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Study on the dynamic characteristics of a new type externally pressurized spherical gas bearing with slot–orifice double restrictors

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ABSTRACT

This study proposes a new type externally pressurized spherical gas bearing with slot–orifice double restricted restrictors, used in a new type gas gyroscope. Based on the spherical Reynolds equation and cylindrical Reynolds equation, small perturbation theory is employed to analyze the dynamic characteristics of the new type externally pressurized spherical gas bearing. The slot gas film and the spherical film are united by means of compatibility condition and a weak solution formula, based on Galerkin residual method, is erected. The nonlinear coupled weak solution equations are solved with FEM and the dynamic coefficients are obtained. Numerical simulation is operated and the change laws that the dynamic coefficients change with dimensionless perturbation frequency f, eccentricity ratio E_h and other structure parameters are analyzed. This paper provides a reference and preparation for analysis on the dynamic characteristics of the similar gas bearings.

1. Introduction

Gas bearings are widely used for low loss, high speed and precision. On the other hand, small load capacity, lower stiffness and bad reliability, especially the stability of gas bearings limit further application [1]. The dynamic characteristics of gas bearings, which can be represented by a set of dynamic stiffness and damping coefficients, associate with the dynamic behaviors of a rotor supported in gas bearings directly, and determine the stability of the gas bearings. Since the critical speeds are almost entirely determined by the stiffness of bearings, and the damping primarily controls the unbalance response; furthermore it is these properties that govern the stability of rotor [2]. Therefore, it is important to investigate the dynamic characteristics and stability for designing gas bearings.

It is reported in [3] there are many experimental and theoretical studies on gas bearings, while it seems that the theoretical research lags behind the experimental study. Lund [4,5] solved the dynamic Reynolds equation using "first-order PH perturbation", and obtained a set of stiffness and damping coefficients; furthermore he proposed a stability criterion after introducing a correction factor. Subsequently, Lund put forward a small parameter perturbation method based on complex function, and paid attention to the whirl frequency. In attention, Plessers [6,7] obtained the equivalent stiffness and damping coefficients through frequency response function of gas film, and represented the dynamic characteristics of the film using this function. Licht [8] proposed the centralized parameter method, subsequently he advanced the distributed parameter method. Yang et al. [9] applied the partial derivative method into tilting-pad gas bearings and self acting gas bearings, and achieved the dynamic characteristics coefficients. Zhang [10] united the method by which the dynamic properties of gas bearings and fluid bearings were got; however the partial terms, pressure p with respect to time t were ignored compulsively before unification in his paper.

In fact, the dynamic response is a nonlinear function with respect to velocity and eccentricity, and the function can be treated as a linear function when the eccentricity is small enough. Czolczynski [2] studied the dynamic coefficients of externally pressurized gas bearings with "the orbit method" considering the nonlinear terms of velocity and eccentricity, and get the dynamic coefficients with respect to the nonlinear terms of velocity and eccentricity.

Although a few researchers made a lot of study on the dynamic properties of gas bearings, many of that were slider gas bearings and tilting-pad gas bearings, and few researches were made on the other type of gas bearings. Gu [11] made an analysis of a spherical gas bearing gyro driven by Hero-jet. Sela [12] studied the properties of a spherical gas bearing gyro and analyzed its stability using the "Step-Jump method", while the dynamic coefficients were not analyzed or discussed. Kawabata [13]

