Feasibility of Air Levitated Surface Stage for Lithography Tool*

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Abstract
The application of light-weight drive technology into the lithography stage has been the current state of art because of minimization of power loss. The purpose of this article is to point out the so-called, "surface stage" which is composed of Lorentz forced 3 DOF (Degree Of Freedom) planar motor (x, y and theta z), air levitation (bearing) system and motor cooling system, is the most balanced concept for the next generation lithography through the verification of each component by manufacturing simple parts and test stand. This paper presents the design method and procedure, and experimental results of the air levitated surface stage which was conducted several years ago, however the author is convinced that the results are enough to adapt various developments of precision machining tool.

Key words: Lithography Tool, Wafer Stage, Linear Motor, Planar Motor, Air Bearing, Motor Cooling, Magnetic Levitation

1. Introduction

Global warming has become a serious worldwide problem recently and there are two possible solutions to the problem as follows, 1) adoption of higher efficient system (stable system); and 2) promotion of 3 R (Reduce, Reuse and Recycle). The author, in parallel, has investigated the possibility of using 3R in semiconductor manufacturing tools in terms of costs and has found that the recycling cost of engineering ceramics is much higher than conventional metals. For this reason and others, some ideas of 6 DOF MAGLEV (Magnetic Levitated) stage which is basically composed of certain kinds of metals, have been studied. However, it is generally hard to eliminate the power consumption for this stage even if a zero-power concept(1) is adopted.

Currently, in semiconductor lithography, the technologies of both ArF(Argon-Fluorine Excited dimer laser) immersion lithography with a multi-exposure system and leading-edge EUVL (Extreme Ultra Violet Lithography) have been extremely accelerated in order to realize the following top three indexes, "smaller and thinner patterns of a few dozen nanometer on wafer devices", "increment of throughput" and "reduction of footprint". Since these targets should be identified, materials of higher stiffness ratio (=stiffness/density) and elements of a higher power ratio (=force constant/mass) are the common benchmarks in not only this field but also in every transportation system from the viewpoint of controlling power consumption.

Some drastic innovations have been typically invented at the stagnation of economic and technical competition. In the early days, a linear drive system made up of linear motor and air bearing was generated in place of a non-linear drive system of rotation motor and rack and pinion unit to implement a higher bandwidth of control by eliminating non-linear...
parts, for instance friction and backlash. In general, it is said that innovation brought about a de facto standard of x and y stage design in a widespread industrial field, especially lithography tool, and was considered as the kind of common platform which is mostly effective for cost reduction. Recently, some MAGLEV 6 DOF concepts have been very actively investigated\(^2(3)(4)\), however both the initial cost of R&D, including manufacturing and debugging cost, and the running cost of power consumption may not be offset no matter how effective this vacuum compatible concept is. There are many significant indexes to evaluate the lithography tool, indicated in followings; 1) preciseness, 2) throughput, 3) footprint, 4) cost (initial and running), 5) date of delivery, 6) tool weight, 7) facility (gases, electricity) and 8) environmental compatibility. The interaction between indexes largely exists; however, indexes for 1) to 3) should be comparatively independent of each other and should be fixed at the beginning of development. Furthermore, 4) and 5) as well as the others are relevant to the concept of each component of equipment. The MAGLEV 6 DOF "reticle" stage was already developed by the author\(^5(6)\), obtaining good results because of the long scanning traveling and short orthogonal adjusting axis. On the other hand, it is easily shown that the development of MAGLEV 6 DOF "wafer" stage implies wasting a lot of time and resource for the large planar compensation. For example, the decoupling of the axes at x and y long traveling plane must be diligently overcome. Therefore the air-levitated 3 DOF wafer stage is focused on in this paper to reduce 4) cost (initial and running) and 5) date of delivery. This is on condition that an additional 6 DOF fine stage is mounted on the 3 DOF stage and a differential vacuum pumping system will be adopted for vacuum lithography tool\(^5\). Some excellent investigations of the stage possibility have been already performed\(^7(8)(9)(10)\), however it seems premature for a practice use in a lithography tool. In this paper, the concept of surface stage is introduced at first, then the procedure of design is indicated exactly.

