Novel Cylindrical Magnetic Levitation Stage with High Precision Motion

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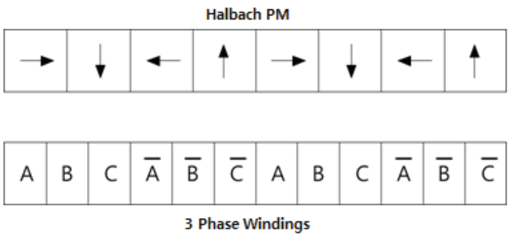
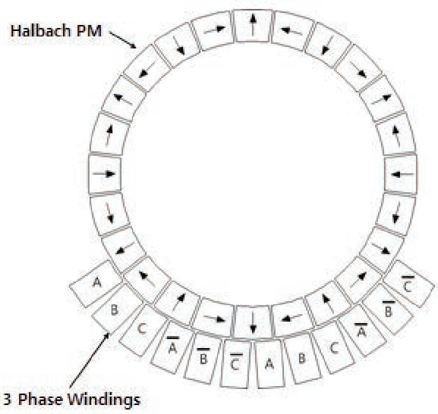
***Abstract*—This paper proposed novel cylindrical magnetic levitation stage. This stage can move the cylinder to rotations and translations as well as levitations with high precision in vacuum. This advantage is useful to make a nano patterning on the surface of cylindrical specimen by using electron beam lithography. In this paper, a conceptual design and a detailed design of the novel cylindrical magnetic levitation stage are shown. Firstly, mathematical modeling and simulation results are shown and then experimental results are compared after manufactured.**

I. INTRODUCTIONS

Nowadays, an application of nano patterns is expanding for display panels and solar cell as well as semiconductors. Roller type nanoimprint lithography is one of best solution to make a nano patterned mass production. There are lots of researches which are related with roller type nanoimprint lithography [1-2]. But, most of these researches are to imprint with a nano patterned flexible plate which was rapped on cylinder. A nano patterned area from those researches can be limited by such as a seam. If nano patterns can be directly manufactured on a surface of a cylindrical stamp, it is very useful to make a nano patterned mass production with roller type nanoimprint lithography. The cylindrical stamp can be manufactured by conventional lithography method such as electron beam lithography technology [3-4]. Here, a special bearing is needed to reduce errors from rotating machine. This special bearing should be rotated with nano resolutions in vacuum. One of best solutions is a magnetic-typed bearing [5-6]. The magnetic-typed bearing can be controlled with nano resolutions and operated in vacuum. But, there are two limitations. The one is that the most magnetic bearing cannot be moved along axles of it. The other is that there is interfere to install with electron beam column. In this paper, novel cylindrical magnetic levitation stage which is proposed can overcome those limitations. A concept of this stage was come from planar typed magnetic levitation stage [7-8]. The cylindrical magnetic levitation stage can move rotations and translations as well as levitations without contacts. A conceptual and detailed design was already proposed [9]. The cylindrical mag-lev stage is composed of a mover and a stator



(a)



(b)

Figure 1. Concepts of MagLev Stage (a) The Plane-Type MagLev Stage (b) The Cylindrical-Type MagLev Stage

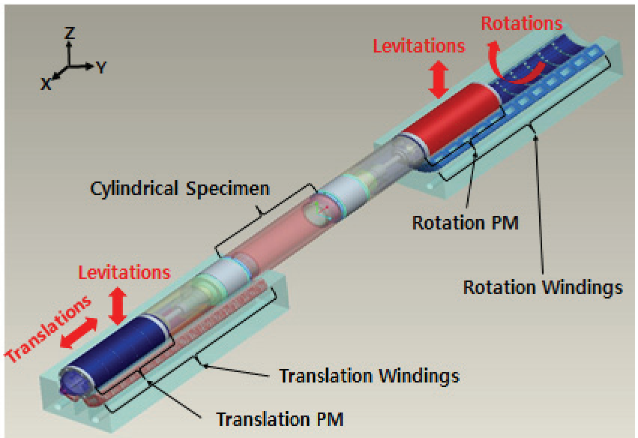


Figure 2. The Novel Cylindrical-Type MagLev Stage (3D Model)

part. The mover part is composed of permanent magnet array and the stator is composed of winding array. This cylindrical mag-lev stage is installed and tested on a test bench and is successfully levitated and maintained with high precisions.

