Development of a high acceleration magnetic bearing stage

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Abstract

Magnetic bearing stages have a great potential in the sense that active magnetic bearing enables a stage to have five degrees-of-freedom motion and ultra-low contamination. It comes at the cost of active control systems and relatively weak dynamic stiffness compared to that of fluidic bearings such as hydrostatic oil bearings and air bearings. While their functionality has been proven in many high precision motion control applications, stages with magnetic bearings seem to put more emphasis on accuracy rather than agility.

We introduce our new development of a high acceleration magnetic bearing stage. The final goal is to obtain up to 5G (49 m/sec^2) from a magnetic bearing stage. To cope with high acceleration, our stage has a parallel mechanism to suppress residual vibration. The preliminary design, analysis, and experimental results will be presented and discussed.

1 Design of a magnetic bearing stage and a reaction force cancellation mechanism

Figure 1 shows our magnetic bearing stage. It is driven by a linear motor with 663 N continuous force and its stroke is 1,000 mm. A fiber optic laser interferometer with a resolution of 20 nm is used for feedback control in the feeding direction. The size of the stage is 352(W)x117(H)x1,540(L) mm^3. The magnetic bearing actuator designed for the stage is a hybrid type where permanent magnets and electric magnets are combined to make zero bias voltage. Each electromagnetic actuator module has three magnetic bearing actuators and four modules are used for the stage. There are eight actuators installed in the vertical direction and four actuators in the horizontal direction. The maximum load capacity of an electromagnetic actuator is 100 N. The pole area is 600 mm^2 and the thickness of the permanent magnet is 1 mm and the number of coil turns is 250 for each actuator. The moving table including a linear motor core and four electromagnetic actuator modules, weighs 14.5 kg and there is a 0.3 mm air gap between magnetic bearings and guide ways.

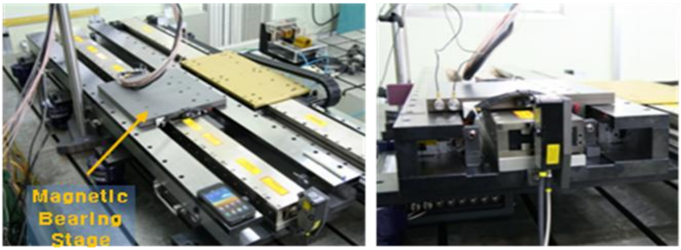

Figure 1: Picture of a 5G magnetic bearing stage

The electromagnetic actuators are required to endure high acceleration and will inevitably undergo high residual vibration. To suppress or cancel out the table vibration, a reaction force cancellation mechanism is installed next to the magnetic bearing stage as shown in Figure 1. The reaction cancellation mechanism is synchronized with the stage dynamics in the opposite direction, such that the rapid momentum change in the feeding direction of the stage during high acceleration will be absorbed by that of the reaction force cancellation mechanism. In our experimental test with the magnetic bearing stage, the input shaping control showed its usefulness in suppressing residual vibration. The input shaping control was inserted in the servo control loop.

2 Dynamic simulation

Because the center of mass of the moving table is not located on the linear motor's centerline which thrust force presumably acts through, there are yaw and pitch motions. Exerting forces at each actuator with a 3G acceleration was computed using a dynamic simulation program and its results are shown in Figure 2. The vertical actuator needs to endure about 21.1 N and the horizontal actuator about 2.2 N at steady-state. Even when 5G acceleration is required, the total force to maintain the air gap does not exceed 50 N for any magnetic bearing in the stage and its value is far under 100 N capacities from the designed magnetic bearing.

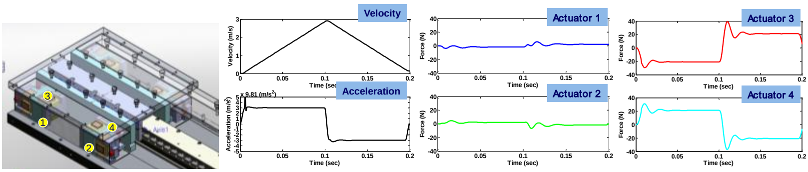

Figure 2: Computation of actuating force to maintain air gap when a 3G acceleration command given

To have a better understanding of the dynamics of the high acceleration magnetic bearing stage, we have built a dynamic simulation model including structure, motion, and control dynamics. Using the combined dynamic model, we could predict a flexible mode vibration occurring at around 450 Hz in our system and a flexible mode suppression control scheme was included in the real-time feedback control system.