2. Concept, details and analytical verification of design

2.1 Planar Motor

The schematic diagram of surface stage is shown in Fig. 1 and is basically composed of three unit, planar motor, air bearing and motor cooling system. The position of 6 DOF fine stage is measured and controlled by laser interferometers and the position of 3 DOF surface coarse stage is controlled by using the above interferometers and XY-2D encoder or gap sensors between fine and coarse stage that is not shown in Fig. 1.

The main specifications of surface stage is as follows: 1) acceleration (X & Y): 2 G peak (recently updated to >5 G), 2) velocity (X & Y): 0.5 m/s, 3) positioning accuracy: 1 µm, 4) bandwidth of control (X, Y & \(\theta_z\)): 50 Hz (mechanical stiffness should be typically four times higher than the bandwidth) and 5) temperature rise of the moving stage: <0.1 degC.

![Fig. 1](image-url)  Schematic diagram of air levitated 3 DOF surface stage with 6 DOF fine stage. The surface stage is levitated on the guide surface by air injection underneath of stage. Both fine stage and surface stage of coarse stage are measured independently; this figure shows the fine stage is controlled by laser interferometer of 0.15 nm resolution.
Fig. 2  Configuration of planar motor. Squared magnets attached to the moving metal plate (back yoke) are arranged on every other pitch of magnet width in x and y plane. On the other hand, squared armature coils whose width is coincident with the three times of magnet width, are mounted adjacent on the stationary plate (coil yoke).

Commonly, the motor is roughly divided into three driving methods, "Lorentz", "Pulse(Stepping)" and "Induction" without hybrid of them, and a Sawyer motor is very common as Pulse type and is developed at many organizations for its higher motor efficiency\(^9\). However, high-band vibration and noise is increased in proportion to a rise of stage velocity, therefore some compensation methods of positioning control is required to achieve a higher accuracy.

Meanwhile, there are generally two types of motor, moving magnet and moving coil, an advantage of the former is to be able to ignore tubes and wires of moving stage, on the other hand, the disadvantage is the need to permit a pitching and rolling torque because a driving force is generated at coils for the case of Lorentz type motor. However cooling of fixed coil is much easier and limit of temperature rise can be relaxed.

The concept of planar motor which is one component of surface stage is two dimensional array of moving magnet and configuration of two phase armature coil that corresponds to the magnet array. Figure 2 shows a concept of planar motor in which the magnets are aligned by every other pitch and an opposite polar on the grid of the plane. As shown in Fig. 2, since two phase coils are excited correspond to the position of magnet array, the total x and y force of the moving part is obviously constant.

Assuming that a) an origin of coordinate system (x,y) which is fixed on stationary coils is the center of one coil and b) a magnetic field at the coils is sinusoidal, the distribution of z component of magnetic flux density at magnetic field synthesized from multi magnets is represented as following.

\[
B_z(x,y)=B_{z0} \cdot \sin(x/Mw \cdot \pi/2) \cdot \sin(y/Mw \cdot \pi/2) \tag{1}
\]

Here, \(B_{z0}\) is a peak value of flux density, (x,y) is the location on the magnet array and Mw is a width of magnet. A width of coil, Cw is obviously three times of Mw. In addition, it is clear that one set of 2 x 2 coils (four coils) focused on detail area C in Fig.2 is magnetically repeated in the plane, so the z component of magnetic flux at active region of coil that contributed to the force for each x and y direction is expressed as,

\[
B_{z0}(dx,dy)=B_{z0} \cdot \cos(dx/Mw \cdot \pi/2) \cdot \sin(dy/Mw \cdot \pi/2) \tag{2}
\]
\[
B_{y0}(dx,dy)=B_{z0} \cdot \cos(dx/Mw \cdot \pi/2) \cdot \sin(dy/Mw \cdot \pi/2) \tag{3}
\]
Fig. 3 Compensation method of unexpected torque. The torque can be canceled and controlled by moment balance theorem while keeping x and y force independently.

