Expriments on a High Precision Planar Magnetic Levitation Stage Structure

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Abstract

This paper is an overview of the experimental work using a Planar Magnetic Levitation Stage System structure proposed by Dr. Won-Jong Kim in his PhD thesis. Based on his results, we built an Experimental Test Stand (ETS), which enabled us to get accustomed with the new technology and to create new control structures and algorithms. The ETS is controlled by a powerful controller made of 4 DSPs mastered by a PC. This controller structure increases the controller bandwidth up to 10 kHz leading to a better emulation of an analog controller and leaving enough room for further development. Based on analyzing all the factors that can affect the performances of the system, we achieved a great accurate positioning performance of sub-nanometer RMS value.

1. INTRODUCTION

In the last years much research works had been focused on the magnetic levitation techniques in high precision positioning systems. These techniques have a great potential for satisfying the precision requirements of present days' processes offering all the benefits of the non-contact operation.

First planar magnetic levitation stage was developed by Dr. Won-Jong Kim at the Massachusetts Institute of Technology in his PhD work [1]. It consists of four three-phase linear permanent magnet (PM) motors. Each linear motor can generate both suspension (vertical) and drive (lateral) forces. By putting the four motors in an orthogonal arrangement shown in Fig. 1 the platen will generate 6 degree-of-freedom motions, being able to provide all the positioning and moving needs in various processes, especially for the modern, deep sub-micron, integrated circuits production ones.

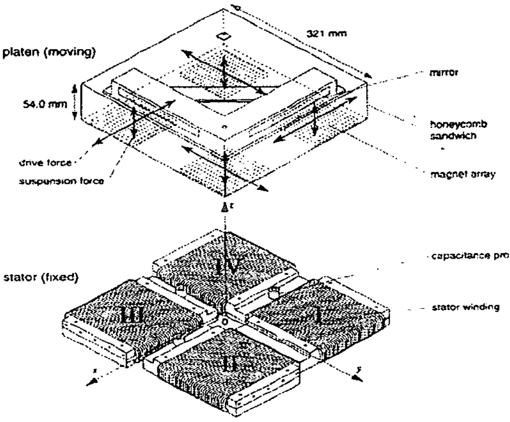

Fig. 1. Schematic view of the magnetic levitation stage, as presented in [1]

The stators are Gramme-type surface-wounded in a slotless structure with no iron. One stator has 33 windings, 6 per pitch, so that a stator consists of 5.5 motor pitches. The PM arrays are of Halbach-type made of 45 PM pieces bonded on the bottom of the platen. Each magnet array has 3.75 motor pitches. For a 25.6-mm long pitch, the maximum trip distance is 44.8 mm. The metrology is made with 3 laser interferometers for the lateral axes and with 3 capacitive gap sensors for the vertical axes. The gap sensors are mounted on the core of three stators. The stators along with all the optical devices are mounted on an optical table intended to attenuate the environmental and coupled vibrations. A DSP based control unit is used to implement the control loop: data acquisition from sensors, control algorithm and actuation. The command is applied to a power amplifier, which supplies the current to the windings. We built the electro-mechanical structure in our laboratory using Dr. Won-jong Kim's thesis as a reference. The hardware and software for the controller we designed and built are presented in the next section.

2. THE CONTROLLER

Controlling the levitated platen requires a great computing power. On the other hand, for an ETS some auxiliary functions such as real time data logging, parameters programmability and user friendly interface, are necessary to be implemented. We decided to use a quad TMSC6701 DSP board, operating at a frequency of 167 MHz along with an 800 MHz PC board. This boards and those that make the interface with the plant (laser axis boards, ADC and DAC modules) are mounted on a VME backplane in a VME rack. A block diagram of the controller is shown in Fig. 2.