II. DESIGN

A. Conceptual Design

Conventional plane-type MagLev Stage is shown in Fig. 1 a). A magnetic repulsion force is generated between Halbach array and windings by properly induced currents at windings. The magnetic repulsion force can generate a traction force as well as a levitation force simultaneously. The mover can be levitated by the levitation force and then moved horizontally by the traction force. A conceptual design of novel cylindrical maglev stage is shown in Fig. 1 b). The Halbach permanent magnet array can be formed like a cylinder shape. The 3 phase winding can be formed like a hemi-cylinder shape. A magnetic repulsion force between cylindrical shaped permanent magnet array and hemi-cylindrical shaped 3 phase windings can be generated similar with it of plane-type maglev stage. This force can generate a rotation force (instead of a traction force at plane-type maglev stage) as well as a levitation force.The 3D model of the novel cylindrical maglev stage is shown in Fig. 2. It can be levitated and then rotated as well as translations of axial with contactless. The cylindrical maglev stage is composed of a cylindrical shape mover and two hemi-cylindrical shape stators. The mover is composed of cylindrical specimen and two cylindrical-shape Halbach permanent magnet array. These Halbach magnet arrays are assembled on both ends of the cylindrical specimen. Array directions of these Halbach magnet array are perpendicular each other. Two hemi-cylindrical shape stators are composed of 3 phase windings. Array directions of two stators are also perpendicular each other like as two magnet array. The mover is put on two stators.

B. Detailed Design

A detail designed cylindrical maglev stage is shown in Fig. 3. Magnetic repulsion forces are generated between Halbach permanent magnet array and 3 phase windings. It can generate traction forces as well as levitation forces. Here, the traction forces are differently generated due to the array direction of permanent magnet and windings. In Fig. 3 (a), the array directions of permanent magnets and windings are located with rotationally. Rotation forces as well as levitation forces are generated. In Fig. 3 (b), the array directions of permanent magnets and windings are located along the axial. Translation forces as well as levitation forces are generated. Two-type permanent magnet arrays are combined in the mover. All magnetic force which are generated from two-type permanent magnet arrays and 3 phase windings are combined due to a properly induced current at windings. Finally, the mover can be rotated and translated simultaneously as well as levitated.

C. Magnetic Forces

In Fig. 3, the 3 phase windings are assembled with I and J rows. One winding module (which is indicated by RED dotted line) is composed of 6 windings. The magnetic repulsion force (Fn) can be represented by Lorenz force. The Lorenz force is

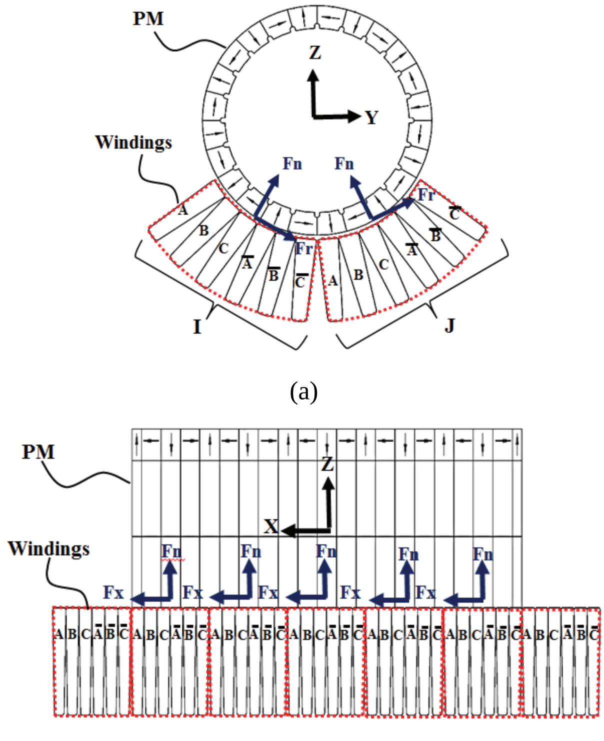


Figure 3. The Detailed Design of Novel Cylindrical-Type MagLev Stage (a) The Front View of the Rotational Part (b) The Side View of The Translation Part

