Axial Impulse Performance of Self-Acting Semi-Spherical Air Bearings*

Woo Chun CHOI**, Keun Hyung PARK***,
Jung Hwan CHOI***, Kwonhee KIM**
and Byung Chun KOH****

In this study we investigate the impulse performance of self-acting semi-spherical air bearings. Parameters affecting the performance of the air bearing are the clearance between the rotor and stator and stator groove depth. Rotation speed is changed from 13 000 rpm to 23 000 rpm. Rotor impulse displacement, impulse stiffness and allowable impulse are selected as axial impulse performance factors. Experimental results show that rotor impulse displacement and impulse stiffness decrease when the speed as well as the groove depth increase and the clearance decreases. Allowable impulse does not change significantly with changes in the clearance, and has a maximum value at a certain groove depth.

Key Words: Air Bearing, Self-Acting, Spiral Groove, Clearance, Groove Depth, Rotor Impulse Displacement, Impulse Stiffness, Allowable Impulse

1. Introduction

Air bearings are being utilized in supporting small high-speed rotating bodies. In the case of mechanical bearings, stable operation is difficult to achieve when the rotation speed exceeds 10 000 rpm due to excess noise, heat, and wear, thereby making air bearings a good alternative. A self-acting air bearing using the surrounding air does not require any extra pressurization devices and is inexpensive and relatively easy to maintain. These characteristics make the bearing appropriate for use in laser printers, hard disks and other computer peripheral parts as well as in multimedia devices.

Considerable research has been carried out on air bearings. The trajectory of the journal bearing rotor, and the method of determining its stability on the σ - $m\sigma$ (Somerfeld number-stability variable) curve⁽¹⁾, the effects of the atomic mean free path on the pressure

distribution of the gas lubricated air dynamic bearing⁽²⁾, the load on the gas lubricated helically grooved semi-spherical bearing and the relationship between the axial stiffness and vibration characteristics⁽³⁾, research on the design optimization of the helically grooved air dynamic bearing used in polygon mirror laser printers⁽⁴⁾, research on the analysis of the effects of the radially off-centered helical groove on spherical and conical bearings⁽⁵⁾, research on the performance and the pressure distribution of the eccentric and finite length gas dynamic bearing⁽⁶⁾, utilization of the exact two-dimensional theory on the eccentric helically grooved spherical bearing and research on various production loading conditions⁽⁷⁾, and a study on the performance of spiral-grooved semi-spherical air bearings using the Taguchi method⁽⁸⁾ are some of the research studies conducted.

As listed above, although considerable research has been carried out on the air bearing, none has been conducted on the performance of the air bearing under the effects of impulse. The most general form of an external effect on the bearing can be said to be in the form of impulse. For example, when a device that is being driven falls on the ground or is accidentally struck by other objects, impulse is applied to the device.

In this study, the main objective is to investigate

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** Associate Professor, Department of Mechanical Engineering, Korea University, 1, Anam-dong, Sungbuk-ku, Seoul 136-701, Korea. E-mail: wcchoi@korea.ac.kr

*** Graduate student, Graduate School, Korea University, Korea

**** Samsung Electronics Inc., Korea

the impulse performance which is the most important consideration in the use of air bearings. This can be achieved by designing and fabricating an experimental setup for measuring air bearing performance. The design parameters affecting the above performance are selected to be, the clearance between the rotor/stator, and the stator groove depth.

2. Air Dynamic Bearing and the Measurement of Performance

The bearing used in this study is the self-acting semi-spherical air bearing and its schematic diagram is shown in Fig. 1. It is composed of a rotor and stator. There is a small clearance of approximately 2 - 10 μm between the rotor and the stator and there is a groove with a depth of 2 - 10 μm in the stator. Initially, the rotor is in contact with the bottom half sphere of the stator, and when power is delivered to the rotor and it starts to rotate, air flows into the stator groove. This causes the wedge effect to take place which produces a high pressure which acts on the rotor, thereby making it float.

The external effects that act on devices using the air bearing are usually impulses. Important axial impulse performances considered in this study are the rotor impulse displacement, axial impulse stiffness, and axial allowable impulse. The definition of each term is as follows.

- Rotor impulse displacement: the average distance moved by the rotor due to impulse in the axial direction.
- Axial impulse stiffness: impulse that causes unit rotor impulse displacement in the axial direction.
- Axial allowable impulse: the amount of impulse that the air bearing can safely uphold.

When the performance of the bearing was measured under high speeds, noncontact methods were chosen when impulse was applied and the displacement was measured. These methods were selected because accuracy is not guaranteed with a contact approach. The stator of the air bearing was fabricated from nonmetallic stainless steel 304, and the rotor from stainless steel 420, so that the electromagnetic force could be applied only to the rotor. Gap sensors

Fig. 1 Schematic of the air bearing

with a resolution of 0.01 μm were used to measure the displacements of the rotor. The impulse used was in the form of an electromagnetic pulse with a duration of 5 ms. The experimental setup is shown in Fig. 2. Impulse is generally a large force acting during a very short amount of time, and thus it is preferable to use a short period of duration. Since the magnitude of impulse is expressed as the product of force and the duration of time, either the force or time could have been selected to vary the impulse, but the duration of time was kept constant in this study while only the magnitude of force was varied. The duration of time selected in this study was somewhat long. This means that the resulting frequency of an impulse was low. Thus, the results of this study cannot be generally applied. The findings of this study, which focuses on the effect of an impulse magnitude rather than the frequency, can be used to determine which air bearing has better impulse characteristics.