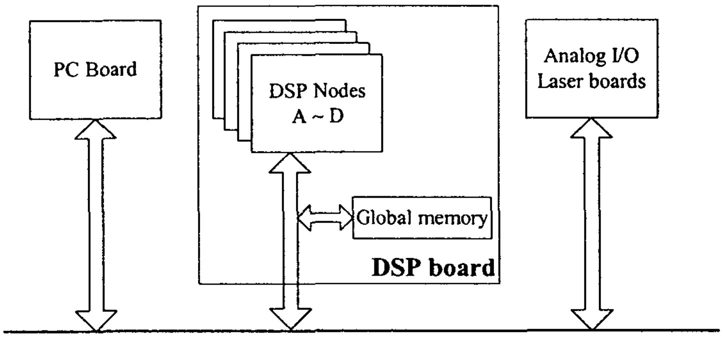

Fig. 2. Block diagram of the controller

The control processing flow is executed in a pipeline structure the data flowing from Node A, which takes the position data, to Node B, which calculates the platen co-ordinates, to Node C, which apply the control algorithm and finally, to Node D, which generates the actuation voltages. Some auxiliary functions are implemented: data logging, position initialization, and frequency response.

The program run by the PC board has the following functions: makes the user interface to the process, periodically scans the global memory containing the process variables and refreshes the on-screen numerical indicators, upon commands from user, initiates motion modes, data logging and saving, position resets, platen position initialization.

3. PERTURBATION FACTORS

Once the system was set up, we started doing experiments that were focused on the three main goals of a stage system: fast step & settle, good position stability and low trajectory error in constant speed scan mode. In time, we tried to identify all the factors that can affect the performances of the stage system. The factors we found are shown in Fig. 3.

The stage system has been set up in usual lab environment, being exposed to some sources of mechanical and electrical noise with variable action in terms of timing and magnitude. It also works in an uncontrolled atmosphere. The optic table proved to be very useful in canceling the external and coupled vibrations, but totally inappropriate for high lateral acceleration movements. During the experimental work, we used the position stability as a benchmark for characterizing the behavior of the system and for making comparisons between control methods. It's measured by the RMS, peak-peak or 2σ values of the position noise with the platen levitated with no lateral movement.

We found that one important perturbation factor affecting the position stability is the skewness between the magnet array and windings. Since we don't have a reference system for platen initializing, doing this manually, from one experiment to other this skew angle could vary, making the experimental results incomparable. On the other hand, after manually placing the platen in the center of the stators, the initial spatial phase between the two magnetic fields is different from the theoretical one. We implemented a software function which determines the deviation of the phase from the theoretical value on both lateral axes and that of the skew angle from a conventional value which is the smallest value that keeps a good stability of the laser measurement system during large trip displacements. The phase and the angle are not directly measured but estimated from the values of lateral forces and that of the torque around Z-axis, respectively. Then the platen is moved and rotated with the estimated values and a position reset is applied to the laser system. Depending of the initial error, 2 or 3 iterations are needed for putting the platen in the center of the stators and with the desired angle.

Since most of the perturbation factors deriving from the environmental conditions and the quality of the electro-mechanical parts of the system need more money to be eliminated, we directed our work, in this phase of the development of the project, to modify the co-ordinates determination and control methods in order to improve the system's performance.