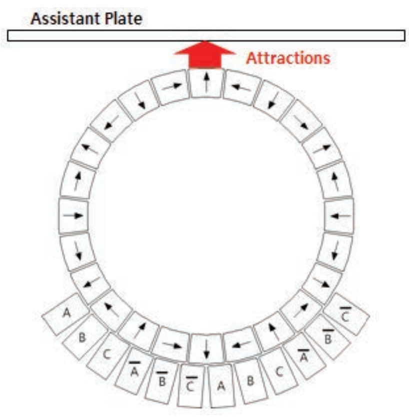


Figure 4. The Concept of Assistant Plate

generated at between 3 phase winding module and permanent magnet array. A direction of the magnetic repulsion force (Fn) is determined by a direction of 3 phase winding module. Values of direction of I and J windings are ±30°. The magnetic repulsion force (Fn) can be divided by the magnetic levitation force (Fz) and the magnetic guidance force (Fy). In Fig. 3 (a), the orthogonal force (Fr) of the magnetic repulsion force (Fn) can be generated due to rotationally arrangements of permanent magnet array and 3 phase winding array. The mover can be rotated. In Fig. 3 (b), the orthogonal force (Fx) of the magnetic repulsion force (Fn) can be generated due to straightly arrangements of permanent magnet array and 3 phase winding array. The mover can be translated.

D. Assistant Force

The magnetic levitation force can be controlled by induced currents at 3 phase winding module. Here, high currents cause high temperature of windings. This is disadvantage in vacuum because a heat cannot transfer through vacuum. In this research, the assistant plate of magnetic levitation is considered to reduce heat problem of windings as shown in Fig. 4. This plate is located upper of the permanent magnet. The attraction force which is generated between plate and permanent magnet can help to levitate the cylindrical mover. This assistance force can be adjusted by distance between plate and permanent magnet. Induced currents can be reduced due to this assistance force. Here, the amount of assistant force is considered with a half of total required levitation forces.

III. MODELING

A. Mathematical Model

The magnetic repulsion forces are generated between the permanent magnets and 3 phase windings for reason of Lorentz Force. These forces are composed of the magnetic repulsive force (Fn) and the orthogonal force (Fr and Fx) which are shown in Fig. 3. The formulas of these forces for one pitches of the magnetic levitation stage are as the following equations [7-9]:

$$\begin{bmatrix} F_r, F_x \\ F_n \end{bmatrix} = \frac{1}{2}\mu_0 M_0 \eta_0 N_m G e^{-\frac{2\pi}{l} z_0} \begin{bmatrix} i_q \\ i_d \end{bmatrix} \quad (1)$$

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

Here, $\mu_0 M_0$ which is magnet remanence is 1.465 [T], η_0 which is turn density is 1.6026e^{+6} [Turn/mm^2], N_m which is number of active magnet pitch is 1, ω which is permanent magnet width of one pitch is 52.18 [mm], l which is 3 phase winding width of one pitch is 52.18 [mm], Γ which is PM array thickness is 10 [mm], Δ which is coil array thickness is 14.04 [mm], z_0 which is Nominal gap is 0.95 [mm]. The repulsive and orthogonal forces of one pitch of our magnetic levitation stage are as the following:

$$\begin{bmatrix} F_r, F_x \\ F_n \end{bmatrix} = 12.1695 \begin{bmatrix} i_q \\ i_d \end{bmatrix} \quad (3)$$

If the values of input current (i_q, i_d) are 1 [A] for each, the values of repulsive force (Fn) and orthogonal force (Fr, Fx) are 12.1695 [N]. The magnetic repulsive force (Fn) is composed of vertical forces (Fz) and horizontal forces (Fy) which are the following equations:

$$\begin{bmatrix} F_z \\ F_y \end{bmatrix} = \begin{bmatrix} F_n \cdot \cos\theta \\ F_n \cdot \sin\theta \end{bmatrix} \quad (4)$$