\[ B_{x,i+1,j}(dx,dy) = B_{z0} \cdot \cos(dx/Mw \cdot \pi/2) \cdot \cos(dy/Mw \cdot \pi/2) \]  
\[ B_{y,i+1,j}(dx,dy) = B_{z0} \cdot \sin(dx/Mw \cdot \pi/2) \cdot \sin(dy/Mw \cdot \pi/2 + \pi) \]  
\[ B_{x,i,j+1}(dx,dy) = B_{z0} \cdot \sin(dx/Mw \cdot \pi/2 + \pi) \cdot \sin(dy/Mw \cdot \pi/2) \]  
\[ B_{y,i,j+1}(dx,dy) = B_{z0} \cdot \cos(dx/Mw \cdot \pi/2) \cdot \cos(dy/Mw \cdot \pi/2) \]  
\[ B_{x,i+1,j+1}(dx,dy) = B_{z0} \cdot \cos(dx/Mw \cdot \pi/2) \cdot \sin(dy/Mw \cdot \pi/2 + \pi) \]  
\[ B_{y,i+1,j+1}(dx,dy) = B_{z0} \cdot \sin(dx/Mw \cdot \pi/2 + \pi) \cdot \cos(dy/Mw \cdot \pi/2) \]

where, i and j coincides with the location of detail area C in Fig. 2 and dx and dy are displacement of stage motion. To explain how to obtain the constant force, y motion is neglected for easy understanding, dy = 0. Provided that the same form of sinusoidal current based on the stage motion is excited into each coil, we get following consequences.

\[ f_x(dx,0) = B_{z0} \cdot I_{i,j} \cdot \sin^2(dx/Mw \cdot \pi/2) + B_{z0} \cdot I_{i+1,j} \cdot \cos^2(dx/Mw \cdot \pi/2) \]  
\[ f_y(dx,0) = B_{z0} \cdot I_{i,j+1} \cdot \cos^2(dx/Mw \cdot \pi/2) + B_{z0} \cdot I_{i+1,j+1} \cdot \sin^2(dx/Mw \cdot \pi/2) \]

Here, \( f_x \) and \( f_y \) are a motor force per unit length of active coil, \( I_{i,j} \) and \( I_{i+1,j} \) are input current for x motion and the same value in this case while \( I_{i,j+1} \) and \( I_{i+1,j+1} \) should be zero. Finally, Eq. 10 becomes \( f_x(dx,0) = B_{z0} \cdot I_{i,j} \) that is constant as anticipated.

Next, let me explain the method of torque control. As shown in Fig.2, there are four sets of units which are composed of nine magnets and four coils in this example. The electromagnetism in physics mentions that the Lorentz force is orthogonally generated at coils excited in mutual and magnets are repelled back by reaction force consequently. It means that driving points on the moving stage are frequently varied and an unexpected torque is periodic at the condition of uniform current excitation to each coil. Figure 3 shows how to compensate and control the torque. If coils are excited by the same current, the unexpected torque is as following, where from F1 to F4 indicates a Lorentz force at each coil and L1(x), L2(x), L3(y) and L4(y) are a function of stage position(x,y) respectively.

\[ \text{Torque} = 2 \cdot F1 \cdot L1(x) + 2 \cdot F2 \cdot L2(x) + 2 \cdot F3 \cdot L3(y) + 2 \cdot F4 \cdot L4(y) \]

Provided that a moment balance theorem is adapted to the torque compensation while keeping total amount of x and y force, the torque can be controlled by using the following
explicit equations:

\[
\text{Torque}(x,y) = 2 \cdot F1(x) \cdot L1(x) + 2 \cdot F2(x) \cdot L2(x) + 2 \cdot F3(y) \cdot L3(y) + 2 \cdot F4(y) \cdot L4(y)
\]

Here, \(F_{\text{com}}, F_y, \text{and } T_{\text{com}}\) are force and torque command into a system.

If both the back yoke and coil yoke are magnetically saturated, a magnetic leak is emitted and surrounds the planar motor. This means not only that the performance of motor will be strictly limited but also that there will be an electromagnetic influence or coupling against a fine stage mounted on the surface stage. At any rate, it became a de facto standard that isolating and de-coupling mechanically, thermally and electromagnetically between fine stage and coarse stage should be observed in a lithography tool. Therefore, some ideas, for instance the Halbach method of magnet array or optimization of edge effect, may be actually applied. During the development of planar motor, an optimization program of planar motor design has been produced. Figure 4 shows a framework of the program in which there are basically four regions as follows:

1) Input region
a) design specifications: for instance moving mass, maximum acceleration and velocity, stage x and y stroke and electric requirements
b) design parameters: size and pitch of magnet, wire gage and thickness of coil

2) Database region
Several kinds of magnetic FEA (finite element analysis) which parameters are thickness of magnet and magnetic gap between magnet and coil yoke have been implemented beforehand in order to make a matrix of magnetic flux density at active coil location.

