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Analysis of Dynamic Characteristics of Air Bearing

Toshio MUKAI*[1]

Abstract

With the use of high-rigidity and low-thermal expansion ceramics, we are able to provide low-gap air stages. The present paper reports dynamic characteristics of air bearing at low gaps calculated by hydrodynamics. The results show that deepening air conduction grooves leads to high-rigidity and high-damping air bearings.

1. Introduction

Non-contact gas bearings or air bearings using the air-floatation effect have come to be used in growing quantities over the last years in the field of precision machinery, such as photolithography machines for semiconductors. A typical example of the gas bearing is an XY stage as shown in **Fig. 1**. An XY stage has ten-odd air pads arranged in a slider to allow its movement in a totally non-contact state. Fine ceramics play a significant role in the latest wide application of XY stages using air bearings.

A gas bearing is formed between a guide and slider of a moving stage; an orifice is provided in the slider, and usually a gas such as air is blown through the orifice towards the guide to form a rigid gaseous film therebetween. The formation of the gaseous film makes a gas bearing function as a non-contact, rigid bearing. Generally, the smaller the bearing gap the higher the rigidity of the gas film becomes. This makes it possible to use an air stage with gas bearings for wider applications.

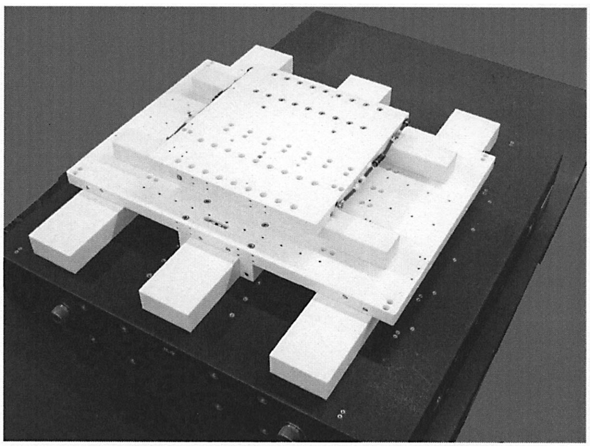

Fig. 1 Alumina-made XY stage (by Nippon Steel)

Aluminum-based metal materials have been widely used for air bearings. However, with these materials, the rigidity of the bearing components is low and their coefficients of thermal expansion are high. As a result, it has been difficult to make the bearing gap smaller than a certain limit. In this respect, alumina, a typical of fine ceramics, has high rigidity and a low coefficient of thermal expansion: its coefficient of thermal expansion is 5.3 ppm/K, only a quarter that of aluminum metal. Thus, it is possible to assemble an air bearing having a small bearing gap and provide a rigid air stage by using alumina as the material. Furthermore, use of silicon nitride or Sialon will enable to provide an air stage with yet better performance since their coefficients of thermal expansion at room temperature are as low as 1.2 ppm/K.

However, because a gas is compressible and it has a small coefficient of viscosity, the vibration damping performance of a gas bearing is poor. Vibration, once excited, decreases in proportion to $\exp(-\zeta\omega_n t)$, where ζ is the damping coefficient of the vibration and ω_n is the specific angular vibration number of the system in question; the value of ζ of an air bearing is typically as small as approximately 0.05. To improve the stopping or synchronizing performance of an air stage, it is necessary to make the damping coefficient ζ as large as possible. This paper describes a method for calculating the damping characteristics of an air bearing based on the fluid dynamics and the structure of a small-gap air bearing that exhibits an excellent vibration damping characteristics.

2. Method of Calculation

The subject of our calculation is a hydrostatic gas bearing that has an orifice as means for blowing a gas. **Figs. 2** and **3** show the geometrical relationship between component elements of a gas bearing, namely, an orifice, air conduction grooves and lands.

A gas fed at a pressure of P_s is blown through the orifice, and the pressure falls to P_z as a result of the restriction effect (an inherently

