_0] = [0, 0, 0]. The net force of Z direction on the central position is the sum of

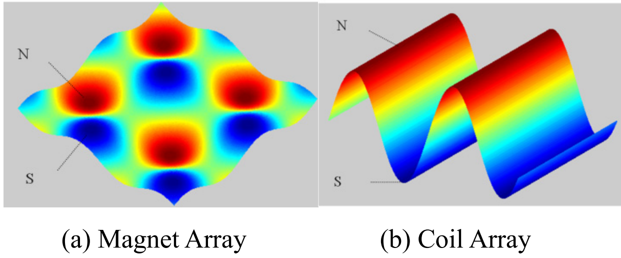


Fig. 2. The estimated magnetic field of MagLev module

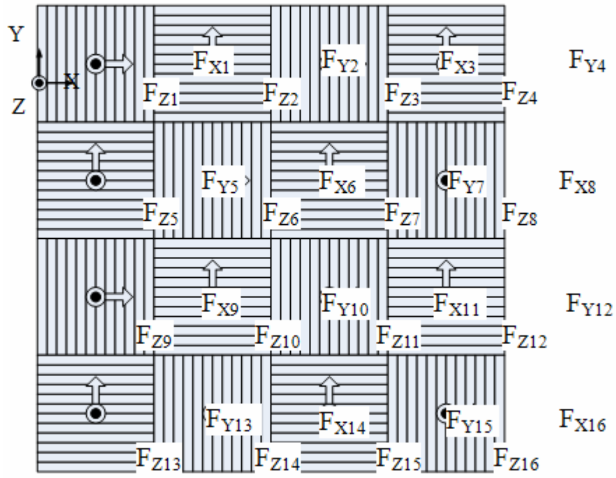


Fig. 3. The proposal coil array (4 x 4) for novel magnetic levitation stage

F_{Z1}, F_{Z2}, …, F_{Z16}. This force is the levitation force of the stage. The net force of X direction on the central position is the sum of F_{X1}, F_{X3}, F_{X6}, F_{X8}, F_{X9}, F_{X11}, F_{X14}, F_{X16}. The net force of Y direction on the central position is the sum of F_{Y2}, F_{Y4}, F_{Y5}, F_{Y7}, F_{Y10}, F_{Y12}, F_{Y13}, F_{Y15}. These forces are the traction force of the stage. The rotation torque (Yaw) of Z axis on the central position also can be generated with composed X and Y direction forces. The rotation torques (roll and Pitch) of X and Y axis on the central position also can be generated with composed Z direction force [6].The formulas of these forces and torques are as followings:

$$F_Z = F_{Z1} + F_{Z2} + \cdots + F_{Z16} = \mathrm{m} \cdot \mathrm{g} \tag{5}$$

$$F_X = F_{X1} + F_{X3} + F_{X6} + F_{X8} + F_{X9} + F_{X11} + F_{X14} + F_{X16} \tag{6}$$

$$F_Y = F_{Y2} + F_{Y4} + F_{Y5} + F_{Y7} + F_{Y10} + F_{Y12} + F_{Y13} + F_{Y15} \tag{7}$$

$$\tau_Z = y_1 \cdot F_{X1} + x_2 \cdot F_{Y2} + y_3 \cdot F_{X3} + x_4 \cdot F_{Y4} + x_5 \cdot F_{Y5} + y_6 \cdot F_{X6} + x_7 \cdot F_{Y7} + y_8 \cdot F_{X8} + y_9 \cdot F_{X9} + x_{10} \cdot F_{Y10} + y_{11} \cdot F_{X11} + x_{12} \cdot F_{Y12} + x_{13} \cdot F_{Y13} + y_{14} \cdot F_{X14} + x_{15} \cdot F_{Y15} + y_{16} \cdot F_{X16} \tag{8}$$

$$\tau_X = y_1 \cdot F_{Z1} + y_2 \cdot F_{Z2} + y_3 \cdot F_{Z3} + y_4 \cdot F_{Z4} + y_5 \cdot F_{Z5} + y_6 \cdot F_{Z6} + y_7 \cdot F_{Z7} + y_8 \cdot F_{Z8} + y_9 \cdot F_{Z9} + y_{10} \cdot F_{Z10} + y_{11} \cdot F_{Z11} + y_{12} \cdot F_{Z12} + y_{13} \cdot F_{Z13} + y_{14} \cdot F_{Z14} + y_{15} \cdot F_{Z15} + y_{16} \cdot F_{Z16} \quad (9)$$

