Active Air Bearing Technology for Compensating Multi-DOF Motion Errors of Ultra-Precision Motion Units

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ABSTRACT

In this paper, we introduce rotary and linear motion units with active magnetic preloads and show experimental results for active compensation of motion errors by feedforward method. To compensate motion errors, linear stage and rotary units supported air bearings preloaded by magnetic actuators were developed. Each magnetic actuator has permanent magnet for nominal preload and coil to change the preload force. The characteristic of the actuation was measured as linear in the small range of motion, and the compensation inputs were able to be calculated. The 5-DOF motion errors were measured with combination of a multi-beam laser interferometer and gap sensors with straight edge target. The measured motion errors could modeled as functions of position, and the compensation inputs could be calculated from error functions and motion gains. The motion errors were reduced as level of measurement repeatability with feedforward compensation using magnetic preload control, under 0.1 μm in 200 mm of movement range in straightness errors for example.

Keywords: Air bearings, active compensation of motion errors, magnetic preloads

1 INTRODUCTION

Air bearings have been applied to ultra precision motion systems such as linear stages and rotary units successfully and widely because the air bearings have no friction and the area averaging effect on the guide error provides a high positioning accuracy and low traveling motion error. The positioning accuracy of some air bearing motion units has reached nanometer or sub-nanometer levels thanks to the recent developments of precision components and technologies for measurement, actuation, and control systems. However, for motion errors such as straightness, pitch, roll, and yaw, certain levels of errors exist and are very difficult to remove completely. The main sources of the motion errors are waviness of the guides or bearings, so form accuracy of the guide should be maintained to minimum by machining. Another possible method to minimize motion errors is to compensate actively for the traveling motion errors, and we introduced an air bearing units with active magnetic preload in previous researches.

In this paper, we introduce rotary and linear motion units with active magnetic preloads and shows experimental results for active compensation of motion errors by feedforward method. Both rotary and linear motion units were designed to have magnetic actuators with permanent magnets and electromagnets with air bearings. To compensate multiple degree-of-freedom motion errors, magnetic actuator implemented on front side of a rotary unit with air bearings, and 5 magnetic actuators were applied for linear stage. All motion errors, radial rotational errors of rotary unit and 5-DOF motion errors of linear stage were measured and modeled as functions of angle or position, and the compensation inputs could be calculated from error functions and motion gains. The motion errors were reduced as level of repeatability with feedforward compensation using magnetic preload control, under 0.1 μm in 300 mm of movement range in straightness for linear stage and 0.1 μm of radial motion for rotary unit.

2 FEEDFORWARD COMPENSATION OF MOITION ERROR COMPENSATION

Figure 1 shows the proposed method of compensation of motion errors in this paper. As the motion errors such as rotational errors, straightness and angular errors are usually repeatable as rotational angle and position, the errors can be modeled as functions of positions or angles. The repeatable measured errors can be modeled mathematically or numerically, for example, frequency components in rotary angle in rotational errors and polynomial function for motion errors of linear stages as function of position. If there are adequate actuators to generate motion to compensate errors, feedforward compensation will applicable to remove the errors.

This method needs accurate models of the motion errors, and it is important to measure the errors accurately. Hence, ultra-precision measurements with multiple capacitive sensors or laser interferometers are required. Considering these instruments require high cost, this feedforward compensation system needs less cost than feedback system because measurement set-up with high cost sensors is needed for only for modeling. However, it should be noted that this method only can reduce repeatable errors. This is basic idea of removing motion errors actively in this study and applied both rotary and linear motion units.

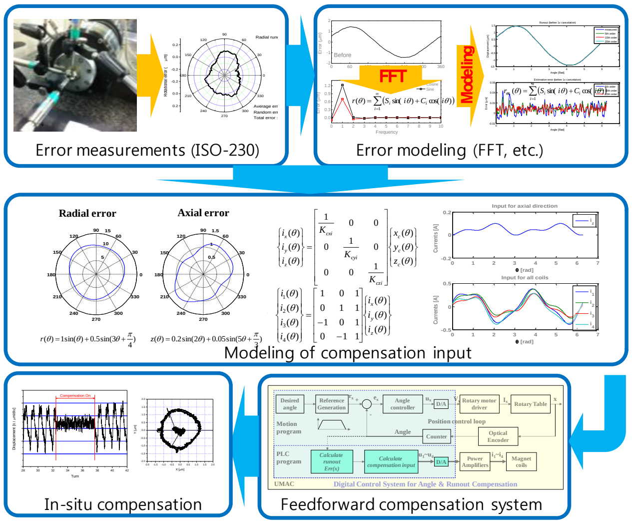


Figure 1: Procedure of motion error compensation with feedforward method (rotational errors)