Figure 3 shows how the electromagnet and sensors were set up. The force applied on the rotor was controlled by the current flowing through the electromagnet, and the electromagnetic force produced by this current was measured by a load cell. Data sampling was carried out at a rate of 20 000 per second, and each sensor channel sampled 800 data points. When the impulse is being applied, three sensors which are placed 120° apart at a constant distance away from the vertical Z axis measure the rotor displacement in the axial direction, after which the average value is taken to be the displacement of the rotor center.

The conversion equation for the displacement of the rotor center is as follows.

$$Z = (L_1 + L_2 + L_3) / 3 \quad (1)$$

where L_1 , L_2 and L_3 are the displacements measured in the Z direction from the three sensors.

The rotation speed of the bearing was varied to be 13 000, 18 000 and 23 000 rpm. The experiment was

Fig. 2 Schematic of the measurement device of the axial impulse performance

Fig. 3 Setup of the electromagnet and sensors

carried out in the following manner. The rotor is rotated at a constant speed, and the impulse is applied to the rotor. The rotor moves due to the impulse and finally returns to the original position. While the rotor is moving, data are collected from the three sensors. The output from the gap sensors is then used as the input through the channel into the PC. The impulse is varied and the resulting data is collected from the three gap sensors.

3. Results and Discussion

Figure 4 shows the rotor displacement measured from each of the three sensors and the averaged displacement of the rotor center at 0.0134 N-s. As observed in Fig. 4, the rotor initially shows displacement due to the axial impulse, but returns to the original position. The average and standard deviations can be obtained from the latter 400 data points that were collected after a sufficient amount of time had passed, out of the total of 800 data points. The difference between the value obtained by subtracting the amplitude from the maximum displacement of the rotor center and the average value was taken to be the rotor impulse displacement.

Figure 5 shows the rotor impulse displacement (maximum displacement in Fig. 4) according to the clearance and the groove depth. As can be seen from Fig. 5, there is an increase of rotor impulse displacement

Fig. 4 Axial movement of the rotor center

ment with the increase of clearance and the decrease of groove depth. This is due to the fact that the rotor and the stator become further apart as the clearance increases, which in turn increases the rotor impulse displacement even under application of the same axial impulse. Also as the groove depth decreases, pressure produced between the rotor and the stator decreases, thereby increasing the possible rotor impulse displacement.

Figure 6 shows the relationship between the axial impulse and the rotor impulse displacement in a particular bearing, and the impulse stiffness according to clearance and groove depth. The impulse-rotor impulse displacement curve shows a constant slope at small rotor impulse displacements and is expected to have a larger slope, eventually approaching a vertical asymptote. Impulse stiffness is defined as the slope of the curve in the linear region. The radial stiffness of the bearing in Fig. 5 is $2.38 \times 10^{-3} \text{ N-s}/\mu\text{m}$.

Figure 7 shows the effects of design parameters on the axial impulse stiffness. Experimental results show the decrease of impulse stiffness as clearance increases. As clearance decreases, a larger impulse stiffness results from the decrease of possible displacement in the axial direction. Also, an increased

(a) Clearance and rotor impulse displacement

(b) Groove depth and rotor impulse displacement

Fig. 5 Rotor impulse displacement due to impulse (13000 rpm)

Fig. 6 The relationship between impulse and rotor impulse displacement

impulse stiffness can be observed from the increase of groove depth. This is due to the fact that the pressure resulting from the wedge effect increases as the groove depth becomes larger.

The axial allowable impulse can be obtained by multiplying impulse stiffness and average clearance as defined earlier. In the experiment, when the impulse is applied in the axial direction, the rotor moves upward,

(a) Clearance and impulse

(b) Groove depth and stiffness impulse stiffness

Fig. 7 Relationship between design parameters and impulse stiffness (13000 rpm)

and the clearance near the upper half of the bearing decreases, thereby bringing about an increase of stiffness resulting in the increase of impulse that the bearing can withstand. However, if the clearance becomes too small, bearing failure might occur due to contact between the rotor and stator even under a very small variation of rotor displacement. Therefore in this study, the allowable impulse is defined as a product of impulse stiffness and nominal clearance. Although this allowable impulse is smaller than an actual impulse which the air bearing can withstand, it guarantees stable operation.

Figure 8 shows that the allowable impulse does not vary greatly as clearance changes. Also, the allowable impulse increases as the groove depth increases, and decreases after a peak at 5.25 μm of groove depth. This implies that there exists an optimum groove depth at which a maximum allowable impulse can be obtained.

Figure 9 shows impulse performance according to rotation speed. As the rotation speed increases, the rotor impulse displacement decreases while impulse stiffness and allowable impulse increase. This implies that as the rotation speed becomes higher, the bearing becomes stiffer and can withstand a larger axial impulse.

(a) Clearance and allowable impulse

(b) Groove depth and allowable impulse

Fig. 8 Relationship between design parameters and allowable axial impulse (13000 rpm)

Fig. 9 Rotation speed and dynamic performance

4. Conclusions

The axial impulse performance of a self-acting

spiral-grooved air bearing was experimentally investigated. From the experiment of measuring the impulse performance of the self-acting air dynamic bearing, the following conclusions were drawn.

- The rotor impulse displacement decreases as the rotation speed increases, as clearance decreases, and as groove depth increases.
- The axial impulse stiffness increases as the rotation speed increases, as clearance decreases, and as groove depth increases.
- The axial allowable impulse does not vary greatly with a change of clearance, and reaches a maximum value at approximately 5.25 μm of groove depth.

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