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Numerical analysis and experimental research on the angular stiffness of aerostatic bearings

Hailong Cui [a,*], Yang Wang [a], Hong Yang [a], Liang Zhou [a], Hai Li [b], Wei Wang [b], Chunjiang Zhao [c]

[a] *Institute of Machinery Manufacturing Technology, China Academy of Engineering Physics, Mianyang, 621000, People's Republic of China*
[b] *School of Mechatronics Engineering, University of Electronic Science and Technology of China, Chengdu, 611731, People's Republic of China*
[c] *School of Mechanical Engineering, Taiyuan University of Science and Technology, Taiyuan, 030024, People's Republic of China*

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ABSTRACT

The machined surface topography in the ultra-precision machining process was obviously affected by the angular stiffness of aerostatic bearings. In this study, a numerical model was established to investigate the influence of operating conditions, geometric parameters and manufacturing error on the angular stiffness of aerostatic bearings with orifice restrictor. The calculation procedure for bearing angular stiffness was proposed based on the finite element method (FEM) and the proportional division method. The numerical results presented that film pressure distribution was significantly affected by the bearing deflection angle and the manufacturing error. It was confirmed that there was a suitable film thickness corresponding to the maximum angular stiffness, and the suitable film thickness increased with the growth of orifice diameter. The bearing angular stiffness increased with the rise of eccentricity, the thrust bearing angular stiffness can be improved by increasing the amplitude of non-flatness error and the thrust eccentricity, which can be used to improve the machining quality of ultra-precision machine tools. Besides, a precision experimental system was constructed to measure the angular stiffness of aerostatic bearings at the different supply pressure. The biggest difference between the experimental data and calculation results was less than 6.7%, which demonstrated the numerical calculation method proposed in this paper can be applied to optimize the angular stiffness of aerostatic bearings.

1. Introduction

Due to the advantages of high rotation accuracy, long operating life, nearly non-friction, low power consumption, aerostatic bearings has been successfully applied in ultra-precision machine tool [1,2]. The quality of the ultra-precision machining was significantly influenced by the static and dynamic performance of aerostatic bearings [3,4]. An et al. [5] demonstrated that the mid-spatial frequency waviness error of large diameter optical component was mainly caused by the tilting motion of aerostatic bearings spindle, and presented the relationship between the spindle tilting motion and angular displacement.

In the reported literature, the studies of aerostatic bearings performance largely concentrated on the load carrying capacity, thrust stiffness, radial stiffness, rotation accuracy and stability [6–10]. However, there were very few literature focused on angular stiffness of aerostatic bearings, only several researchers carried out studies on the tilt characteristics of aerostatic bearings. Rao et al. [11] proposed a theoretical method to analyze the static stiffness, load capacity and gas mass flow rate of rectangular thrust aerostatic bearings at the condition of offset load, and found that the bearing load capacity decreased with the growth of tilt, the maximum load capacity and stiffness could not be obtained at the same design parameters. Singh et al. [12] investigated the effect of offset load on the static characteristics of aerostatic porous thrust bearing at different operating parameters, and concluded that the load capacity and stiffness could be improved by reducing the bearing tilt, while the mass flow rate increased with the rise of bearing tilt. Bender et al. [13] presented a study on the tilt stiffness and damping coefficient of circular aerostatic bearings with the central gas feeding, and showed that the tilt stiffness proportionally increased with bearing load, but the damping coefficient decreased sharply with the growth of bearing load. Nakamura et al. [14] carried out a comparative research on the tilt moment of rectangular double pad aerostatic thrust bearings between conventional feedhole restrictors and compound restrictors, and proved that the tilt moment of aerostatic thrust bearings could be improved by using compound restrictors rather than feed-hole restrictors. The comparative study of double pad thrust bearings between single feeding row and

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* Corresponding author.
E-mail address: cuihailong61@foxmail.com (H. Cui).