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Nomenclature

A	sectional area of nozzles
$\overline{A}=A/c^2$	dimensionless sectional area of nozzles
A_1, B_1	coefficient matrix of static nodal pressure in static equation
A_{x1}, A_{x2}	coefficient matrix of dynamic nodal pressure $\overline{p}_x$ in dynamic equation
B_{x1}, B_{x2}	coefficient matrix of dynamic nodal pressure $\overline{p}_{\dot{x}}$ in dynamic equation
C_{ij}	damping coefficients (i, j=x, y, z)
C_D	discharge coefficient
D	diameter of nozzle
E_h	eccentricity ratio
F_0	load carrying capacity
$\overline{F}_0=F_0/(P_aR^2)$	dimensionless load carrying capacity
K_1, K_{x1}, K_{x2}	constant matrix
K_{d1}, K_{d2}, K_c	coefficients in continuity equation
K_{ij}	stiffness coefficients (i, j=x, y, z)
L	slot length expanded along circle direction
$\overline{L}=L/c$	dimensionless slot length expanded along circle direction
R	radius of spherical stator
RR	gas constant
T	bearing temperature
a	thickness of slot film
$\overline{a}=a/c$	dimensionless thickness of slot film
c	average clearance of spherical film
h	thickness of spherical film
$\overline{h}=h/c$	dimensionless thickness of spherical film
k	isentropic exponent
l	depth of the slot
$\overline{l}=l/c$	dimensionless depth of the slot
p	pressure
$\overline{p}=p/p_a$	dimensionless pressure
$\overline{p}_x,\overline{p}_y,\overline{p}_z$	dimensionless dynamic pressure for perturbing quantity
$\overline{p}_{\dot{x}},\overline{p}_{\dot{y}},\overline{p}_{\dot{z}}$	dimensionless dynamic pressure for perturbation velocity
p_a	ambient pressure
q	gas mass flow
$\overline{q}=q/(p_ac^3)$	dimensionless gas mass flow
r	radius from z-axis to any point in slot
t	time
$\overline{x},\overline{y},\overline{z}$	dimensionless perturbing quantity
$\dot{x}$, $\dot{y}$, $\dot{z}$,	dimensionless perturbation velocity
υ	whirl frequency
v	outflow velocity from nozzles
$\overline{v}=v/c$	dimensionless velocity
ω	angular velocity
τ=ωt	dimensionless time
μ	gas viscosity
Λ=$6\mu\omega/p_a(R/c)^2$	compressibility number
σ=$12\mu\upsilon/p_a(R/c)^2$	squeeze number
$\overline{\mu}=\mu/p_a$	dimensionless gas viscosity
θ	meridional angle of sphere
ϕ	vectorial angle of sphere
ε	eccentricity

Subscripts

d	slot entry
e	end of bearing
p	double throttle pocket
s	gas supply
0	static state

obtained the dynamic coefficients of a spherical spiral groove gas bearing through small parameter method, but the cross-coupled stiffness and damping coefficients between axial and radial directions were only considered.

A detail study was conducted based on the new type spherical gas gyroscope bearing with slot–orifice restrictors including the dynamic coefficients of the gas gyro bearing and dynamic characteristics with respect to frequency ratio, eccentricity ratio and other structural parameters.

2. Govern equation and perturbation analysis

2.1. Govern equation

The geometry of new type externally pressurized spherical gas gyro bearing with orifice and slot entry is shown in Fig. 1. The rotor is made up of two cylinders, which are combined together using bolts, and each cylinder has a semi-spherical cavity. The stator consists of three parts including two spherical caps and a spherical segment, by which the slot restrictor is shaped. Supply gas flows into the cavity located in the stator through the hollow shaft, then passes through two slot restrictors, which are formed by the spherical cap and segment of the stator, into the spherical lubrication region shaped by the spherical stator's surface and the spherical cavity of the rotor, finally exhausts into ambient atmosphere via twelve tangential nozzles that are mounted regularly along the circumference of the rotor and connected with the double throttle pocket. The rotor is then driven by the aerodynamic force arising from the nozzles and rotates at a high speed.

The spherical lubrication layer thickness and slot film thickness are 25 and 12 μm, respectively. When the supply pressure is up to four standard atmospheric pressures, the Knudsen number is $Kn>0.1$; thus the first-order slip flow condition can be neglected.

With the usual assumption that the process is isothermal in the slot region and spherical lubrication layer, the dimensionless

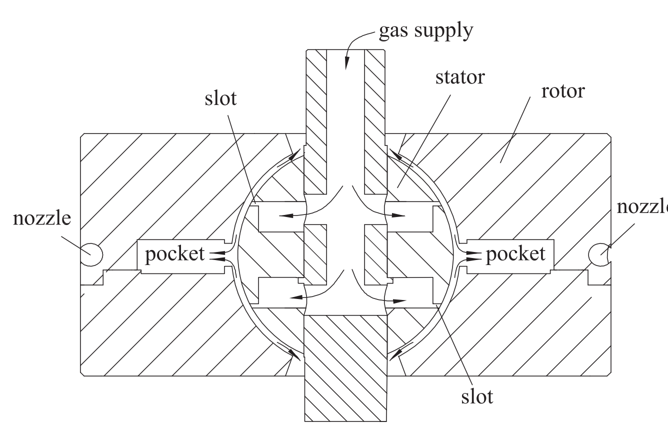

Fig. 1. Structure of the gas bearing gyro.