Air Bearing Design Optimization

Fuzhang Zhao and Clarence A. Andersson
Advanced Materials Division, M Cubed Technologies, Inc., Newark, DE 19711

Jai R. Singh and Craig Emmons
M Cubed Technologies, Inc., Monroe, CT 06468

1. Introduction

Air bearings widely used in precision engineering can be classified into two types: orifice and porous media. The air bearings discussed here refer to a porous graphite type. Many parameters influence the performance of air bearings. A model is needed which provides a design tool for motion system designers to correctly predict the performance of porous bearings. The modeling of fluid flow through porous material is well established. For the low permeability porous materials of greater thickness, Darcy equation was used [1]. For high permeability porous materials of smaller thickness, a modified Reynolds equation was used to study the viscous shear and stress jump at the interface between the porous material and the gas film [2]. The modeling of fluid flow through the atmosphere is mainly based on the classical Reynolds equation [3-5]. The key physical quantity to choose or control in an air bearing design is the permeability of a porous material. Although increasing the permeability of a porous media increases the efficiency of load capacity, it will decrease the stability of levitation. An optimum bearing should possess high efficiency of load capacity, high stiffness and good stability during levitation. In order to optimize the air bearing design, a novel simplified one-dimensional steady-state model was developed based on flow equilibrium. The model was divided into two parts: porous material pad and thin air layer. The Darcy equation was used to describe the air diffusing through a porous material pad. Film coefficient was successfully used to model the air releasing to the environment.

2. Modeling of Porous Air Bearings

When an air bearing is put in service, a supply air pressure p_0 is applied through a porous material pad with cross sectional area A, circumference c, and height H; and forms a gap layer with gap height h and gap pressure p_H. Air is released to the environment with film coefficient f, and ambient pressure $p_{\breve{U}}$. The model and the corresponding coordinate systems are shown in Figure 1.

To balance the flow in both the porous material pad (using Darcy equation) and in the air gap (using film coefficient), one may use the governing equations (Eqs. (1) & (3)) and boundary conditions (Eqs. (2), (4) and (5)),

$$\frac{d}{dx_1}\left(k_1 \frac{dp}{dx_1}\right) = 0 \quad where \;\; k_1 = \frac{k}{m} \tag{1}$$

$$p\Big|_{x_1=0} = p_0 \quad and \quad -\frac{k}{m}\frac{dp}{dx_1}\Big|_{x_1=H} = q_H \tag{2}$$

$$\frac{d^2 p}{dx_2^2} - a^2 p = 0 \;\; where \;\; a = \sqrt{\frac{fc}{Ak_2}}, \;\; f = \frac{h^{\frac{3}{2}}}{12m\sqrt{L}} \quad and \quad k_2 = \frac{h^2}{12m} \tag{3}$$

$$-k_2 \frac{dp}{dx_2}\Big|_{x_2=0} = q_H \quad and \quad -k_2 \frac{dp}{dx_2}\Big|_{x_2=h} = 0 \tag{4}$$

$$p\Big|_{x_1=H} = p\Big|_{x_2=0} = p_H \tag{5}$$

where q is the fluid flow flux, k is the permeability of porous material, m is the viscosity of air and L is an effective length that makes the pressure drop to ambient pressure.

Solving equations assuming that k_1 is not a function of pressure, applying boundary conditions and eliminating q_H, one may derive the efficiency of load capacity as follows,

$$h = \frac{p_H A}{p_0 A} = \frac{p_H}{p_0} = \frac{1}{1+q} \quad where\ q = \frac{a\ Hk_2}{k_1} \frac{e^{2a\ h} - 1}{e^{2a\ h} + 1} \tag{6}$$

We define the q as the dimensionless stability for an air bearing. In order to optimize both the efficiency of load capacity and the dimensionless stability, they have to be equalized. With $q = h$, Eq. (6) becomes,

$$h^2 + h - 1 = 0 \tag{7}$$

thus the maximum efficiency of load capacity, one of the roots, is 0.618.

Taking the derivative of h with respect to h and using the definition of stiffness, which is the slope of load-gap height curve, we define the dimensionless stiffness $\bar{S}$ as,

$$\bar{S} = -\frac{dh}{dh} h = 1.75\left(h - h^2\right) = \frac{S\,h}{p_0 A} \tag{8}$$

where S is stiffness.