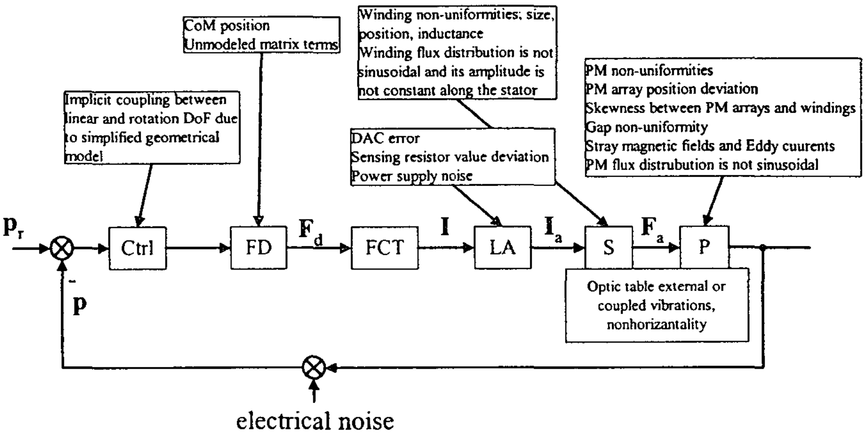

Fig. 3. Block diagram of the stage system with perturbation factors shown

p – measured position vector (6 components – $x, y, z, \theta_x, \theta_y, \theta_z$)
p_r – reference position vector (6)
F_m – modal forces vector; output of the controller (6)
F_d – decomposed forces vector; output of the controller (8 components, 2 per motor)
I – current vector (12 components, 3 for each motor with a 60° phase difference);
I_a – actual current vector (12)
F_a – actual forces vector: decomposed (12) or modal (6)
Ctrl – Lead-lag-integration controller
FD – Force Decomposition based on platen's geometry
FCT – Force to Current Transformation
LA – Linear Amplifier
S – Stators
P Platen

4. OUR CONTRIBUTION

We've first used the co-ordinates determination procedure and control method (de-coupled control) and parameters found in [1] and tried to obtain similar results. Then we tried to improve the performances by taking actions in three main directions:

- Bandwidth extension
- A more accurate co-ordinates computing procedure
- A different control approach

A. Bandwidth extension

By extending the bandwidths of the lateral modes loops while keeping those of the vertical modes unchanged we noticed an improvement in the position stability. We extended the bandwidth by increasing the gain of the lead-lag controller in steps. After each step we checked the quality of the control by using a Bode diagram builder implemented in the software of the ETS and the actual result of platen positioning. Since the determination of the Bode diagrams for one axis is performed with all the other axes working freely, we can assume that the shape of the diagrams is distorted by the dynamics of the other axes. Actually we had to stop when the bandwidth became to closed to the platen's resonance frequency. Fig. 4. Contains the Bode diagrams for the closed-loop controlling the X-axis. The bandwidth value is 230 Hz, the natural frequency is at 120 Hz, and the phase margin is 88°. Platen's resonance is placed around 240 Hz.

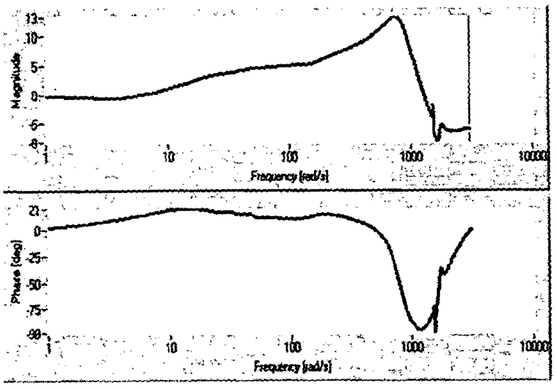

Fig. 4. Bode diagrams for the closed-loop controlling the X-axis

B. *A more accurate co-ordinates computing procedure*

Another problem we approached is the implicit coupling between linear and rotation DoFs due to the simplified geometrical model. According to this model, presented in Fig. 5., the rotation angle is determined based on the difference between the measurements of the two position sensors, while the displacement is determined from the measurement of PS1. Even when the platen is performing only rotation, a small displacement will be encountered, marked with a thick line in the drawing

Fig. 5. Schematic representation of the measurement procedure for one linear axis and one rotation; PS – position sensor

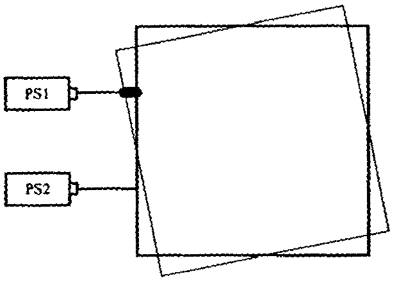

Fig. 5. Schematic representation of the measurement procedure for one linear axis and one rotation; PS – position sensor

In some situations, e.g. during the specimen alignment based on marker matching, this fake displacement could appear as a perturbation. We implemented a software mechanism for determining and correct this source of perturbation. Applying this procedure is useful only in case of real rotations. It could worsen the quality of the control if the rotation is actually produced by the measuring noise, becoming a way of spreading this noise in the "clean" axes.