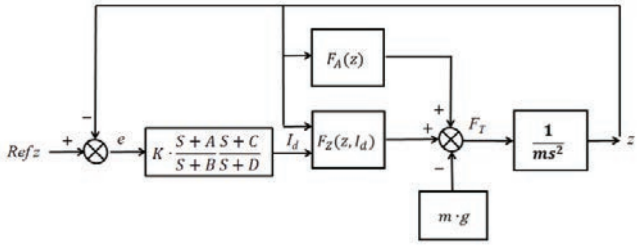
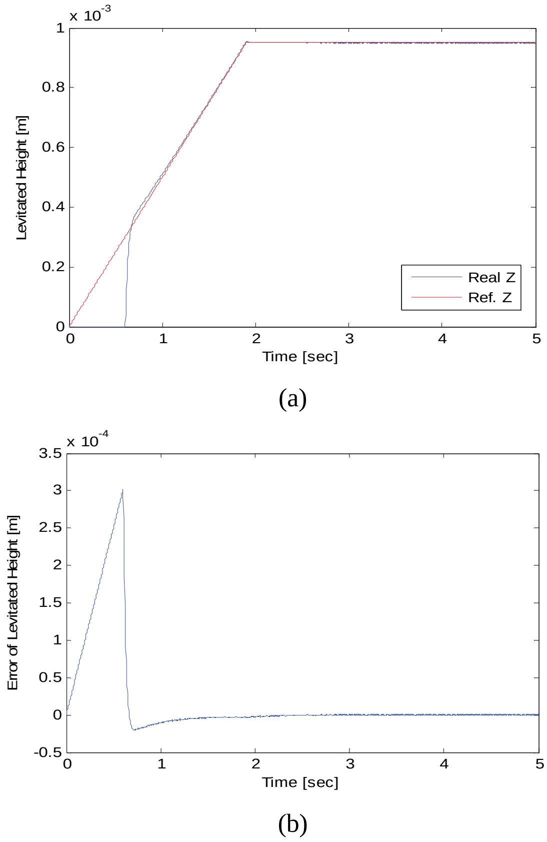


Figure 5. The Dyanmic Model of Simulation



(a)

(b)

Figure 6. The Simulation Results (a) Levitation (b) Error

Here, θ is the angle of the magnetic repulsive force and the value is 30 degree. The values of vertical forces (Fz) and horizontal forces (Fy) are about 10.5391 [N] and about 6.0847 [N]. If the valid ratio of winding shape (L2/L1 = 0.731) is considered, these values is corrected by 7.7041 [N] and 4.4479 [N]. Here, a sum of vertical forces (Fz) is 154.0814 [N] because a number of one pitch winding modules of rotation part and translation part are 10 each other. This calculated magnetic vertical force (Fz) is not much different than results from the above analysis.

B. Dynamic Model

The dynamic model for simulation of magnetic levitation is configured in Fig. 5. The levitation height (z) is feed back into the controller, the assistant force calculation model and the magnetic levitation stage model. The controller output (Id) is feed into the magnetic levitation stage model. The dynamic model of the cylindrical magnetic levitation stage is as the following equations:

$$m \cdot \ddot{z} = F_z(z, I_d) + F_A(z) - m \cdot g \quad (5)$$

Here, m is total mass of the mover and the value is 30 [kg], z is the levitation height, I_d is input currents of 3 phase windings, Fz(z, I_d) which is came from equation (2) is total vertical force of magnetic repulsive forces (Fn), $F_A(z)$ is the attractive force between the assistant plate and permanent magnets, g is gravity accelerations. Total vertical force (Fz(z, I_d)) is sum of each 10 winding modules of the rotation part and the translation part. The assistant force ($F_A(z)$) is calculated by the electromagnetic FEM analysis. The assistant force ($F_A(z)$) is as following equations:

$$F_A(z) = 4{,}948e(-238.1 \cdot z) + 24.02e(11.78 \cdot z) \quad (6)$$

Here, total assistant force is twice time of $F_A(z)$ because these assistant forces are simultaneously generated at the rotation part as well as the translation part. The Lead-Lag compensator is used for magnetic levitation control as following equations:

$$C(s) = K\frac{s+A}{s+B}\frac{s+C}{s+D} \quad (7)$$

Here, K = 1.051 x 10^6, A = 38.7857, B = 1252.3954, C = 2.9483, D = 0.0013. The linearization result of closed loop system with controller at steady state is:

$$G(s) = \frac{6.054\times10^5(s+38.79)(s+2.948)}{(s+41.02)(s+3.061)(s^2+1{,}208s+5.513\times10^5)} \quad (8)$$

Here, crossover frequency is 356.6469 [rad/sec] and phase margin is 134.9171 [deg].