3 EXPERIMENTAL RESULTS

3.1 Rotary Air Bearing Unit with Magnetic Actuators

Figure 2 shows the proposed air bearing rotary table with a 3-DOF magnetic actuator. To control the radial and axial displacement of the rotary motion, the magnetic actuator is located in front of the air-bearing servo spindle. Total size of the unit is 140 mm of diameter and 260 mm of length. Porous pads made with carbon material were used for both radial and axial air bearings. A slotless DC servo motor (S-76, Aerotech) and an optical rotary encoder with 0.1 arcsec were applied to control angular position precisely. It also has 3-DOF magnetic actuator at front side to generate maximum force as 55N for radial and 120 N for axial direction.

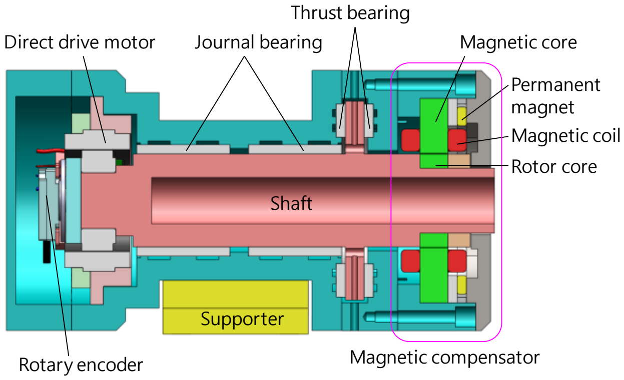


Figure 2: Schematic diagram of rotary air bearing unit with magnetic actuators

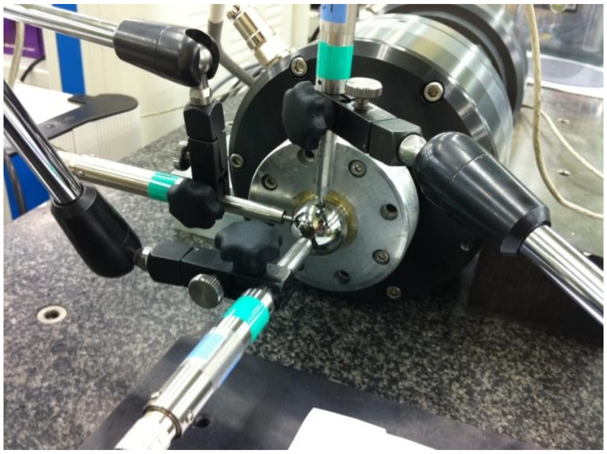


Figure 3: Manufactured prototype and set-up for runout measurement.

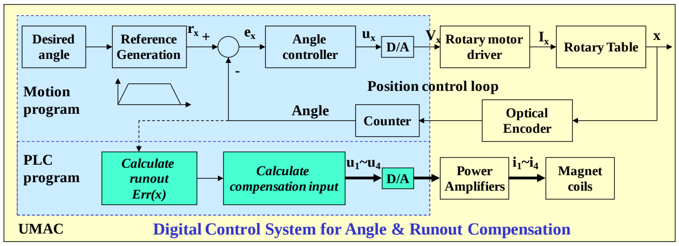


Figure 4: Block diagram for control system of active air bearing rotary table.