C. *Different control approach*

As shown in Fig. 3, the controller generates a command vector ($\mathbf{F}_m$), but the actual force vector applied on the platen ($\mathbf{F}_a$) could differ more or less. The distance between these two vectors has a major influence on the quality of control. It depends of many factors including the force de-composition procedure that has the following drawbacks:

Some terms in the de-composition matrix are not taken into account

- De-composition is made with respect to the Center of Mass (CoM) whose position is an approximation and is also modified by the specimen

Our proposal is presented in Fig. 6. By using the position vector **p** and the reference vector $\mathbf{p}_r$, the actual and the desired co-ordinates of the centers of the magnet arrays, considered force application points, are calculated. Two position data are calculated for each magnet array: one vertical and one for the lateral axis for which the magnet array is used. The error is applied to 8 lead-lag controllers that generate the command vector, $\mathbf{F}_d$ in this case.

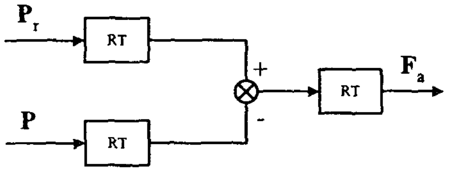

Fig. 6. Bock diagram of the proposed control approach

p – measured position vector (6 components – $x,y,z,\theta_x,\theta_y,\theta_z$)
p_r – reference position vector (6)
PM – actual position vector for the centers of the magnet arrays
PM_r – reference position vector for the centers of the magnet arrays
Ctrl – Lead-lag-integration controller
F_d decomposed forces vector; output of the controller

Two axis systems are used: a mobile system that is attached to the platen, with the origin in its geometrical center, and a fixed one with the origin in the center of stators. Actually, for this method, the origin of the axes systems can be placed anywhere.

Comparing the experimental results obtained with the two methods in similar conditions we found that the proposed method brings a 40% reduction in the position noise and in trajectory error during constant speed displacement. It has also the advantage of simplicity: one has only to chose the two axes system and find the co-ordinates of the forces application points in the platen's system. This simplification does not bring a decrease in the computing time. The force de-composition function is not needed anymore but instead of it a function for computing the actual and reference positions of force application point and the emulation for two more lead-lag controllers must be run.

D. Object localizer

A function has been implemented for finding the mass and the position of the CoM of a specimen placed on the platen. It could be useful in some application for a course positioning of the specimen after placing.

5. EXPERIMENTAL RESULTS

Four motion functions have been implemented for experimental and demonstration purpose. Any function execution starts with platen's levitation to Z-axis setpoint and ends by returning the platen to the initial position and putting it down; lateral trips are made using a trapezoidal speed profile.

- **Go to point**: The platen is moved to the set points on the other 5 axes while keeping Z-axis with constant.
- **Up'n'down**: The platen is moved ±20 μm around the Z-axis set point value without any directional motion.
- **Square**: The platen is moved on a square shaped trajectory
- **Circle**: The platen is moved on a circular trajectory

We noticed a smooth motion without vibrations and contact between PM arrays and windings, anywhere in the 40x40 area of the stators.

In the following the experimental results are presented in relation with the three main goals of a stage system: fast step & settle, good position stability and low position error in constant speed scan mode. The control method presented in the previous section was used.

A. Position stability

Using **Go to point**, we measured the position stability in many points of the trip span. The conclusion is that the position stability does not depend of the point where the platen is stopped. The results measured on lateral axis are less than the following values:

- Peak-to-peak: ±5 nm
- RMS: 1 nm
- 2σ: 2 nm
- Resolution of the mean value: 0.1 nm

B. Step & settle

The maximum speed allowed by the laser head (250 mm/s) was obtained. The optic table we used proved to be totally inappropriate during high acceleration movements. For this reason an acceleration of only 0.3 g could be achieved and the settling time is too long. In the future work an active table will be used.

C. Scan mode

The evolution of the error during a constant speed (10 mm/s) motion is presented in Fig. 8. The error on the axis, along which the platen is moved, X in this case, presents a big ripple (220 nm p-p). It has the spatial period of the winding pitch, about 4 mm. We assume that it is because the poor execution of the windings.