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Nomenclature

A	amplitude of waviness or non-flatness errors
A_r	cross-sectional area of orifice
e	complex eccentricity
e_0	initial eccentricity
err	calculation error
f_ω	waviness spatial wavelength
$f(x,y)$	pressure square function
f_{dr}	orifice outlet pressure square
f_{dr}^*	orifice outlet initial pressure square
$F_{(u+v)\times 1}$	matrix of pressure square on nodes
G	factor of proportional division method
$\bar{h}$	dimensionless gas film thickness
$\bar{h}_0$	initial dimensionless film thickness
h_e	waviness error of journal bearing
$\bar{h}_j$	ideal dimensionless film thickness of journal bearing
$\bar{h}_J$	actual dimensionless film thickness of journal bearing
$\bar{h}_t$	ideal dimensionless film thickness of thrust bearing
$\bar{h}_T$	actual dimensionless film thickness of thrust bearing
h_ε	non-flatness of thrust board of thrust bearing
k	entropic expansion index
K_θ	angular stiffness of journal bearing
$K_{J\theta}$	angular stiffness of journal bearing
$K_{T\theta}$	angular stiffness of thrust bearing
$K_{u\times(u+v)}$	position coefficient matrix
$\bar{L}$	dimensionless distance
m	number of triangle cell
m_r	gas mass rate flow through the orifice
M_J	moment of journal bearing
M_T	moment of thrust bearing
num	number of orifice restrictor
N	waviness spatial number
p_a	atmospheric pressure
p_d	pressure at the outlet of orifice
p_s	supply pressure
$\bar{p}$	dimensionless gas pressure
$\bar{Q}$	dimensionless mass flow rate
$\bar{r}$	dimensionless polar coordinates of thrust bearing
R_J	shaft radius of journal bearing
$T_{u\times 1}$	mass rate function matrix
u	nodes with unknown pressure
v	nodes with known pressure
W_J	load capacity of journal bearing
W_T	load capacity of thrust bearing
$\bar{x}, \bar{y}$	dimensionless Cartesian coordinates of journal bearing
θ	deflection angle
β	circumferential angle coordinate of thrust bearing
$\bar{\beta}$	dimensionless angle in Polar coordinates
$\bar{\xi}$	dimensionless logarithmic variable
γ	angle in the circumferential direction of journal bearing
τ	proportional factor in the radial direction of thrust bearing
δ_i	orifice restrictor location function
ρ_a	gas density at condition of p_a
Γ	dimensionless mass flow factor
ϕ	mass flow coefficient
ψ_r	mass flow function
$\Phi_J(\bar{f})\Phi_T(\bar{f})$	normalized functional
ζ	calculation error limit

double feeding rows was conducted by Nakamura and co-workers [15], who found that the maximum tilt stiffness of the thrust bearing with double rows was much higher than single row. The above conclusions and results provide an effective reference for investigating the angular stiffness of aerostatic bearings.

The calculation result of pressure distribution in the bearing film is the fundament for the study of bearing angular stiffness. In the calculation process of angular stiffness, the film thickness at different positions is a variable rather than a constant, so the effect of manufacturing errors on the film pressure distribution is more significantly. Therefore, both geometric parameters and manufacturing errors should be considered in the analysis of aerostatic bearings angular stiffness. Kwan et al. [16] classified the manufacturing errors of rectangular aerostatic thrust bearings with inherently compensated restrictor into waviness, convexity, concavity, and tilt, and illustrated the effect of different manufacturing errors on the bearing load capacity and static thrust stiffness. Cui et al. [17] found that the manufacturing errors of aerostatic journal bearing can be described as concavity, convexity, taper and circumferential waviness with different spatial wave length, and the concavity, taper, circumferential waviness resulted in the growth of bearing load capacity and stiffness. Based on dynamic mesh technology, the effect of waviness and non-flatness on the rotation accuracy of aerostatic porous spindle was conducted by Cui and co-workers [18], who discovered that the circumferential waviness was the major source of bearing rotation error. Wang et al. [19,20] presented the influence of surface waviness on static and dynamic characteristics of aerostatic journal bearings, and showed that the bearing performance can be improved by increasing the waviness amplitude.

In order to calculate the performance of gas bearings, the different numerical calculation methods were used to solve the Navier-Stokes (N-S) equations or Reynolds equation. Yoshimoto et al. [21] applied three different theories to solve the gas pressure distributions at different film thickness, and showed that the pressure reduction near the orifice inlet could be described by the numerical results of the three-region theory and N-S equations, but the pressure recovery obtained from the results of the three-region theory was more rapid than those from the N-S equations and experimental data. Because of high calculation precision and convenient visualization of the pressure distribution in the bearing film, the computational fluid dynamics (CFD) method is widely used to study the bearings performance. Belforte et al. [22] carried out a CFD analysis on aerostatic bearings with a simple orifice type feeding system. Gao et al. [23] used the CFD method to investigate the influence of orifice chamber shapes on the performance characteristics of aerostatic thrust bearings. Eleshaky et al. [24] investigated the pressure depression phenomenon using CFD numerical calculation. However, the numerical results of the CFD method are obviously influenced by the quality and number of computational grids. Compared to the CFD method, the finite difference method (FDM) and finite element method (FEM) are less time-consuming and more efficient. The Reynolds equation of externally pressurized grooved thrust bearings was solved using the FDM [25]. Wang et al. [19] used the FDM to calculate the influence of surface waviness on the static characteristics of aerostatic bearings. The FDM was also applied to model the radial running error of aerostatic journal bearings [26]. Otsu et al. [10] investigated the dynamic performance of aerostatic porous journal bearings with a surface-restricted layer based on FDM. However, the accuracy of FDM is seriously dependent on the orifice discharge coefficient. Chang et al. [27] introduced a golden section search optimization method to determine the discharge coefficient by comparing the simulation results of CFD with numerical calculations of FDM, and noted that the discharge coefficient was sensitive to the orifice diameter and film thickness. Nishio et al. [28] indicated that the FDM calculation results were inconsistent with the experimental data at a