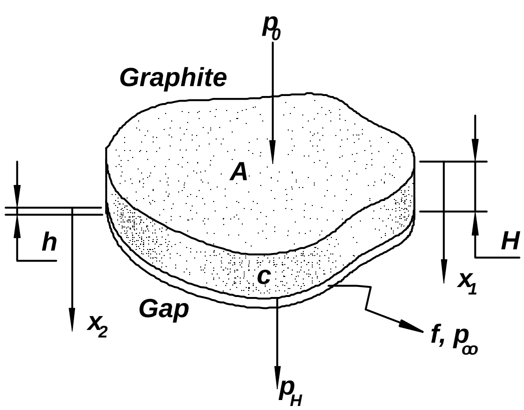

Fig. 1 Fluid flow model for air bearing.

Fig. 2 M Cubed Technologies' porous graphite air bearings.

In practice, k_1 is a linear function of pressure,

$$k_1 = a + b\,p \tag{9}$$

where a and b are constants determined by experiment. Considering that k_1 is a linear function of pressure, the dimensionless stiffness turns out to be,

$$\bar{S} = \frac{S\,h}{p_0 A} = \frac{7}{4} \frac{\left[1 + \frac{1}{2}\left(\frac{b}{a}\right)p_0\right]h - \left[1 + \frac{1}{2}\left(\frac{b}{a}\right)p_0 h\right]h^2}{1 + \frac{1}{2}\left(\frac{b}{a}\right)p_0\left(1 + h^2\right)} \tag{10}$$

3. Applications of the Model

Theoretically, the maximum efficiency of load capacity is 61.8%. Experimentally, a 51-mm diameter circular bearing was used to test its maximum efficiency. When the bearing was loaded up to about 63% efficient at a gap height of 6.35 μm, it started to buzz audibly. As the efficiency was further increased, the bearing became vibrationally unstable. Therefore, a maximum efficiency of 60% of the load capacity is recommended in air bearing design.

In order to validate the model, stiffness comparisons between theory and experiment have been made. Both circular and rectangular graphite air bearings (Fig. 2) were tested.

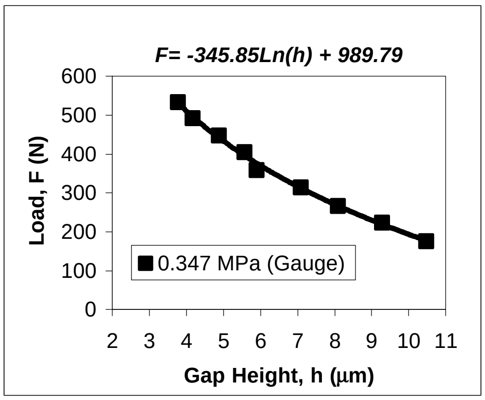

Fig. 3 Load as a function of lift for 51-mm diameter circular graphite bearing.

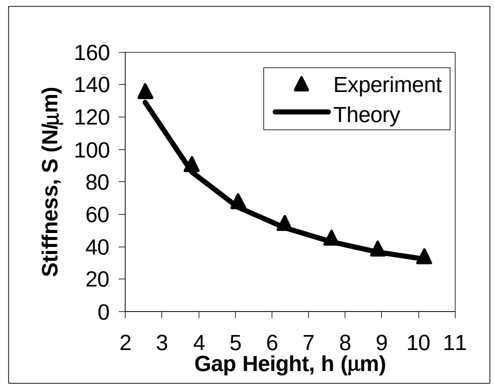

Fig. 4 Stiffness comparison between the model and experiment for 51- mm diameter circular bearing.

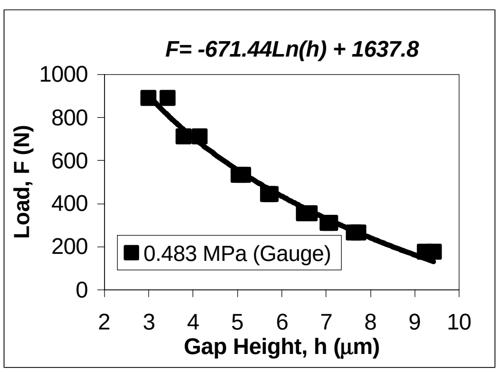

Fig. 5 Load as a function of lift for 76-mm by 51-mm rectangular bearing.