$$\tau_Y = x_1 \cdot F_{Z1} + x_2 \cdot F_{Z2} + x_3 \cdot F_{Z3} + x_4 \cdot F_{Z4} + x_5 \cdot F_{Z5} + x_6 \cdot F_{Z6} + x_7 \cdot F_{Z7} + x_8 \cdot F_{Z8} + x_9 \cdot F_{Z9} + x_{10} \cdot F_{Z10} + x_{11} \cdot F_{Z11} + x_{12} \cdot F_{Z12} + x_{13} \cdot F_{Z13} + x_{14} \cdot F_{Z14} + x_{15} \cdot F_{Z15} + x_{16} \cdot F_{Z16} \quad (10)$$

Here, $x_{n=1,2,\cdots,16}$ and $y_{m=1,2,\cdots,16}$ are x and y position of center of each coil modules. m is mass of mover and g is acceleration due to gravity.

2.3 The real structure

We proposed the real structure of the novel magnetic levitation stage as shown in Fig. 4 and Fig. 5. It is composed of the stator part and the mover part. The stator part is composed of 100(=10 x 10) coil module arrays (I-1) which are checkered matrix structure and the stator frame (I-2). The mover part is composed of the PM array (II-1), the mover frame (II-2), two plane mirrors (II-3) for the laser interferometer system, and three capacitance sensors (II-4). The area of PM array is same with 4 x 4 coil module arrays. We used three laser interferometer systems (III) with composed of the stator part and the mover part. The stator part is composed of 100(=10 x 10) coil module arrays (I-1) which are checkered matrix structure and the stator frame (I-2). The mover part is composed of the PM array (II-1), the mover frame (II-2), two plane mirrors (II-3) for the laser interferometer system, and three capacitance sensors (II-4). The area of PM array is same with 4 x 4 coil module arrays. 0.15nm of the resolution from Agilent Company to measure X, Y and Yaw motions and three capacitance sensors with 7.8nm from ADE Company of the resolution to measure Z, Pitch, and Roll motions.

The weight of the mover is about 12 [kg].