*[1] New Materials Division

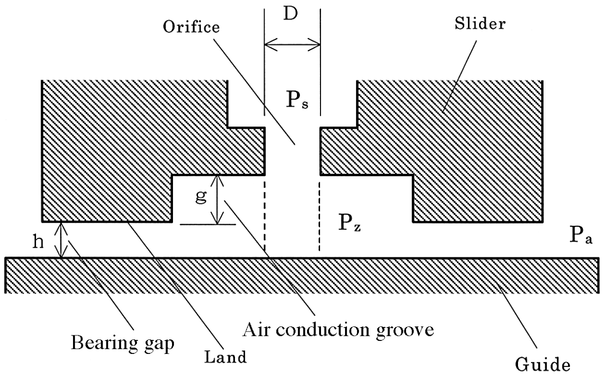

Fig. 2 Orifice-type air bearing

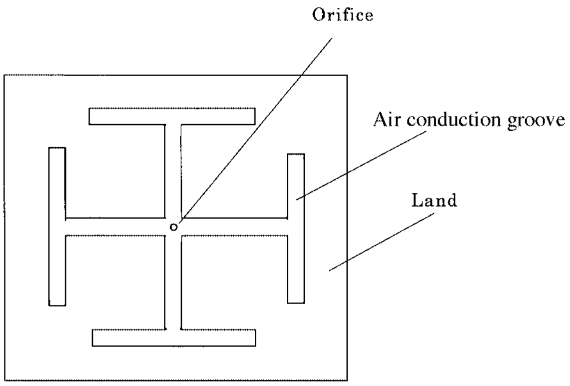

Fig. 3 Cross T-type air pad

compensated restriction effect, in the case of Fig. 2) due to adiabatic expansion as the gas expands in the air conduction grooves. The gas spreads from an imaginary cylinder immediately below the orifice to the air conduction grooves, and is discharged to the outside of the bearing through the lands. In the course from the air conduction grooves through the lands to the ends of the bearing, the pressure of the gas falls to the atmospheric pressure P_a owing to viscous resistance.

According to the hydrodynamics, the mass flow rate of the gas is expressed as follows[1]:

(i) The mass flow rate of a gas injected through an orifice

$$M_1 = [AP_s / (RT)^{1/2}] \cdot \psi_0, \quad (1)$$

where $A = \pi D (g + h)$, and

$$\psi_0 = [2\kappa / (\kappa - 1)]^{1/2} \cdot [(P_z / P_s)^{2/\kappa} - (P_z / P_s)^{(\kappa+1)/\kappa}]^{1/2},$$

when $P_z / P_s \geq [2 / (\kappa + 1)]^{\kappa/(\kappa-1)}$.

(ii) The mass flow rate of a gas discharged through the bearing gap under viscous resistance

$$M_2 = [(h + g)^3 / 24\mu RT] \cdot [C_{i,j} P^2_{i,j} - C_{i,j-1} P^2_{i,j-1} \cdots] \quad (2)$$

as a matrix expression based on the calculation by the finite difference method. In the above equations, $P_{i,j}$ is the pressure at a lattice point (i, j), $C_{i,j}$ is a coefficient of $P_{i,j}$, D is the diameter of the orifice, g is the depth of the air conduction grooves, h is the bearing gap, μ is the coefficient of the viscosity of the gas, R is the gas constant, T is the temperature, and κ is the ratio of specific heat of the bearing gas.

In an equilibrium state, the mass flow into and out of each of divided elements that include the orifice is balanced, which means $M_1 = M_2$. Since the mass flow rate is preserved also in the air conduction grooves and lands other than the orifice, a relational equation of pressures at different lattice points can be derived for each divided element, and the distribution of equilibrium pressure is obtained by solving the relational equations.

In the case where the pressure changes over time, the equation is as follows (for a divided element not including the orifice, $M_1 = 0$):

$$M_1 - M_2 = (1 / RT) \cdot \partial (P_{i,j} \cdot V_{i,j}) / \partial t, \quad (3)$$

where $V_{i,j}$ is the volume of the bearing gap in the divided element of a lattice point (i, j). The dynamic characteristics of an air bearing were calculated about an equilibrium point using the method of perturbation, that is, using the equations $h = h_0 + \triangle h \cdot \exp(i\omega t)$ and $P_{i,j} = P_0 + \triangle P_{i,j} \cdot \exp(i\omega t)$, a relational equation for calculating a complex dynamic rigidity $E_{i,j} = \triangle P_{i,j} / \triangle h$ was derived for each lattice point.

The value of $E_{i,j}$ was calculated for each lattice point by solving the relational equations simultaneously. When the sum of the real-number component of $E_{i,j}$ for all the lattice points is expressed as A and that of the imaginary-number components as B, the damping coefficient ζ is given as $\zeta = B / (2A)$. The damping coefficient changes depending on the frequency f of the vibration (here, $\omega = 2\pi f$). By hydrodynamic calculations, the calculation results are rearranged by the squeeze number σ, which varies in proportion to the frequency. The squeeze number of a rectangular air pad having a length of a and a width of b is expressed by the following equation:

$$\sigma = (12\mu\omega / P_a) \cdot (a \cdot b / c^2), \quad (4)$$

where c is a representative bearing gap. Although the value of c may be defined arbitrarily, it was assumed c = 5 μm for our calculation. Here, the word “air pad” means the portion defining the bearing surface in which the gas pressure is greater than the atmospheric pressure.

