

Performance analysis of high-speed spindle aerostatic bearings

Cheng-Ying Lo^a, Cheng-Chi Wang^{b,*}, Yu-Han Lee^c

^a Department of Aeronautical Engineering, National Hu-Wei Institute of Technology, Huwei, Yulin, Taiwan, ROC

^b Department of Automation and Control Engineering, Far-East College, 49, Chung-Hwa Road, Hsin-Shih, Tainan 744, Taiwan, ROC

^c Department of Mechanical Engineering, National Cheng-Kung University, Tainan, Taiwan, ROC

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Abstract

The methods adopted to derive the pressure distribution and precision of bearing rotation are fundamental issues in the arena of gas bearing design. The current study presents a detailed theoretical analysis of bearing performance, in which the gas flow within the bearing is initially expressed in the form of simplified dimensionless Navier Stokes equations. Adopting the assumption of mass flow continuity between the bearing clearance and the orifice, the nonlinear dimensionless Reynolds equation is then derived and subsequently discretized using the Newton method. Finally, the modified Reynolds equation is solved by means of the iterative rate cutting method. The current numerical models are valid for the analysis of the film pressure distribution, friction effects, loading capacity, rigidity, lubricating gas flow rate, and eccentricity ratios of a variety of static and dynamic pressure aerostatic bearings, including high-eccentricity ratio journals, high-speed non-circular journals, thrust bearings, and slider bearings, etc. The proposed analytical models provide a valuable means of analyzing the static and dynamic performance of a high-precision rotating gas bearing, and allow its design to be optimized accordingly.

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1. Introduction

Gas bearings are characterized by low noise under rotation and by their low frictional losses. As a result, they are frequently employed within precision instruments, where they yield zero friction when the instruments are used as null devices, and within high-speed electrical motors. Compared with traditional oil bearings, gas bearings have the advantages of lower heat generation, less contamination, and a higher precision. However, their major disadvantage is that they tend to be rather unstable, and this frequently restricts their permissible range of application.

In 1961, Gross and Zachmanaglou [1] first developed, and then applied, perturbation solutions to steady, self-acting, infinitely long journal and plane wedge films. The proposed perturbation solutions are

valid for all ranges of geometrical parameters, and yield highly precise results. In 1975, Majumdar [2] presented a theoretical method to derive the steady-state performance characteristics of stationary and rotating journals by considering a three-dimensional flow in the porous material of a bearing. It is known that the response of gas bearing supported systems is greatly influenced by the dynamic characteristics of the gas film, and that the important parameters are the film stiffness, the damping, and the stability range. As the majority of bearings are intended to operate in a stable manner, a detailed knowledge of their relative stability characteristics is of fundamental importance. Accordingly, Majumdar [3] constructed theoretical models for the stiffness and damping characteristics of an externally pressurized, rectangular, porous thrust bearing with a compressible lubricant.

In 1985, Gero and Ettles [4] evaluated the relative precision of the FDM and FEM approaches when applied to a steady, isoviscous, incompressible lubrication problem. In their study, it was assumed that the

* Corresponding author. Tel.: +886-6-5977970; fax: +886-6-5977974.

E-mail address: ccwang@cc.fec.edu.tw (C.-C. Wang).

Nomenclature

$a_{i,j}, b_{i,j}, c_{i,j}, d_{i,j}, e_{i,j}, s_{i,j}$	coefficient matrices
d	orifice diameter
Δe	eccentricity
h	gas film thickness
h_m	average gas film thickness
k	specific heat ratio of gas ($= c_p/c_v$)
l	characteristic length
\dot{m}	mass flow rate
n	number of supply stations
p	gas pressure distribution function
\bar{p}	non-dimensional gas pressure distribution function
\bar{p}_{rN}	gas pocket pressure of N th orifice
p_a	atmospheric pressure
p_0	non-dimensional reference gas pressure
r_i, r_o	inner and outer radius of circular thrust bearing
r_m	radius of orifice
u, v, w	dimensionless velocity in x -, y -, z -direction
\bar{v}	flow velocity of orifice
x, y, z	coordinates
$\bar{x}, \bar{y}, \bar{z}$	dimensionless coordinates
A	area of orifice
C_w	dimensionless load coefficient
D	diameter of bearing
G	cutting factor
K_n	Knudsen number
K_w	bearing stiffness
L	length of bearing
N	orifice number
\bar{Q}	flow factor ($\bar{Q} = (12\eta l^2 p_a / h_m^3 p_0^2 \rho_a) \rho \bar{v}$)
p_s	supplied pressure
R	gas constant
T	temperature
V	characteristic velocity
W	load capacity
α	factor of fast convergence
δ^n	corrected value of pressure
ε	rate of eccentricity
ψ	flow coefficient of orifice
θ, ξ	dimensionless load coordinates
ω	relaxation factor
ρ	gas density
μ	gas viscosity
Λ_x	bearing number in x direction ($\Lambda_x = 12\mu u_1 l / h_m^2 p_0$)
Λ_z	bearing number in z direction ($\Lambda_z = 12\mu w_1 l / h_m^2 p_0$)

solution of a complicated coupled problem could be derived by solving a sequential series of simple, uncou-

pled, steady problems. The results for two-dimensional bearings demonstrated that the relative errors of the FDM solutions were smaller than those associated with the FEM approach. Furthermore, it was shown that the FDM approach was more rapid than the FEM technique, with an average CPU time of 0.15 s as compared to 0.17 s for the FEM method.

In 1992, Slocum [5] performed experimental studies to develop comprehensive design procedures for orifice-compensated gas journal bearings. More recently, the influence of surface roughness on bearing performance has been investigated [6,7]. The results have confirmed the commonly held belief that surface roughness has a negligible effect on the lubrication characteristics of gas bearings in the case of laminar flow. In 1996, Hughes et al. [8] analyzed a gas lubricated thrust bearing experimentally and presented detailed measurements of the flow in the idealized bearing. The pad surface temperature measurements confirmed that the bearing flow was locally isothermal.

In 1994, Malik and Bert [9] considered the differential quadrature method (DQM), and applied it for the first time to the solution of steady-state oil and gas lubrication problems in self-acting hydrodynamic bearings. The quadrature solutions of the Reynolds equation for the case of incompressible lubrication were compared with the exact solutions of finite-length bearings. Furthermore, the quadrature solutions of the compressible Reynolds equation for finite-length plain journal bearings were compared with those obtained using the FED and FEM approaches. The CPU times associated with the quadrature solutions were compared with those of the trigonometric series and the finite element solutions for oil-lubricated plain slider and journal bearings. Additionally, the CPU times of the quadrature solutions were compared with those of the finite solutions for the case of a gas-lubricated journal bearings. In all cases, it was found that the DQM method was capable of yielding precise solutions to the lubrication problems, and that it was computationally more efficient than either the FED or the FEM method.

2. Mathematical modeling

2.1. Governing equation and its non-dimensional form

The aerostatic bearings model incorporates the following design assumptions:

- Gas lubricating films are very nearly isothermal because the ability of the bearing materials to conduct away heat is greater than the heat generating capacity of the gas film. Thus, we may assume that the flow is isothermal.
- As gas viscosity is somewhat insensitive to changes in pressure, and the temperature is virtually con-

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