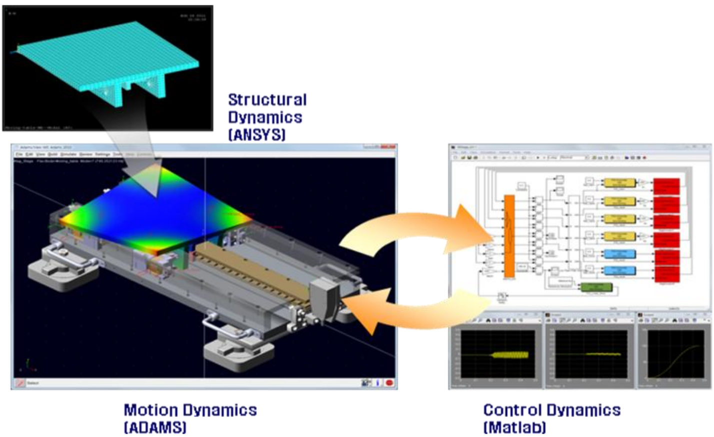

Figure 3: Structure/motion/control combined dynamic co-simulation

3 Experimental results

The real-time feedback control system is implemented on a DS1006 dSPACE system using a 25 kHz sampling rate. The control block consists of six PID loops for levitation of the moving table and a lead-lag type flexible mode compensator. Figure 4 shows an experimental result when 3G (29.4 m/sec^2) and 5G (49 m/sec^2) commands with an 80 mm travel were given. The acceleration signal measured by a separately attached accelerometer clearly showed that the developed magnetic bearing stage underwent above 5G acceleration.

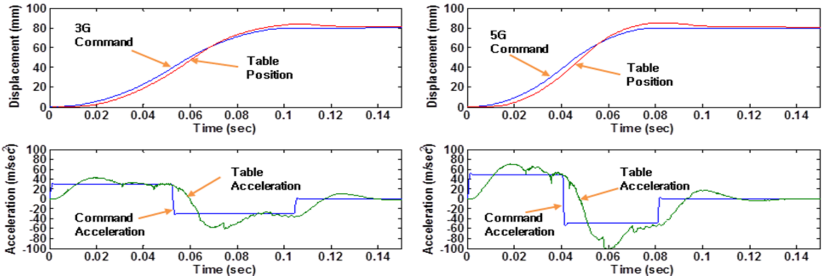

Figure 4: Table motion (80 mm travel with 3G and 5G acceleration)

We compared the effect of the reaction force cancellation mechanism with a 2 Hz, 70 mm stroke command in the following figure. When the reaction force cancellation was turned on, the displacement of frame vibration reduced from 193.3 pv µm to 10.3 pv µm (5.3%) in the horizontal moving direction, from 37.8 pv µm to 13.8 pv µm (36.5%) in the vertical direction.

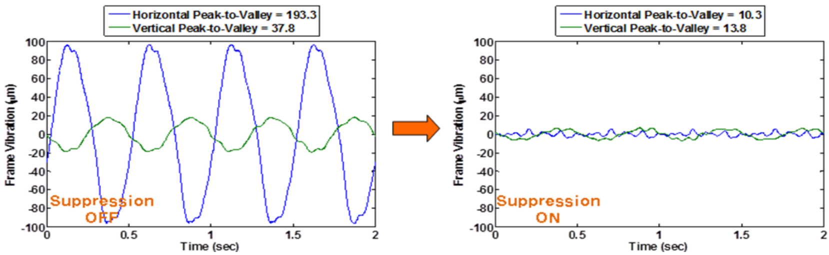

Figure 5: Effect of the reaction force cancellation

4 Conclusion

This paper described the development of a high acceleration magnetic bearing stage. Using reaction force cancellation, the developed stage achieved a 5G acceleration capability. The flexible mode vibration was identified through a structure, motion, and control combined dynamic model and a counter-acting suppression control scheme was included in the feedback control system.

Reference:

[1] M.L. Norg et al., Active Magnetic Bearing Technology Applied in High Precision Application, Magnetics Magazine, 2007