<table>
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<th>Design Specifications</th>
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<tr>
<td>(m_{\text{load}} = 28.5 \text{ kg})</td>
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<td>(V_{\text{max}} = 75 \text{ volt})</td>
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<tr>
<td>(I_{\text{max}} = 20 \text{ amp})</td>
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<tr>
<td>(Z_{\text{c}} = 5.5 \text{ mm})</td>
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<tr>
<td>(Z_{\text{c}} = 10 \text{ mm})</td>
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<tr>
<td>(P_{\text{t}} = 35.83 \text{ mm})</td>
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<td>(I_{\text{step}} = 13.48 \text{ amp})</td>
</tr>
<tr>
<td>(A_{\text{awg}} = 25)</td>
</tr>
<tr>
<td>(X_{\text{s}} = 430 \text{ mm})</td>
</tr>
<tr>
<td>(V_{\text{max}} = 75 \text{ volt})</td>
</tr>
<tr>
<td>(I_{\text{max}} = 20 \text{ amp})</td>
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<tr>
<td>(m_{\text{load}} = 28.5 \text{ kg})</td>
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<table>
<thead>
<tr>
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<td>(I_{\text{step}} = 13.48 \text{ amp})</td>
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<tr>
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<tr>
<td>(I_{\text{step}} = 13.48 \text{ amp})</td>
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<tr>
<th>RESULTS</th>
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<tbody>
<tr>
<td>(I_{\text{step}} = 13.48 \text{ amp})</td>
</tr>
<tr>
<td>(I_{\text{step}} = 13.48 \text{ amp})</td>
</tr>
<tr>
<td>(I_{\text{step}} = 13.48 \text{ amp})</td>
</tr>
</tbody>
</table>

Motor Design Engine

FEA Results

Fig. 4  Design program of planar motor that consists of four regions; input, database, calculation and output region. Regarding a database region, results of magnetic FEA is transformed into a numerical matrix.
3) Calculation region
Details are not shown in Fig. 4. It is just a mathematical calculation of vector and matrix. The range of parameters might be changed once a singular value is obtained.

4) Output region
Result of the calculation based on two parameters (row and column) shows motor constant and power consumption, etc.

The results proves that a set of a magnet pitch and thickness of 35.8 mm and 16 mm, wire gage of around 17.5 and magnetic gap of around 7.5 mm is the best solution in this case, then an amplifier or other key design can be started based on this results.

2.2 Air bearing system
Because magnets of planar motor are arranged like a checker board as mentioned in 2.2, multi air pad units can be installed between magnets. An advantage of this concept is that a magnetic attraction force between two yokes is used to get a preload for air bearing to maintain the higher stiffness of levitation. A schematic diagram is shown in Fig. 5 and Fig. 6 that shows a cross section of the surface stage to explain a preload of the system. A set of positive stiffness of air levitation and negative stiffness of magnetic preload makes a system quite stable and is very similar to conventional air bearing that is made up of air levitation and vacuum preload unit.

Fig. 5  Schematic view of air bearing system. Air pads and magnets are aligned every other portion such as a checker board. a) bottom view of a surface stage, b) one idea of air pad pattern and c) dimensions of air pad.

Fig. 6  Schematic view of preload for air bearing. Because higher stiffness of air bearing is required to obtain a higher positioning controllability of lithography stage, the balance point at which the air levitation force corresponds to magnetic attractive force plus gravity force of moving stage is a few micrometers higher than maximum stiffness point experimentally.
2.3 Motor cooling system

