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Improving the pneumatic hammer stability of aerostatic thrust bearing with recess using damping orifices

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ABSTRACT

In order to improve the pneumatic hammer stability of aerostatic thrust bearing with recess, an array of damping orifices is introduced in the high pressure region of the bearing. The analysis model of pneumatic hammer is established based on modified Reynolds equation and motion equation. The 4th order Runge–Kutta method and FEM (finite element method) are employed to analyze the time-dependent dynamic behaviors of the bearing. Experimental results indicate that the graphical method can be applied to analyze quantitatively the pneumatic hammer stability of aerostatic thrust bearing and damping orifice can be used to improve the pneumatic hammer stability.

1. Introduction

Aerostatic bearings are widely utilized in ultra-precision machining equipment and measurement equipment due to their extremely high accuracy. However, inappropriate parameter and structure of the bearing will lead to instability, such as the pneumatic hammer instability of aerostatic thrust bearing. Pneumatic hammer is generally considered to be a self-excited vibration because of the compressibility of air and inertia coupling [1,2].

At present, there are enormous methods to study the pneumatic hammer stability of aerostatic bearing, such as stable boundary method, dynamic stiffness and damping method, graphic method and experimental method. Stable boundary method is the mean that the stability criterion of aerostatic bearing is deduced by the dynamic equation of the bearing, small disturbance and flow continuity condition. The theoretical and experimental analyses are carried out on the stable boundary of aerostatic bearings with concentric circular shape [3], circular shape [4,5], spherical shape [6], circumferential groove [7] and stabilizing restrictors [8,9]. This method can quickly determine whether pneumatic hammer occurs under certain parameters, however the results are not accurate enough, and the influence of the bearing mass on the pneumatic hammer stability cannot be analyzed. Dynamic stiffness and damping of aerostatic bearing can be obtained by perturbation method in the equilibrium position, and damping characteristic of the bearing is utilized to determine its stability. The dynamic stiffness and damping characteristics of a circular pad aerostatic thrust bearing are studied with dynamic grid technique of ANSYS [10]. Elrod describes the dynamic stiffness and damping of the bearing by the coefficients of the Lagrange polynomial [11]. The dynamic stiffness and damping characteristics of the annular throttle [12] and Orifice [13] bearing and aerostatic bearings with stabilizing restrictors [14,15] are studied. The improvement in stability was obtained by decreasing bearing stiffness. Dynamic and static tilt characteristics of aerostatic bearings with compound restrictors [16–18] are also studied. Dynamic stiffness and damping method is a quantitative analysis method in frequency domain, however, the influence of stiffness and damping of external structure supporting bearing on the pneumatic hammer stability are not taken into consideration. In graphic method, the vibration model of aerostatic bearing is transformed into the initial value problem of differential equations and the solutions of the equations are shown as h–t curve or v–h curve. Kong et al. establish the vibration model of aerostatic bearing, and the influence of gas supply pressure and film thickness on the pneumatic hammer stability are analyzed [19]. Chen studies the time-dependent dynamic behaviors of aerostatic bearing with groove by REM (Network Method Resistance) method [20]. Chen calculates the transient response of aerostatic bearing with groove by the finite difference method and Euler method [21]. The graphic method can directly identify the vibration characteristics of bearing in time domain and conduct experimental research easily. However those current researches mainly remain in the qualitative analysis. The experimental method is the approach to research the pneumatic hammer stability of aerostatic bearing through experiment. Talukder. H.M studies the influence of the depth of groove, the diameter of orifice and the mass of the bearings on the pneumatic hammer stability [22]. Tao' research shows that reducing the supply pressure and film thickness can

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Nomenclature

h	Film thickness;
p_{di}	Downstream pressure of recess;
p	Pressure;
t	Time;
u_1,u_2	Velocity at x direction;
w_1,w_2	Velocity at y direction;
Δ_i	Depth of pocket at orifice;
p_{di}	Downstream pressure of orifice;
p_{di}	Downstream pressure of damping orifice;
η	The kinematic viscosity of air;
p_a	Ambient pressure;
$\tilde{v}$	The average speed of outflow orifice;
ρ_a	Air density;
Δ_j	Depth of recess;

improve the pneumatic hammer stability [23]. Belforte studies the influence of the diameter and the number of micro holes on static characteristic of air pads with micro holes using experimental method [24]. Ye studies the influence of the shape of the groove on the pneumatic hammer stability using experimental method [25]. Experimental method can obtain the characteristics of pneumatic hammer on aerostatic bearing, but it cannot confirm the cause of pneumatic hammer instability. Therefore the analysis model of pneumatic hammer is established by the modified Reynolds equation with the squeeze film effect and motion equation in this paper. The 4th order Runge–Kutta method and FEM are adopted to analyze quantitatively the time-dependent dynamic behaviors of the bearing by graphical method, and the influences of the number of damping orifices, supply pressure and recess on the pneumatic hammer stability of aerostatic bearing are carried out systematically.