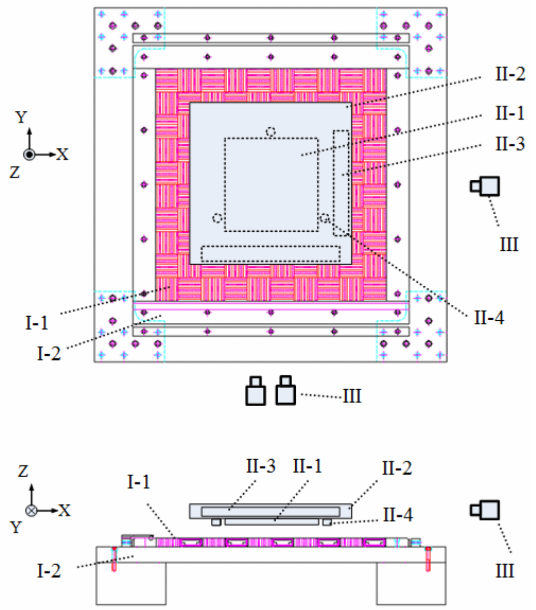


Fig. 4. The real structure of the magnetic levitation stage

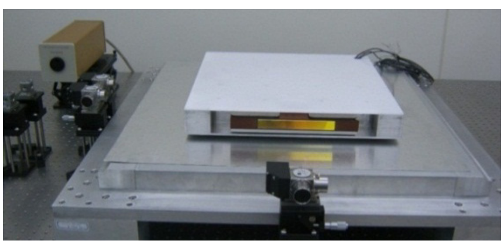


Fig. 5. The experimental system

2.4 The control block diagram

The control block diagram of the proposed novel magnetic levitation stage is shown in Fig. 6. For understandings, we can consider a structure made of an array of 16 coil modules (4x4matrixes) and an infinite PM array. The size of the 4x4 coilmodule array is same with the size of PM array in the actual structure.Thus, coil modules are completely faced by the magnet array, for anyposition of the mover.The **Controller** block takes the reference position vector (**P**$_r$) and the current position vector (**P**), apply the control algorithm providing the values of DQ currents (**I**$_D$[16] and **I**$_Q$[16]) for all the coil modules. A position vector contains mover's coordinates in six degree of freedom (X, Y, Z, θ_X, θ_Y, θ_Z). The control algorithm is run for all 16 coil modules resulting 16 values of **I**$_D$ and 16 values of **I**$_Q$. This block is completely implemented in software.The **Current generation** block makes the transformation from DQ currents (**I**$_D$[16], **I**$_Q$[16]) to 3 phase currents (**I**$_A$[16], **I**$_B$[16], **I**$_C$[16]) by software and outputs the values by means of linear drivers.The **Electromagnetic block** contains the interaction between the coil modules and PM array which yields the vertical (**F**$_Z$[16]) and lateral (**F**$_X$[8] or **F**$_Y$[8]) forces.The **Mechanical block** is the mover whose position is changed by the forces. The mover's position is measured in the **Position measurement** block resulting **P**. All the

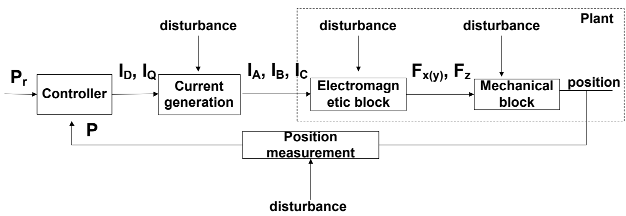


Fig. 6. The Control Block Diagram

other blocks except the **Controller** can be affected by specific disturbances.The basic control algorithm is Lead PI controlleras the following:

$$H(s) = K\frac{s+A}{s+B}\frac{s+C}{s} \quad (11)$$

2.5 The structure of control system

The structure of control system is shown in Fig. 7. The control system is composed with higher level control part and lower level control part. The higher level control part which is the Master DSP board manages measurement of positions of mover with laser interferometer and capacitor probe and calculation of 16 local position of the mover.These position values are transferred to lower level control part. The lower level control part which is seven numbers of Slave DSP board manages executions of control algorithm and command to the Linear Driver Module.

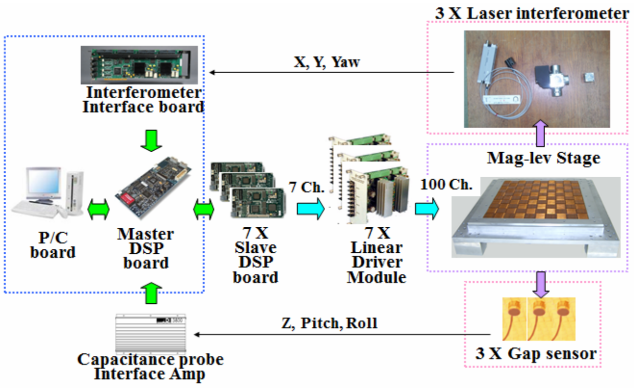
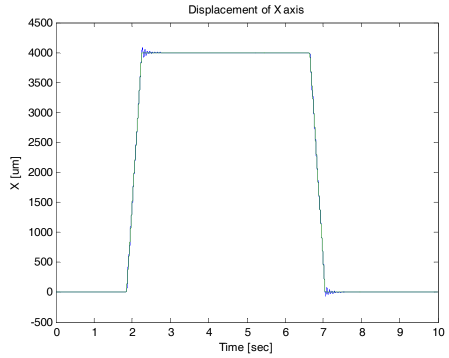