Fine temperature control of sub-deg C is necessary to guarantee a stage performance of µm or sub-µm level positioning control. Especially, if armature coils are installed inside an air guide block as described in this article, it is necessary to regulate a variation of surface deformation of air guide surface less than 0.5 µm which is almost equal to a temperature rise of the guide surface of 0.1 degC and to a rise of armature coils of 10 degC approximately. Therefore, the amount of heat generated by coils should be conducted to the opposite side of air guide. Motor cooling concept, so called “parallel flow” is shown in Fig. 7. An upper flow of laminar condition makes a laminar boundary layer inside the upper channel isolating the heat transfer from coils to the air guide surface effectively. On the other hand, a lower flow of turbulence condition makes a higher heat conductance inside the lower channel promoted the heat transfer from coils to the bottom of coil yoke. Because a thickness of thermal boundary layer is theoretically decided by flow rate and properties of coolant, a gap of top channel may be larger than the thickness to maintain a boundary layer region\(^{11}\). The thickness of layer is 1.5 mm and the gap of the channel is 2 mm in this article. To identify a top and bottom flow rate and other critical scales, a model of heat transfer network shown in Fig. 8 was earlier constructed. All considerable heat transfer paths and models, such as heat conduction and convection are included in the network.
The model is made up of heat balance equation and some thermal resistance equations expressed by a temperature gradient as followings.

\[ Q = Q_1 + Q_2 + Q_3 + Q_4 + Q_f + Q_w \] \hspace{1cm} (15)

\[ dT_i = R_i \cdot Q_i \hspace{1cm} \text{for} \ i = 1, 2, \ldots, Ne \] \hspace{1cm} (16)

where Q is an input heat generated by coils, Q1 and Q2 are heat transferred through an upper flow and through a post to air guide surface, Q3 and Q4 are heat transferred through a post to support frame which is not shown and finally Qf and Qw are heat absorbed to upper and lower flow that are illustrated in Fig. 8. Also, \( dT_i, R_i \), and Q indicate a temperature gradient, heat resistance and transferred heat between two points in heat transfer network in which Ne is a number of thermal resistance equations in the network respectively. Therefore, each temperature at any points of network can be identified by solving these simultaneous linear equations.

Since a top flow should be laminar, cross section of post at the top flow channel is strongly taken into account. After watching around aerospace industries to investigate an appropriate airfoil, the author finally found a NACA64 A218 shape shown in Fig. 9.

![Shape Data of NACA64 A218](chart)

**Shape Data of NACA64 A218 (percent value)**

\[ \begin{align*}
\alpha_{100} & = 0 \hspace{1cm} 10 \hspace{1cm} 20 \hspace{1cm} 30 \hspace{1cm} 40 \hspace{1cm} 50 \hspace{1cm} 60 \hspace{1cm} 70 \hspace{1cm} 80 \hspace{1cm} 90 \hspace{1cm} 95 \hspace{1cm} 100 \\
\beta_{100} & = 0 \hspace{1cm} 22.8 \hspace{1cm} 43.2 \hspace{1cm} 55.2 \hspace{1cm} 63.6 \hspace{1cm} 76.6 \hspace{1cm} 86.4 \hspace{1cm} 93.6 \hspace{1cm} 98.8 \hspace{1cm} 102.6 \hspace{1cm} 97 \hspace{1cm} 84 \hspace{1cm} 66.5 \hspace{1cm} 46.0 \hspace{1cm} 23.4 \hspace{1cm} 13.9 \hspace{1cm} 0 \\
\delta_{100} & = 225
\end{align*} \]

**Real post (airfoil) design**

![Post shape in a top flow to keep a laminar flow for making a thermal boundary layer.](image)

Fig. 9  Post shape in a top flow to keep a laminar flow for making a thermal boundary layer.

![FEA of thermal flow dynamics](image)

Fig. 10  FEA of thermal flow dynamics. The model represents a mirror boundary in parallel of flow direction and a half pitch offset of column of airfoils. An input heat is a constant 20 W per coil which is a worst case and a flow rate is an upper flow of 1.5 L/min and lower flow of 7.5 L/min. A commercial software "STREAM" is used.
To conform to how to maintain a thermal boundary layer by using the shape of NACA64 A218 in advance, FEA of thermal flow dynamics was carried out. One of the results is shown in Fig. 10 that seems as if a thermal boundary layer is relatively maintained. Furthermore, this figure shows a worst case scenario of simultaneous excitation of three coils, so a real case of independent switching excitation will be much better than this.

3. Experiment

3.1 Planar motor

The test stand to verify a planar motor performance is shown in Fig. 11. To facilitate testing and reduce development costs, the author employed the "proof of concept" philosophy and therefore, verification of air bearing and motor cooling was separated from this stand.

