euspen's 16th International Conference & Exhibition, Nottingham, UK, May 2016

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Modelling opposite effects of the damping chamber and gas chamber on the stability of aerostatic thrust bearings

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Abstract

In this paper, the dynamic models of aerostatic thrust bearings without damping chamber and with damping chamber are established by adopting the lumped parameter method. The numerical computational results indicate that the instability of aerostatic thrust bearing is mainly caused by the compressibility of gas and the presence of gas chamber, in which gas can be stored. The damping chamber, which is similar to the damping chamber inside the pneumatic vibration isolator, can increase the damping of the gas-mass system in the film direction, thereby increase the bearing stability. The gas chamber and the damping chamber play opposite effects on the stability of aerostatic thrust bearings.

Keywords: Aerostatic thrust bearings   Stability   Damping chamber   Gas chamber

1. Introduction

Aerostatic bearings are widely used on ultra-precision equipment, such as diamond turning and coordinate measuring machines due to their higher precision, lower friction and hardly any wear. Stability is the basic requirement of bearings, but the compressibility of air often causes self-excited vibration, which is known as pneumatic hammer.

Much work has been done on pneumatic hammer. Mohamed Fourka et al built a non-linear model based on finite element method of air thrust bearings and this model can be applied to various types of geometrical and supply situations for the stability analysis [1]. Farid Al-Bender provided an example showing pneumatic hammer can be avoided by employing active dynamic compensation [2]. Chen Xuedong et al conducted an experimental study and the results illustrated pneumatic hammering is related to the natural characteristic of aerostatic bearings, and the vibration status of the pneumatic hammer is deeply affected by recess shape [3]. Du Jianjun studied the self-excited vibration of externally pressurized gas thrust bearing with circumferential groove and pointed out the effect of supply pressure, orifice diameter and diameter ratio on self-excited vibration [4]. Tan Jiubin et al analysed the pneumatic hammer in rectangular aerostatic thrust bearings with groove using the perturbation theory [5].

In this paper, the dynamic lumped parameter models of aerostatic thrust bearings with gas chamber or damping chamber are established. Those models indicate the instability of aerostatic thrust bearing is mainly caused from gas chamber, while the damping chamber can increase the bearing stability by increasing damp. The gas chamber and the damping chamber play opposite effects on the stability of aerostatic thrust bearings.

2. Lumped Parameter Model

An aerostatic thrust bearing consists of an upper and lower thrust plate. The upper plate is suspended in mid-air under the impetus of gas film. Gas stream flows into the recess from the feed hole, then into the surrounding environment along the thrust bearing radially outward.

Parameters are defined as follows:

$\xi = (\frac{\partial \dot{m}_{out}}{\partial P_d})_{P_{d0}}$, $\theta = \left(\frac{\partial \dot{m}_{out}}{\partial h}\right)_{h_0}$ --- Partial derivative of mass flow rate out of the bearing

$\alpha_{cc} = -\left(\frac{\partial \dot{m}_{inc}}{\partial P_c}\right)_{P_{c0}}$, $\alpha_{cb} = \left(\frac{\partial \dot{m}_{inb}}{\partial P_c}\right)_{P_{c0}}$, $\alpha_{db} = -\left(\frac{\partial \dot{m}_{inb}}{\partial P_d}\right)_{P_{d0}}$, $\alpha_{dc} = \left(\frac{\partial \dot{m}_{inc}}{\partial P_d}\right)_{P_{d0}}$ --- Partial derivative of mass flow rate into the bearing and damping chamber

$q_b = \left(\frac{\partial m_b}{\partial P_d}\right)_{P_{d0}}$, $q_c = \left(\frac{\partial m_c}{\partial P_c}\right)_{P_{d0}}$, $r = \left(\frac{\partial m_b}{\partial h}\right)_{h_0}$ --- Partial derivative of stored gas' mass inside of the bearing and damping chamber

The NS equation in cylindrical coordinates can be written as $\frac{dP}{dr} = \eta \frac{\partial^2 v_r}{\partial z^2}$ under the assumption of one-dimensional flow. Thus, airflow velocity distribution expression can be obtained as $v_r = \frac{1}{2\eta}\frac{dP}{dr} z(z-h)$ when the upper thrust plate is static.