C. Simulations

The simulation results of dynamic model are shown in Fig. 6. A reference levitation height (Ref. Z) is smoothly increased up to 950 [um]. This is to minimize transient state at the beginning of levitations. In Fig. 6 (a), the real levitation height (Real Z) is very well following the reference. In Fig. 6 (b), the error is maintained within small ranges. After levitations, the net force of assistant plates is about 166 [N] and the net force of magnetic levitation is about 128 [N]. The total levitation force which is sum of these forces is about 294[N]. The current of one winding module is about 0.83 [A]. The assistant force is help to reduce required currents of winding modules for levitations.

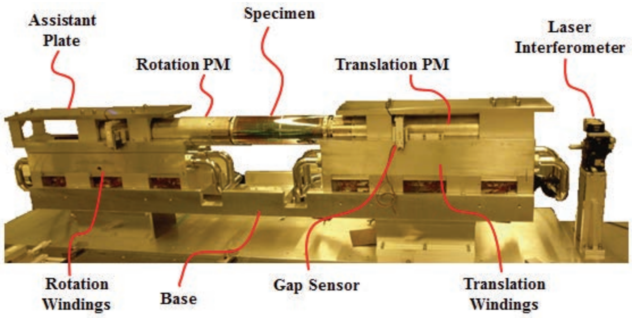
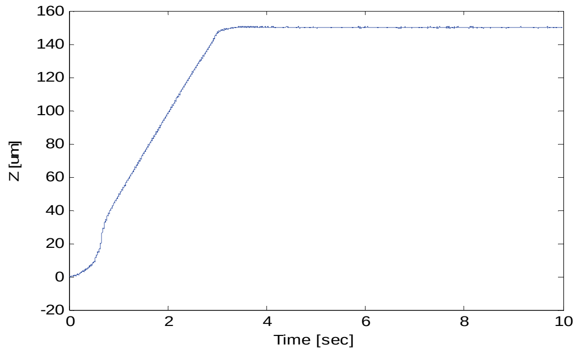
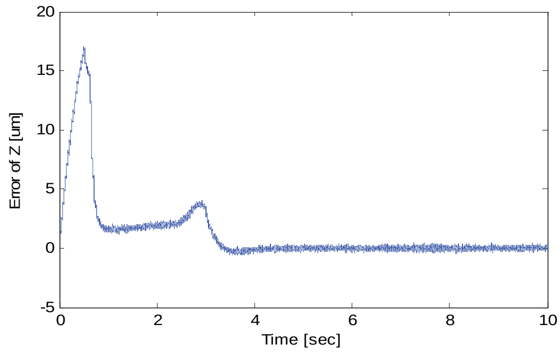


Figure 7. The Test Bench



(a)



(b)

Figure 8. The Experimental Results (a) Levitation (b) Error

D. Experiments

The test bench of cylindrical maglev stage is shown in Figure 7. This test bench is composed of a base part, mover parts (cylindrical specimen, rotation PM, and translation PM), stator parts (rotation windings and translation windings), assistant plates, cooling pipe, and measurement sensors (one laser interferometer, four capacitive probe sensors, and one optical rotary encoder). The levitation test results of cylindrical maglev stage are shown in Fig. 8. The goal of levitation height is 150 [um]. The beginning of levitation is shown to unstable situations. After take-off, the error is shown to be stable. The errors of Z axis is maintained under 1 [um].

IV. CONCLUSIONS

This paper proposed novel cylindrical magnetic levitation stage. This stage can move the cylinder to rotations and translations as well as levitations with high precision in vacuum. This advantage is useful to make a nano patterning on the surface of cylindrical specimen by using electron beam lithography. The cylindrical specimen with nano patterned is applicable for roller-typed nano imprint lithography for mass productions. The mathematical modeling was used for dynamic simulation with the lead-lag compensator. The assistant plates which were located at top of the permanent magnet array were considered. These plates are useful to reduce required currents of winding modules for levitations and minimize heat problems in vacuum. The simulation and experimental results were shown that the cylindrical stage can be levitated and controlled by the lead-lag compensator. For the future, experimental results of rotations as well as translations will be showed.

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