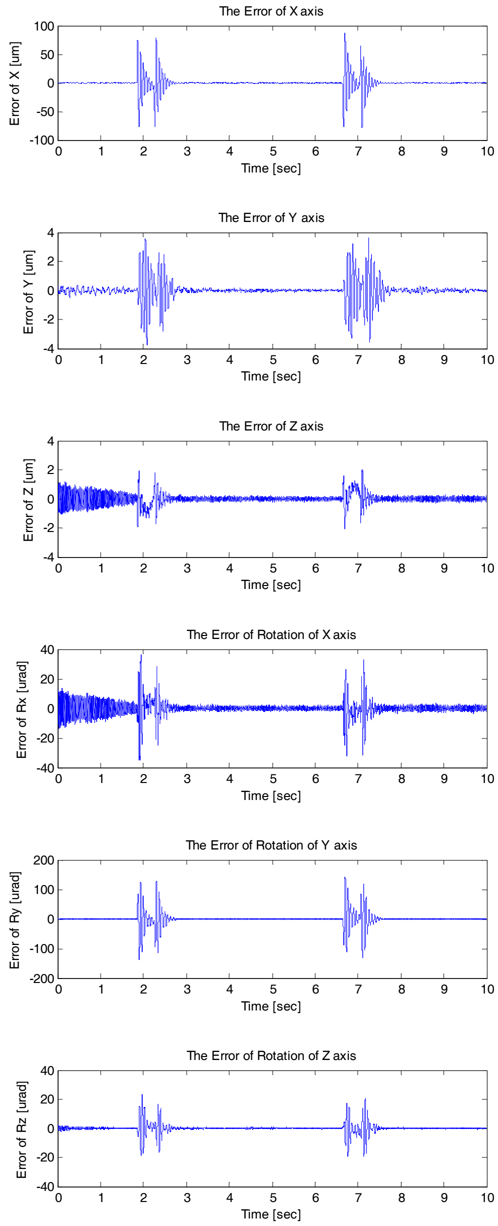
Fig. 7. the structure of control system

3. The Results of Experiment

The results of short distance (4 [mm]) step and settle motion are shown in Fig. 8. Here, the nominal levitation gap is 100 [um] and the nominal speed is 10 [mm/sec]. The results of steady errors of each axis after settle are [X, Y, Z, Rx, Ry, Rz]≤ [±200nm, ±200nm, ±250nm, ±3urad, ±2urad, ±1urad]. It shows that nano scale positioning can be done. The results of long distance (160 [mm]) step and settle motion are shown in Fig. 9. Here, the nominal levitation gap is 200 [um] and the nominal speed is 20 [mm/sec]. The results of steady errors of each axis after settle are [X, Y, Z, Rx, Ry, Rz]≤ [±200nm, ±200nm, ±250nm, ±1.5urad, ±2urad, ±0.5urad]. It shows that wafer size movement as well as nano scale positioning can be done. The results of circle motion with 6 [mm] diameter are shown in Fig. 10. Here, the nominal levitation gap is 200 [um] and the nominal speed is 10 [mm/sec]. The results of tracking error of each axis are [X, Y, Z, Rx, Ry,