When applying the isothermal assumptions $\frac{P}{\rho} = \frac{P_a}{\rho_a}$, the mass flow rate is $\dot{m}_{out} = -2\pi r \int_0^h \rho v_r \, dz = \frac{\pi h^3 \rho_a}{12\eta P_a \ln\frac{R_2}{R_1}}({P_d}^2 - {P_a}^2)$ (2-1)

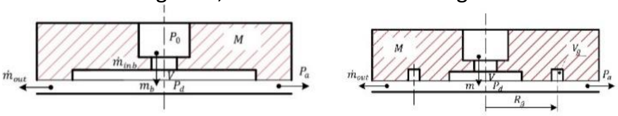
When pressure changes with time, the carrying capacity consists of steady-state part and time-varying part, $W = W_0 + W_1(t) = A_e[P_{d0} + P_{d1}(t)]$, thus, the stiffness of the film-mass system is $K_b(s) = -\frac{W_1(s)}{h_1(s)} = -A_e\frac{P_{d1}(s)}{h_1(s)}$ (2-2)

According to Newton's second law, the transfer function of gas film-mass system is $G(s) = \frac{h_1(s)}{f(s)} = \frac{1}{Ms^2 + K_b(s)}$ (2-3)

Due to the negative feedback, system may become unstable if the solution of transfer function's characteristic equation has a positive real part.

2.1. Models with Gas Chamber

As shown in figure 1, there are two forms of gas chamber.



(a) (b)

Figure 1. Two kinds of gas chamber. (a) shows the normal gas chamber designed for increasing the carrying capability. Concave structures in (b) on the thrust surface play the same

effect with gas chamber for their ability to store compressed gas when the air gap pressure grows.

When gas clearance and bearing carrying capacity changes dynamically, the total differential or variation of the mass continuity equation in and out of the bearing is

$$q_b \frac{dP_{d1}(t)}{dt} + r\frac{dh_1(t)}{dt} = -\alpha_{db}P_{d1}(t) - \xi P_{d1}(t) - \theta h_1(t)$$

The stiffness of gas film-mass system can be deduced according to eqn.(2-2), $K_b(s) = \frac{\theta A_e}{\alpha_{db}+\xi}\frac{1+\frac{r}{\theta}s}{1+\frac{q_b}{\alpha_{db}+\xi}s}$. System will be stable only if $\frac{r}{\theta} > \frac{q_b}{\alpha_{db}+\xi}$ by applying Routh Criterion [6]. (2-4)

Once the structure of bearing is determined, parameters mentioned previously can be deduced as $\frac{r(\alpha_{db}+\xi)}{\theta * q_b} = \frac{f(h_0)}{3(V+h_0A_e)}$, where $f(h_0)$ is determined by steady supply pressure and steady clearance. (2-5)

From equation (2-5), it can be clearly seen that the bearing is less likely stable when recess is bigger. As a result, thrust's recess should be designed small if only it satisfy the static characteristics, such as carrying capability and static stiffness.

When concave structures are added into the plate surface, the denominator of equ.(2-5) becomes $3\left(V + h_0A_e + \frac{R_1-R_g}{R_2-R_1}V_g\right)$, supposing the pressure on the surface is not affected by those concave structures and the pressure distribution is linear approximately. It can be concluded that bearing will vibrate more easily if there are concave structures on the surface of bearing.

2.2. Models with Damping Chamber

Restrictor itself can produce a damping effect. Vibration isolator, which can be applied in vibration isolation table, often employs an orifice as the restrictor. There are two patterns to add those damping structures into the design of aerostatic bearing to suppress pneumatic hammer. Figure 2(a) shows the case when the damping chamber and inlet are connected in series, which means the gas has to go through the damping chamber before it enter the inside of bearing through the feed hole.

