Tribology International 90 (2015) 157–163

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Numerical analysis of discharge coefficients in aerostatic bearings with orifice-type restrictors

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ARTICLE INFO

Article history:
Received 13 February 2015
Received in revised form
9 April 2015
Accepted 17 April 2015
Available online 28 April 2015

Keywords:
Aerostatic bearing
Discharge coefficient
Orifice-type restrictor

ABSTRACT

Determining film pressure by solving the Reynolds equation is more effective than conducting bearing experiments or computational fluid dynamics simulations. The Reynolds equation can be solved easily in a numerical model; however, the accuracy of each model is dominated by the orifice discharge coefficient. This study compared two orifice flow models in inherent orifice restrictors and investigated the influences of geometry and flow parameters on the discharge coefficient. The results indicate that both orifice flow models can be used in inherent orifice restrictors, and the discharge coefficient of orifice-type restrictors is sensitive to the orifice diameter and film thickness.

1. Introduction

In aerostatic bearing analysis, film pressure can be derived by solving the Reynolds equation, conducting bearing experiments, or performing computational fluid dynamics (CFD) simulations. Solving the Reynolds equation is the most effective approach among these methods because a bearing experiment and CFD simulation are comparatively more time-consuming. The Reynolds equation can be solved easily by using the finite difference method (FDM) in a numerical model; however, the accuracy of each model is dominated by the orifice discharge coefficient. This discharge coefficient is generally a predetermined number [1–3] and can be calculated based on experimental results [4–5] or results of CFD simulations [6–8].

Belforte et al. [4] experimentally investigated the discharge coefficient of aerostatic bearings. They discovered that the discharge coefficient is variable and proposed approximation functions based on Reynolds numbers. However, their definition of downstream pressure differs from that used in FDM calculations because the pressure drop cannot be determined by solving the Reynolds equation. Therefore, these approximation functions may not be applicable in FDM calculations. Nishio et al. [5] examined the static and dynamic characteristics of aerostatic thrust bearings and determined the discharge coefficient in the FDM calculations by comparing the experimental results. The discharge coefficients are constant in a designed bearing. The results indicated that the results of the FDM calculations were inconsistent with the experimental results when a small film thickness was used.

Miyatake and Yoshimoto [6] analyzed aerostatic bearings composed of small feed holes by investigating the effects of the orifice diameter and number of feed holes on bearing performance. They also compared FDM calculations with the results of CFD simulations to determine the discharge coefficient. The results indicated that the FDM calculations performed using constant discharge coefficients were inconsistent with the results of the CFD simulations when a small film thickness was used. Neves et al. [7] studied the performance of aerostatic journal bearings. They solved the Reynolds equation by using the finite element method and determined the discharge coefficient by comparing the results of CFD simulations. They also proposed an approximation function of the discharge coefficient based on an absolute pressure ratio. However, this pressure ratio is produced by a numerical model, and the numerical model must be solved iteratively to derive the matched pressure ratio and discharge coefficient. Aerostatic bearings with inherent orifice restrictors were studied in [8]. In this study, the influences of bearing geometry and flow parameters on discharge coefficient was investigated and a surrogate model of the discharge coefficient based on the orifice diameter and film thickness was proposed. This surrogate model is useful in performing FDM calculations; however, the aerostatic bearings with pocketed orifice restrictors are not studied.

In recent studies, two types of orifice flow models are applied in inherent orifice restrictors. One flow model considers the feed holes as orifice restrictor and the other model considers the feed holes as inherently compensated restrictor [6]. The orifice flow models can affect the value of discharge coefficient. The current

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http://dx.doi.org/10.1016/j.triboint.2015.04.030
0301-679X/

Nomenclature

C_d, $C_{d,1}$, $C_{d,2}$ Discharge coefficient
d Orifice diameter
d_p Pocket depth
E Load difference ($E = \left|\frac{W_{CFD} - W_{FDM}}{W_{CFD}}\right|$)
h Film thickness
k Specific heat ratio of air
$\dot{m}_b$ Mass flow rate from the bearing
$\dot{m}_o$,$\dot{m}_{o,1}$,$\dot{m}_{o,2}$ Mass flow rate through the orifice
$\dot{m}_t$,$\dot{m}_{t,1}$,$\dot{m}_{t,2}$ Theoretical mass flow rate
n_h,n_R,n_θ Number of elements
p Film pressure
P_d, $P_{d,1}$, $P_{d,2}$ Downstream pressure
P_s Supply pressure
R_b Bearing radius
R_p Pocket radius
W_{CFD} Load capacity determined from the CFD simulation
W_{FDM} Load capacity determined from the FDM calculation
μ Air viscosity
ρ Air density
ρ_s Supply air density

study compared the discharge coefficients determined by both types of models in the analysis of aerostatic bearings with inherent orifice restrictors. This study also investigated the influences of bearing geometry and flow parameters on the discharge coefficient in the pocketed orifice restrictors. Furthermore, the discharge coefficients of the inherent and pocketed orifice restrictors were also examined.