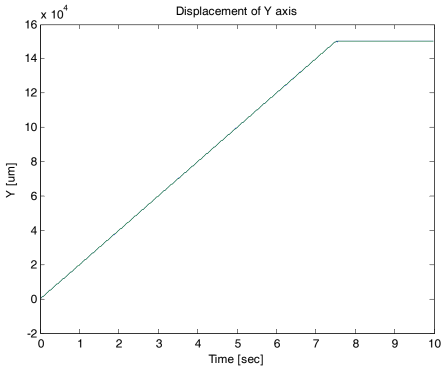


(a) The short step and settle motion

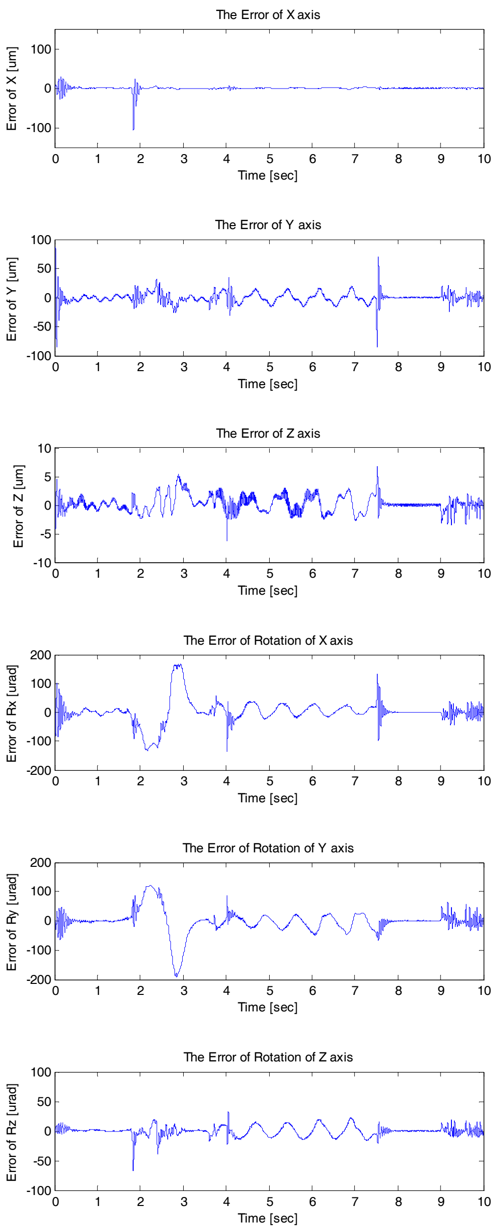


(b) The errors of each axis

Fig. 8. the results of 4 [mm] step and settle motion

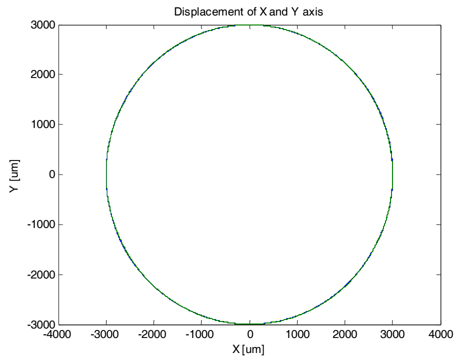


(a) The long step and settle motion

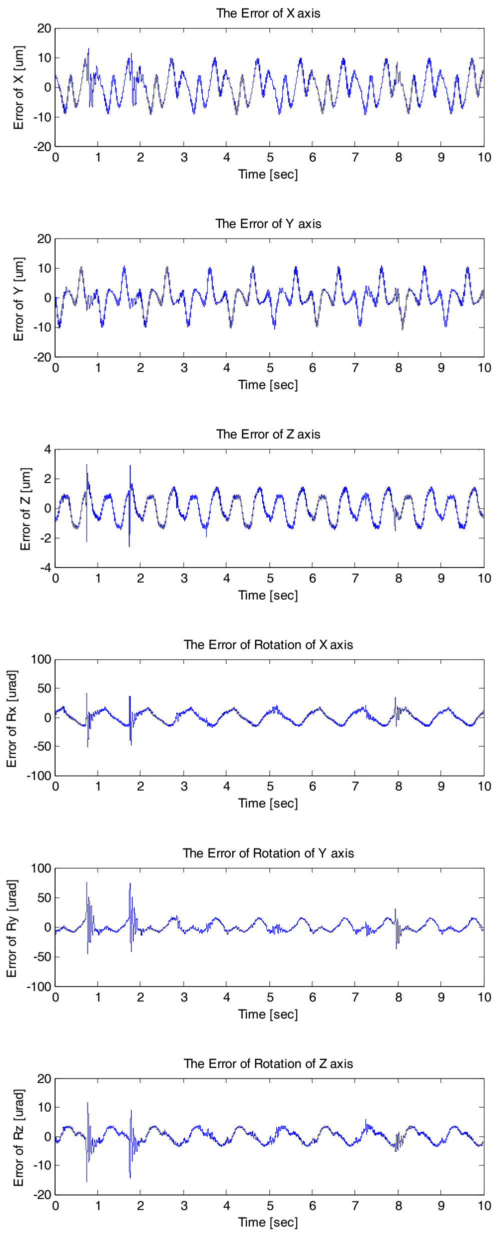


(b) The errors of each axis

Fig. 9. the results of 160mm step and settle motion



(a) The circle motion



(b) The errors of each axis

Fig. 10. the results of circle motion test with 6mm diameter

Rz]≤[±10um, ±10um, ±3um, ±20urad, ±20urad, ±5urad]. It shows that the good synchronous movement of X and Y directions as well as control of other axis can be done.

4. Conclusions

This paper shows some experimental results of proposednovel magnetic levitation stage system without other assistant devices. This system has 10 x 10 coil arrays which are checkered matrix structure and PM arrays which are correspondence with 4 x 4 coil arrays. The results of short (4 [mm]) and long distance (160 [mm]) motion test shows that the proposed magnetic levitation stage system can be moved in wafer size as well as in nono scale positioning.

Also, the results of circle motion with 6 [mm] diameter shows that this proposed system can be moved simultaneously in X and Y directions.This novel magnetic levitation stage could be applied to nano-scale positioning stage for semiconductor.

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