2. The analysis model of pneumatic hammer stability on aerostatic bearing

2.1. The model of aerostatic bearing

The load capacity and stiffness of an aerostatic bearing can be improved by providing a ring of shallow recesses around its central land to create a high pressure region. However, pneumatic hammer occurs in an aerostatic bearing because of its volume effect. As shown in Figs. 1 and 2, an array of inherent damping orifices is introduced in the high pressure region to improve the stability of pneumatic hammer. The geometrical configuration of damping orifices is shown in Fig. 3. Table 1 shows the dimensions of the aerostatic bearing with inherent. There n_1 is defined as the number of orifice, d_1 is the diameter of orifice, n_2 is the number of damping orifices and d_2 is the diameter of damping orifice.

2.2. The method of analysis for pneumatic hammer stability

Generalized Reynolds equation used to analyze the load capacity of an aerostatic bearing is given by:

$$\frac{\partial}{\partial x}\left(h^3 p\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial z}\left(h^3 p\frac{\partial p}{\partial z}\right)$$

$$=12\eta\frac{\partial(ph)}{\partial t}+6\eta\left[\frac{\partial ph(u_1+u_2)}{\partial x}+\frac{\partial ph(w_1+w_2)}{\partial z}\right] \quad (1)$$

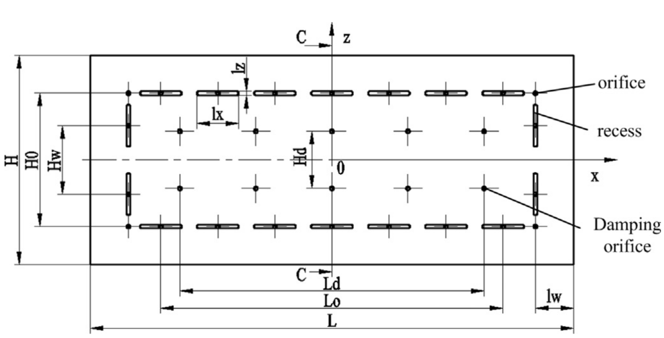

Fig. 1. Aerostatic thrust bearing 1 with recess and damping orifice.

As shown in Eq. (1), the physical meaning of Reynolds equation is the product the change rate per unit time of mass flow in the computational domain per unit area with a common factor of $12\eta p_a/\rho_a$.

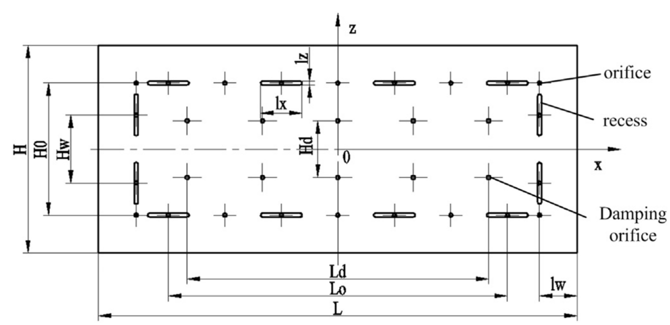

Fig. 2. Aerostatic thrust bearing 2 with recess and damping orifice.

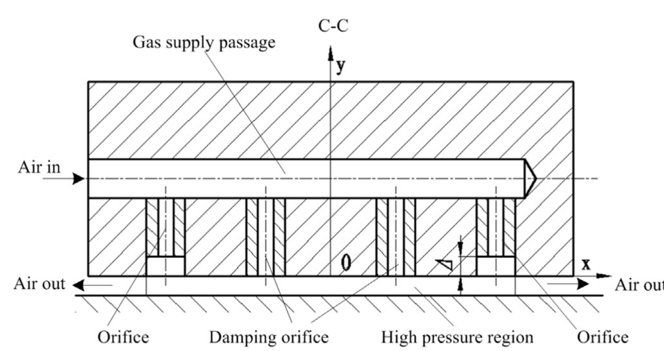

Fig. 3. Cross-sectional view of the designed aerostatic thrust bearing 1.

Table 1
Dimensions of the designed aerostatic bearing.

Parameter	Value
$L\times H$ (mm × mm)	127 × 55
Lo (mm)	90
Ld (mm)	80
lw (mm)	10
Ho (mm)	35
Hw (mm)	18
Hd (mm)	15
$lx\times lz$ (mm × mm)	12 × 1
n_1	22
n_2	10
d_1 (mm)	0.2
d_2 (mm)	0.2