2. Aerostatic bearing modeling

2.1. Orifice discharge coefficient

Fig. 1 depicts an aerostatic bearing with an orifice-type restrictor. Externally pressurized air flows into the bearing via an orifice restrictor. The air pressure is reduced from P_s to P_d. The mass flow rate of air through an orifice can be calculated as follows:

$$\dot{m}_o = C_d \times \dot{m}_t \tag{1}$$

where C_d is the orifice discharge coefficient and $\dot{m}_t$ is the theoretical mass flow rate. The orifice discharge coefficient is generally a given number in the range $0 < C_d \le 1$.

Recent studies have commonly used two types of orifice flow models. The flow model of Eq. (2) considers the feed holes as orifice restrictor and the flow model of Eq. (3) considers the feed holes as inherently compensated restrictor [6].

$$\begin{aligned} &\dot{m}_t = \frac{\pi d^2}{4}\sqrt{2\rho_s P_s\left(\frac{k}{k-1}\right)\left[\left(P_d/P_s\right)^{2/k} - \left(P_d/P_s\right)^{(k+1)/k}\right]} && \text{if}\frac{P_d}{P_s} \ge \left(\frac{2}{k+1}\right)^{k/(k-1)} \\ &\dot{m}_t = \frac{\pi d^2}{4}\sqrt{\rho_s P_s k\left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}} && \text{if}\frac{P_d}{P_s} < \left(\frac{2}{k+1}\right)^{k/(k-1)} \end{aligned} \tag{2}$$

$$\begin{aligned} &\dot{m}_t = \pi dh\sqrt{2\rho_s P_s\left(\frac{k}{k-1}\right)\left[\left(P_d/P_s\right)^{2/k} - \left(P_d/P_s\right)^{(k+1)/k}\right]} && \text{if}\frac{P_d}{P_s} \ge \left(\frac{2}{k+1}\right)^{k/(k-1)} \\ &\dot{m}_t = \pi dh\sqrt{\rho_s P_s k\left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}} && \text{if}\frac{P_d}{P_s} < \left(\frac{2}{k+1}\right)^{k/(k-1)} \end{aligned} \tag{3}$$

where h is the film thickness, P_s is the supply pressure, ρ_s is the supply air density, P_d is the downstream pressure, d is the orifice diameter, and k is the specific heat ratio of air.

The theoretical mass flow rates of inherent orifice restrictors were determined using Eq. (2) in [1,4,8]. However, this mass flow rates were determined by using Eq. (2) when $h \ge d/4$ or Eq. (3) when $h < d/4$ in [6,9]. In the most of operations, $h < d/4$ is satisfied and Eq. (3) is used. The current study compared the discharge coefficients determined by both types of flow models in inherent orifice restrictors. For pocketed orifice restrictors, only the orifice flow model of Eq. (2) was used in the references. This study investigated the influences of bearing geometry and flow parameters on the discharge coefficient in aerostatic bearings with pocketed orifice restrictors.

2.2. Finite difference method calculation

In aerostatic bearings, an air film separates the bearing surface from the reaction plate. The supply air forms this film and provides the bearing load capacity, stiffness, and damping. The pressure distribution of the film can be derived by solving the Reynolds equation. The general form of the Reynolds equation is expressed as follows:

$$\frac{\partial}{\partial x}\left(\frac{\rho h^3}{12\mu}\frac{\partial p}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\rho h^3}{12\mu}\frac{\partial p}{\partial y}\right) = \frac{U}{2}\frac{\partial(\rho h)}{\partial x} \tag{4}$$

where p is the film pressure, h is the film thickness, ρ is the air density, μ is the air viscosity, and U is the speed. Assume that the air is an ideal gas ($\rho = p/RT$) and that the bearing is operated in an isothermal

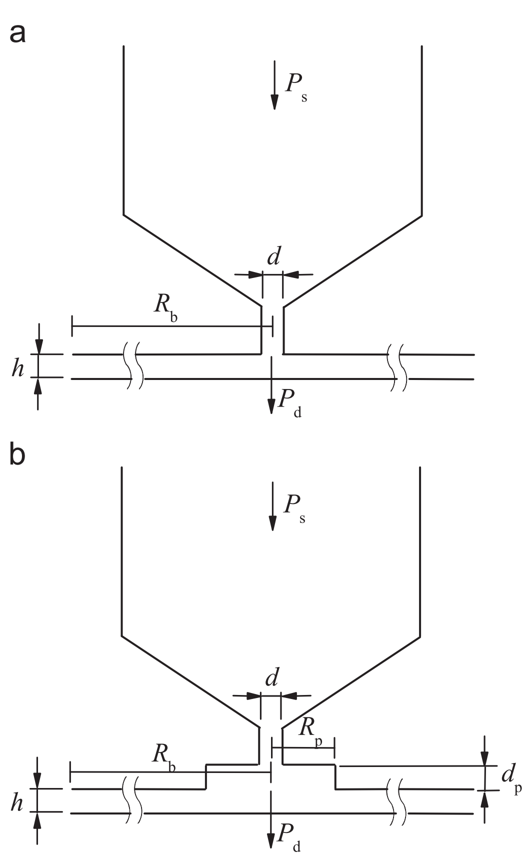

Fig. 1. (a) Aerostatic bearing with an inherent orifice restrictor. (b) Aerostatic bearing with a pocketed orifice restrictor.