![Fig. 11 Test stand for verification of planar motor performance. The moving object of planar motor is attached to the XY guide with 6 DOF force sensor block](image1)

![Fig. 12 Moving part and stationary part of planar motor. The coils are wound by round shape wire and attached to the back yoke. On the other hand, the magnets of Nd-Fe-B are glued to the yoke.](image2)
The stage is constrained by X, Y linear guide with X and Y encoder and Z rotation guide with 6 DOF integrated force sensor in order to measure X and Y displacement and generated force and torque. Moving part and fixed part of planar motor for test stand is shown in Fig. 12. The moving magnet type motor as early mentioned indicates the moving part is composed of magnets and the field is magnetically limited. Therefore, number of magnets and edge shape of magnet should be experimentally and analytically optimized to avoid a saturation of magnetic flux inside yokes and for a uniform distribution of magnetic field on the magnet array as depicted in Fig. 12. The amplitude of magnetic flux density at air gap and force constant are shown in Table 1 which is compared with design values and FEA results. The difference between numerical design or FEA, and measurement results on force constant may come from the following reasons.

a) Armature coil was designed at a minimum tolerance (minimum dimensions)

b) Permanent magnet was used at a minimum properties in FEA (minimum B-H curve)

It will be evident to obtain a good coincidence provided that parameters of each element are finely adjusted based on manufacturing results in terms of productivity.

Next, dynamics test of the motor were performed. Figure 13 indicates a response of position feedback in which the stage is controlled by encoders and the result implies a bandwidth of servo is limited around 25 Hz due to a mechanical resonance frequency of 75 Hz which was caused by guide support beam. The target specification of control bandwidth of 50 Hz shown in 2.2.1 will be satisfied if an air bearing system is adapted to the planar motor because the system becomes a monolithic body. Furthermore, as a canceling method defined in Fig. 3 is adapted, a coupling between x/y force and z torque is achieved as less than 10%.

A simple, well used classic controller, PID, was adopted in this test, so the results will be much better when the better and more effective methods that have recently been developed are used, such as a modern controller, a robust or H-infinity controller, a model base.

Table 1  Comparison table of magnetic properties of planar motor

<table>
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<th>Design</th>
<th>FEA</th>
<th>Measured</th>
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<tbody>
<tr>
<td>Magnetic Flux Density T</td>
<td>0.48</td>
<td>0.48</td>
<td>0.48</td>
</tr>
<tr>
<td>Force Constant N/A</td>
<td>51.7</td>
<td>55.9</td>
<td>58</td>
</tr>
</tbody>
</table>

Fig. 13  Frequency response of position feedback control with torque cancelling. Horizontal and vertical axis is a frequency and position to position ratio respectively after fourier transfer from a measurement data of time domain.
controller, etc. Also passive or active vibration compensator can be used for the test; for example, a mass dumper or piezo actuator which is commonly used to decrease amplitude of resonance frequency in order to increase a bandwidth of control. These means are good for practice use, however it was not possible to prove the vibration compensation experimentally because series of test was finished over 10 years ago.

3.2 Air bearing system

Quarter part of full scaled air bearing unit shown in Fig. 14 was made to verify a manufacturability and controllability of flatness of monolithic ceramic block with multi air pad. Figure 14 shows a picture of quarter unit under measurement and results of height and flatness of each air pad. Height of each air pad was measured from regulated Jouban and the variation is less than 1.5 µm, so that it is no influence for an air levitation of 5 µm. In addition, slow grindings were repeatedly needed to obtain a desired flatness, however there was no critical difficulty during processing.

![Air bearing unit (1/4 model)](image)

**Fig. 14** Manufactured quarter model of air bearing. The results of height and flatness is also attached. Dimensions of air pad groove is same as a pattern shown in Fig. 5.

### Table 2  Results of air bearing test. Upper table shows the results of individual properties of each air pad, and lower table shows total properties of five air pads.