3. Results of Calculation

The damping coefficient ζ was calculated using a model air pad having a typical air conduction groove pattern of a cross-T type as shown in Fig. 3. The size (each of a and b) of the air pad was 40 mm, the diameter D of the orifice was 0.2 mm, the width of the air conduction grooves was 1 mm, and the distance from the center line of an outermost air conduction groove to an edge of the air pad (namely the width of a land) was 6 mm. The damping coefficient ζ was calculated for representative values of the bearing gap h and different groove depths g under the condition of an air-feeding pressure of 0.4 MPa in terms of the pressure difference from the atmospheric pressure. **Fig. 4** shows the calculation results versus different values of the squeeze number σ in the cases where h = 3, 5 and 7 μm.

With a commonly employed bearing gap of 5 to 7 μm, the damping coefficient changed significantly depending on the depth of the air conduction grooves, and in the case where the groove depth exceeded 20 μm, the damping coefficient was negative in some range of σ. Since a gas bearing undergoes self-excited vibration in the region where the damping coefficient is negative, it is not used in such a region. The tendency was markedly different in the case where h was 3 μm: the larger the depth of the air conduction grooves the larger the damping coefficient became, staying in the positive region (the damping of vibration was improved); this result was totally different from past expectations. Since the rigidity of the gas film increases as the bearing gap decreases, both high rigidity and good damping characteristics are obtained with a bearing gap of 3 μm.

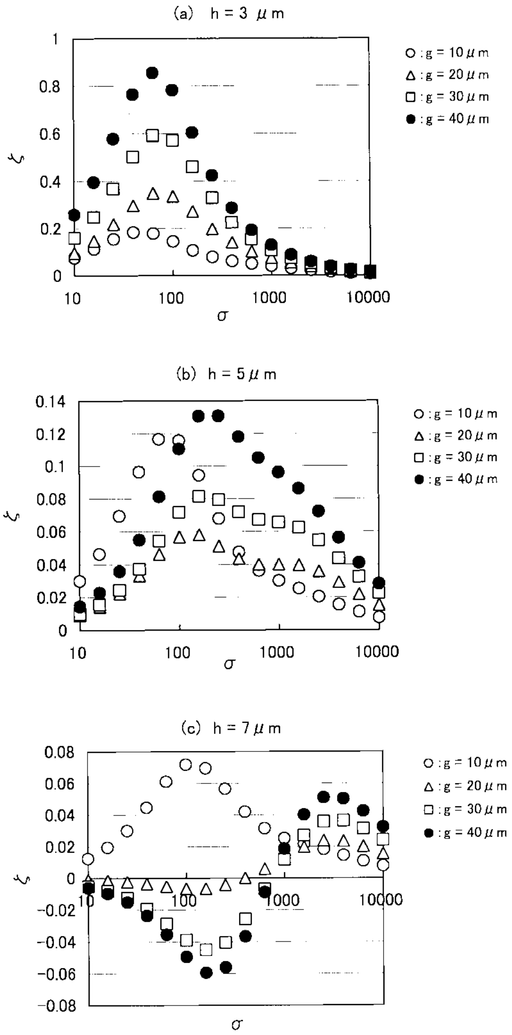

Fig. 4 Calculated results of damping coefficients

4. Closing

The level of precision of the latest machining of ceramics is such that a surface of a work can be finished in a mass-production scale to a deviation from flatness of as small as 0.5 μ m or less across a length of 1 m, and it is now possible to provide an air stage having a bearing gap of 3 μ m by assembling components machined to such a precision. Use of air bearings has expanded only very slowly because of their shortcomings such as the low rigidity of the air film and the vibration that occurs when the air pressure is forcibly increased to enhance the rigidity. A small-gap air bearing did not attract general attention owing to the difficulty in manufacturing. Despite this, focus was trained on the characteristics of a small-gap air bearing, and as has been reported herein, proved that there was a possibility of further improving the performance of such an air bearing. The intention was to continue to propose uses of air stages for a variety of applications based on the technologies that Nippon Steel Corporation possesses in the fields of the precision machining of ceramics, manufacturing of air bearings and assembly of air stages.

Reference

1) Togo, S.: Guide Book for Gas Bearing Designing (Japanese). 1st edition, Kyoritsu Shuppan, 2002, p.18