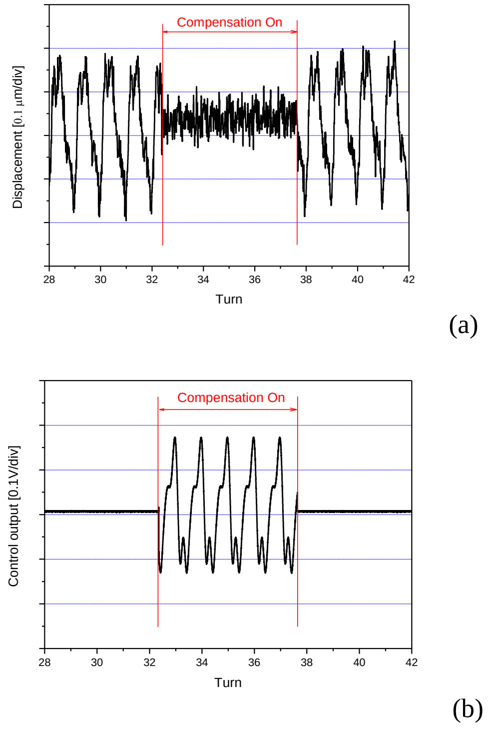


Figure 5: Feedforward compensation results for radial runout (a) and control output (b).

The rotational errors were measured using capacitive sensors as shown in Figure 3, and the measured runouts including set-up error of the master ball were about 0.4 μm for radial direction as shown in Figure 5a. The repeatable runout was modeled as a function of rotational angle as summation of sinusoidal functions up to 5 main frequency components, and compensation inputs were calculated and inserted to the magnetic actuator by the PLC program of the controller (UMAC, Delta-Tau) as Figure 4. It can be noticed that the runouts were reduced to 0.1 μm peak-to-peak with feedforward compensation, and the control command output were generated during active compensation. Considering this result is applied for the runout with larger displacement, some components were remained because of non-linear effect of the actuator. However, this shows that proposed method can be used for reducing rotational errors of air bearing rotary units.

3.2 Linear Air Bearing Unit with 5-DOF Active Magnetic Preloads

Figure 6 shows proposed 1-axis linear air bearing stage with five magnetic actuators for preloading and control of motions. Each magnetic actuator has permanent magnet for nominal preload and coil to adjust magnetic force. The air bearing pads are composed with porous material and designed based on numerical calculations. As the air bearings are preloaded by magnetic forces, only two guide way surfaces are required. Five magnetic actuators were located to generate vertical and horizontal directional preloads, and combination of five forces can generate control force for generating 5-DOF motions. The magnetic actuators were designed to generate nominal preload of 160 N and control force of 38.4 N/A. Considering vertical stiffness of 120 N/μm, vertical motion can be expected about 0.65 μm/A by applying same current for actuator 1 and 2. The vertical stiffness of the air bearing table could be examined by simply measuring deformation with known weights, and it was measured as 130.8 N/μm at 0.3 MPa of supplied air pressure.

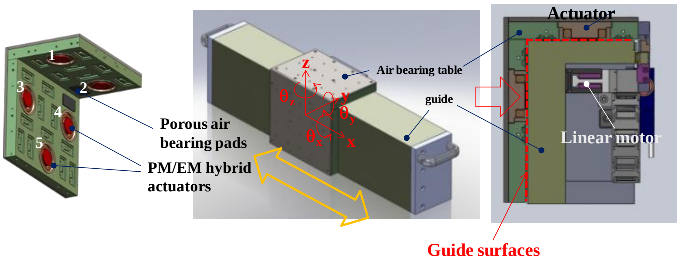


Figure 6: A linear air bearing stage with 5-DOF magnetic preloads.

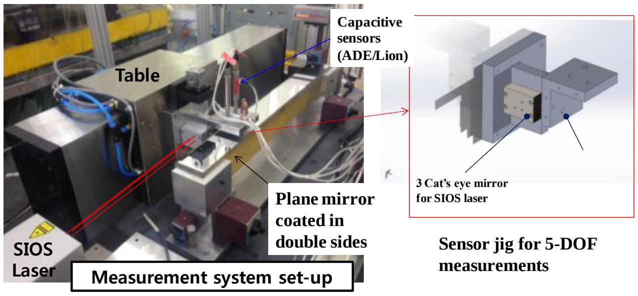


Figure 7: Measurement set up for 5-DOF motion errors.

Figure 7 shows the set-up for measuring 5-DOF motion errors. A laser interferometer with three beams measure position (x), pitch (θ_y) and yaw (θ_z) motions simultaneously. Vertical (z) and horizontal (y) straightness and roll motion (θ_x) are measured with four capacitance probes as using a plane mirror with in dual side as reference. For higher resolution measurement of roll and straightness errors, capacitance sensors were implemented using combined two point method which can remove form error of reference surface. All measurements were done in 5 times over 300 mm of travel range.