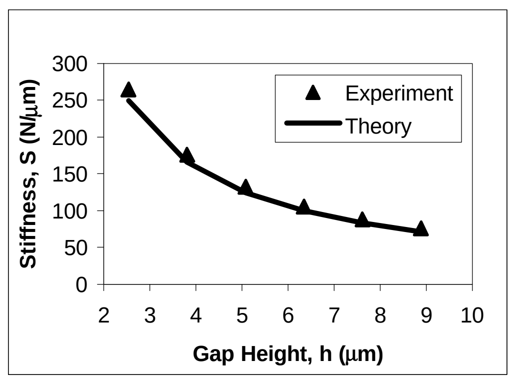

Fig. 6 Stiffness comparison between the model and experiment for 76-mm by 51-mm rectangular bearing.

The experimentally determined load-gap height curve for the 51-mm diameter circular bearing is shown in Figure 3. The experimentally derived stiffness versus gap height curve was determined based on the equation obtained from curve fitting given in Fig. 3. Using Eq. (10), the corresponding theoretical stiffness as a function of gap height was also calculated. As the circular bearing is 50.16% efficient at h=6.35 μm, the following parameters p_0=0.347 MPa, h=0.5016, A=2.027×10^{-3} m^2 and b/a=2.175×10^{-6} Pa^{-1} were used to evaluate the theoretical stiffness shown in Figure 4.

The model is equally applicable to air bearings with rectangular shape. The load was also measured with respect to the gap height for the 76-mm by 51-mm rectangular bearing shown in Figure 5. A stiffness-gap height curve with solid triangular legend was, similarly, derived from the experimentally obtained load-gap height curve. Again, using Eq. (10), the corresponding theoretical stiffness as a function of gap height was calculated. As the rectangular bearing is 23.95% efficient at gap height of 6.35 μm, the following parameters p_0=0.483 MPa, h=0.2395, $A=3.871\times10^{-3}$ m^2 and $b/a=2.175\times10^{-6}$ Pa^{-1} were used to evaluate the theoretical stiffness shown in Figure 6.

The comparisons between experiment and theory show that the stiffness calculated from the current model is accurate. Therefore, it is feasible to use this model in air bearing design.

4. Concluding Remarks

A model that describes the functioning of porous air bearings has been derived. The model agrees well with the experiments. It is applicable to air bearings with a variety of shapes. The dimensionless stiffness and dimensionless stability were defined. In practice, the commonly used supply air pressures for porous air bearings are in the range of 0.345 to 0.552 MPa in gauge (50 to 80 psig). Air bearings with levitation heights of about 5.1 to 7.6 μm (200 to 300 μin) perform well since the bearing will tend to be pinned if it levitates too low above the working surface. On the other hand, it will tend to be vibrationally unstable if it flies too high. Although many parameters influence a bearing's function and behavior, the most important parameters are the efficiency of load capacity (or inversely the dimensionless stability) and bearing area. In making a porous air bearing the key physical property to choose or control is the efficiency of air diffusion through the porous media—permeability. As a general design rule, we propose the following guidelines:

1) In general, the efficiency of load capacity chosen in air bearing design must be less than or equal to 0.60. In other words, the dimensionless stability must be larger than or equal to 0.60.
2) If the bearing area is limited, stiffness can be improved by increasing the efficiency of load capacity close to 0.60.
3) If both a high stability and a high stiffness are required, a larger area with lower permeability material will be needed.

In fact, the first rule must be satisfied in making any porous air bearing before either the second rule or the third rule is applied.

5. References

[1] Park, J.E., Giles, Jr. G.E., Rasnick, W.H., and Steger, P.J., 1978, "Computation and Measurement of Flow Rate and Load Capacities for Graphite-Fed Externally Pressurized Gas Bearings", *Interim Report of Oak Ridge National Laboratory*.

[2] Li, W.-L., 1999, " Derivation of Modified Reynolds Equation—A Porous Media Model", ASME *Journal of Tribology*, Vol. 121, pp. 823-829.

[3] Faria, M.T.C., and Andres, L.S., 2000, "On the Numerical Modeling of High-Speed Hydrodynamic Gas Bearings", ASME *Journal of Tribology*, Vol. 122, pp. 124-130.

[4] Hu, Y., Jones, P.M., Chang, P.T., and Bogy, D.B., 1998, "Partial Contact Air Bearing Characteristics of Tripad Sliders for Proximity Recording", ASME *Journal of Tribology*, Vol. 120, pp. 272-280.

[5] Peng, J.-P., and Hardie, C.E., 1995, "A Finite Element Scheme for Determining the Shaped Rail Slider Flying Characteristics with Experimental Confirmation", ASME *Journal of Tribology*, Vol. 117, pp. 136-142.