**a) Individual Air Supply**

<table>
<thead>
<tr>
<th>Pad No.</th>
<th>Design</th>
<th>Supply Pressure MPa</th>
<th>Air Flow Rate NL/min</th>
<th>Load N</th>
<th>Stiffness N/µm</th>
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<tr>
<td></td>
<td></td>
<td>-</td>
<td>0.455</td>
<td>8.75</td>
<td>299.9</td>
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</table>

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<tr>
<th>Pad No.</th>
<th>Design</th>
<th>Supply Pressure MPa</th>
<th>Air Flow Rate NL/min</th>
<th>Load N</th>
<th>Stiffness N/µm</th>
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<tr>
<td></td>
<td></td>
<td>-</td>
<td>0.455</td>
<td>8.75</td>
<td>299.9</td>
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</table>

**b) Batch Air Supply for five pads**

<table>
<thead>
<tr>
<th>Design</th>
<th>Air Gap µm</th>
<th>Design</th>
<th>Air Flow Rate (l/min)</th>
<th>Load (N)</th>
<th>Stiffness (N/\mu m)</th>
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<th>Air Gap µm</th>
<th>Design</th>
<th>Air Flow Rate (l/min)</th>
<th>Load (N)</th>
<th>Stiffness (N/\mu m)</th>
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**Measurement**

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<td>Air Flow Rate NL/min</td>
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<td>Load N</td>
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</tbody>
</table>
Table 2 indicates the results of air bearing experiment. The upper table shows characteristics of individual air pad and the measurement of the air flow rate is three times smaller than design value at large because an effective cross section area is tightened by a steep change of the area. On the other hand, the experimental values of load and stiffness agree well with the design results. The lower table shows the air bearing performance of five pads that the air is simultaneously supplied to the five pads by single tube and experimental results are relatively smaller than design value because the lower height of air pad which means larger air gap makes the performance inferior. The author carried out the experiment as follows.

a) Independence of air gap : 3, 5, 7 µm
b) Independence of supply pressure : 0.39, 0.45 MPa

The results are almost same as anticipated values and it is said that the air gap of maximum stiffness is less than 3 µm. Moreover, it came to light that the gradient of stiffness per unit pressure at 5 µm gap is approximately 300 N/m and the gradient of stiffness per gap at 0.45 MPa is around -7 N/µm². A numerical design was done by using nikon’s original and reliable software.

### 3.3 Motor cooling system

It is well known that a heat expansion and fluctuation intensively affect position control of the lithography stage, therefore the temperature rise is restricted less than critical value which comes from the permissible error for the measurement. The test fixture that is manufactured based on the concept of Fig.8 to Fig.10 and the results are shown in Fig. 15 and Fig.16. In this test, the flow rate of the upper and lower flow is 1.5 L/min and 7.5 L/min respectively and the coolant is fluorinert produced by 3M. The heat generation of coil excitation is also constant of 10 W per coil and the thermal expansion coefficient of each material is almost equaled to the real system.
To check a possibility of the model simulated prediction, the test results were compared with simulation results shown in Table 3. The results show good mutual relations between experiment and simulation except one thing that a temperature rise of the lower flow is much higher than simulation result. But, it is not easy in fact to explain the rise by the heat removal theorem of heat flow convection, so additional heat may be coming into the system, for example, remaining wire for coil excitation exists in the lower flow region. Since even the on-the-spot survey did not disclose the reason definitely, the author has surmised the problems lie in a failure on the test stand for identification. The thermal modeling seems to be a worthwhile subject to investigate for both accustomed environment and vacuum situation.

4. Conclusion

In this paper, a higher stability of surface stage with Lorentz type planar motor and air levitation was proposed comparing with other type of stages, for instance magnetic levitated stage. After the procedure of each design was introduced concretely, the experimental results of planar motor, air bearing and cooling system were indicated step by step. Regarding the statics of planar motor, the experimental results agree qualitatively and quantitatively with simulation results, however the dynamics shows that the bandwidth of experiment was two times lower than a target specification because of structural difference between production stage of Fig. 1 and test stand of Fig. 11. Next, a performance of air bearing generally agrees with fluid simulations and a stable stiffness of levitation coupling.
with magnetic attractive force of planar motor was conformed. Finally, notified errors were not existed in a cooling experiment, however there were some different trends between test and calculation results due to additional paths of heat transfer in the test stand. More accurate modeling will be conducted in near future work in order to obtain a higher certainty of prediction.

The author concludes from the results described above that the surface stage with air bearing system is worth finding a solution for the next generation lithography. A further study regarding vacuum compatibility and possibility of material recycling will be carried out in next phase.

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