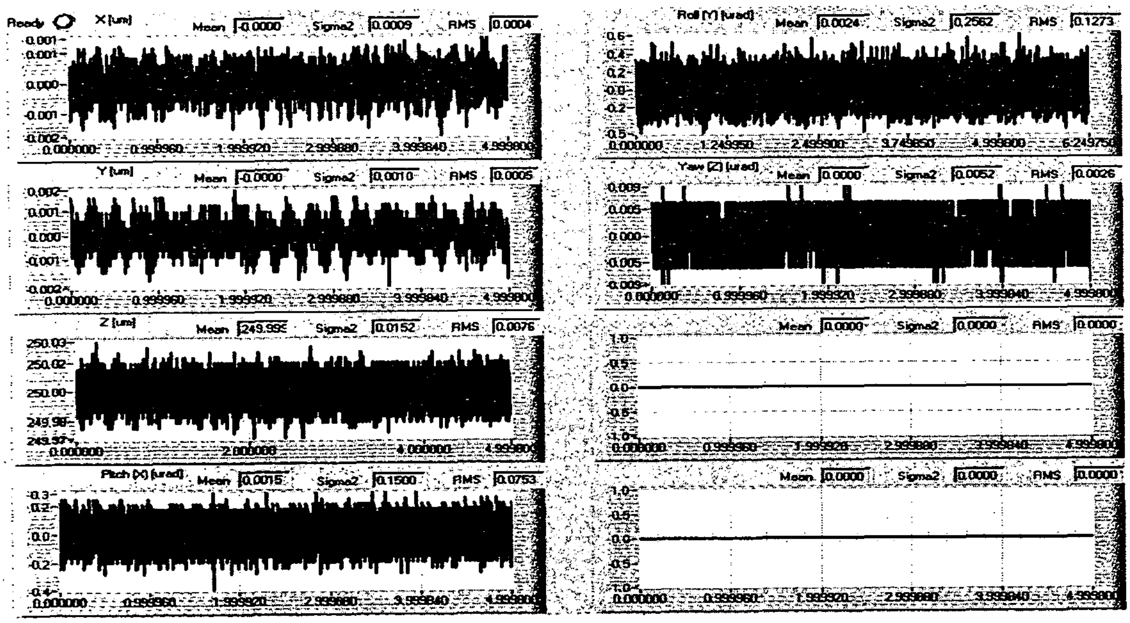

Fig. 7. Position plots on the 6 DoFs in μm or μrad, versus time in seconds.

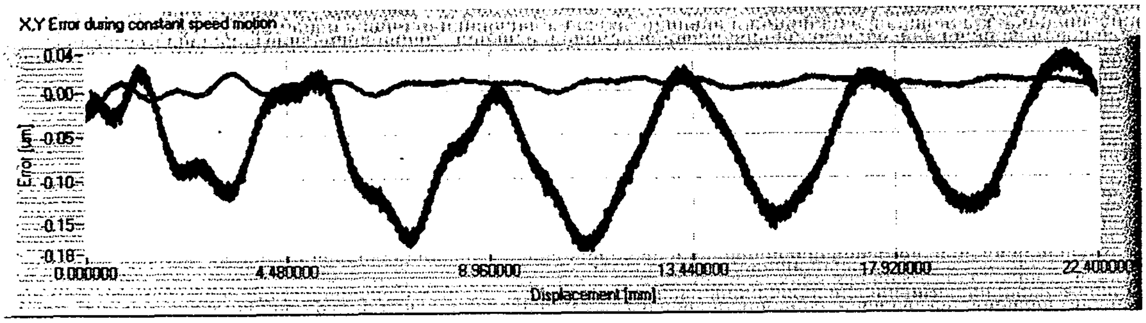

Fig. 8 Trajectory error plot during a constant speed displacement along the X-axis

REFRENCEC

[1] Won-Jong Kim , "High-Precision Planar Magnetic Levitation" PhD thesis at Massachusetts Institute of Technology, June 1997