Figure 8 shows measured 5-DOF motion errors without active compensation. Roll error was compared with result with electronic level meter and shown good agreement. The all five errors were fitted as fourth order functions of x. The compensation commands can be calculated from the error functions and relationship between motion errors and 5 actuator inputs.

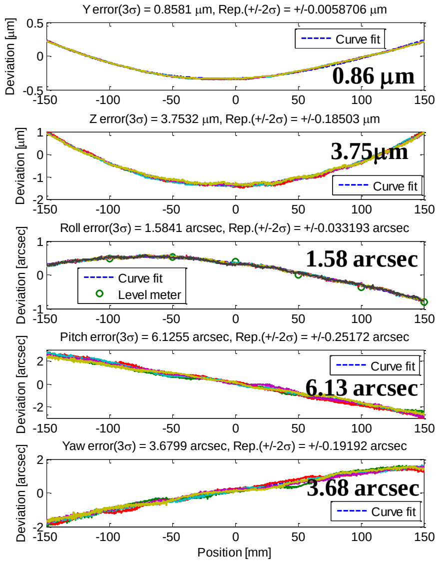
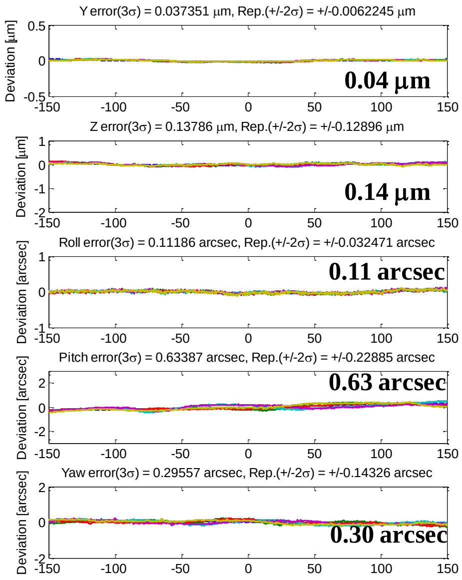
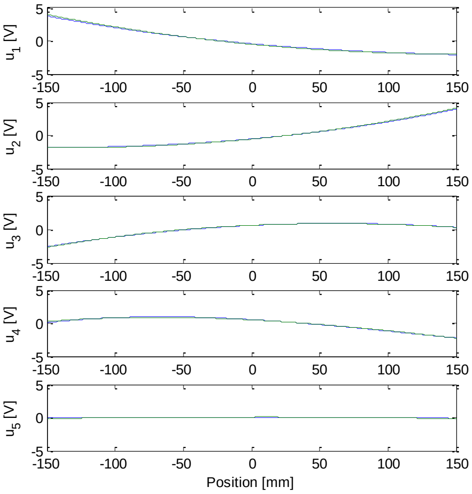


Figure 8: Measured 5-DOF motion errors without compensation



Errors with active compensation

(a)



(b)

Figure 9: Results of active compensation of motion errors (a) and compensation commands (b).

Figure 9(a) shows the compensated motion errors with feedforward compensation. This system has same control system as rotary unit with UMAC controller with PLC program running as background. The y and z straightness errors of 0.86 and 3.75 μm (3σ) reduced to 0.04 and 0.14 μm, and roll, pitch and yaw errors of 1.6, 6.1 and 3.7 arcsec were reduced to 0.11, 0.63 and 0.30 arcsec in 300 mm of travel range. Those values of the motion errors are close to the measured repeatability errors. From the Figure 9(b), which shows the command input for 5 actuators, 1~4 magnets had command less than 5 V, 1 A of coil currents. Considering the resistance of the coils, 2.5 Ohm, it can be the power loss of each coils are less than 2.5 W.

4 CONCLUSION

The proposed method of feedforward compensation of motion errors of air bearing rotary table and stage was tested with novel air bearing unit system with active magnetic actuators. As the designed systems have linear characteristics for controlling motion errors, and the motion errors of air bearing units are highly repeatable, feedforward method can be used for canceling errors based on error functions measured and modeled as linear or rotational position. This method of feedforward compensation for air bearing motion systems is expected to be used for ultra precision machine with minimum range of motion errors.

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