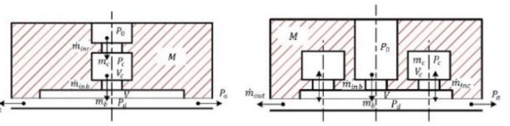


Figure 2. Damping chamber and inlet are in series or separated

Mass continuity equation in and out the recess and damping chamber are $\dot{m}_b = \dot{m}_{inb1} - \dot{m}_{out1}$,$\dot{m}_c = \dot{m}_{inc} - \dot{m}_{inb}$. The total differential form of mass continuity equation is

$$q_b \frac{dP_1(t)}{dt} + r\frac{dh(t)}{dt} = -\alpha_{db}P_{d1}(t) + \alpha_{cd}P_{c1}(t) - \xi P_{d1}(t) - \theta h_1(t)$$

$$q_c \frac{dP_c}{dt} = -\alpha_{cc}P_c(t) + \alpha_{db}P_{d1}(t) - \alpha_{cd}P_{c1}(t)$$

The stiffness of gas film-mass system can be deduced as $K_b(s) = A_e \frac{\theta+rs}{(q_b s+\alpha_{db}+\xi)-\frac{\alpha_{cb}\alpha_{db}}{q_c s+\alpha_{cc}+\alpha_{cd}}}$ form formula (2-5) and the stable condition of gas film-mass system can be obtained by utilizing Hurwitz criterion, $\frac{r}{\theta} > q_b/(\xi + \frac{\alpha_{cc}\alpha_{db}}{\alpha_{cc}+\alpha_{cd}})$. Compared with inequality (2-4), α_{db} has been changed into $\frac{\alpha_{cc}\alpha_{db}}{\alpha_{cc}+\alpha_{cd}}$. To possess the same static stiffness, the left item of inequality must keep the same, which makes the mass flow rate decrease, and θ becomes smaller. Therefore, the right item of the inequality will increase and makes the bearing more stable.

When gas film becomes thinner, pressure downstream the feed hole becomes higher, the airflow will shrink for the pressure difference decreases, and the extra gas will be stored in the damping chamber, which is equivalent to reduce the compressibility of air film.

When the damping chamber and inlet are connected independently like figure 2(b), mass continuity equation in and out the bearing and damping chamber can be written as $\dot{m}_b = \dot{m}_{inb1} - \dot{m}_{out1} - \dot{m}_{inc1}$,$\dot{m}_c = \dot{m}_{inc1}$. The total differential form of mass continuity equation is $q_c \frac{dP_c}{dt} = -\alpha_{cd}P_{d1}(t) - \alpha_{cc}P_c(t)$

$$q_b \frac{dP_1(t)}{dt} + r\frac{dh(t)}{dt} = -\alpha_{db}P_{d1}(t) - \alpha_{cd}P_{d1}(t) + \alpha_{cc}P_c(t) - \xi P_{d1}(t) - \theta h(t)$$

The stiffness of gas film-mass system can be deduced as $\frac{-A_e(\theta+rs)(q_c s+\alpha_{cc})}{(q_b s+\alpha_{db}+\alpha_{cd}+\xi)q_c s+\alpha_{cc}-\alpha_{cc}\alpha_{cd}}$ form (2-5), which deduces the stable condition $\frac{r}{\theta} > \frac{q_b}{\xi+\alpha_{db}}$. It shows that the damping chamber independent of the air stream does not affect the stability of the bearing.

3. Numeric results

The stable and unstable area of bearings is shown in Figure 3 when supply pressure and constant load change. The stable scope of bearing reduces with the increase of recess volume. Predictably, when recess volume increase to a certain degree, bearing cannot stably work in any gas supply pressure. With the increase of the damping chamber volume, the stable scope of bearing increase.

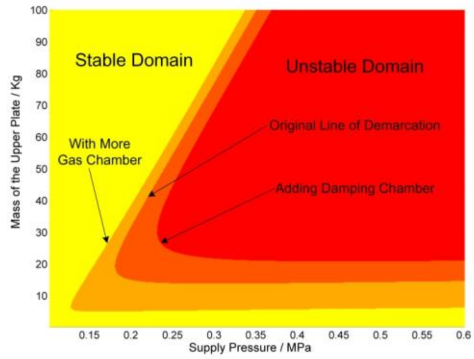


Figure 3. The stable areal distribution of bearings

The gas chamber and the damping chamber play opposite effects on the stability of aerostatic thrust bearings.

4. Conclusion

The instability of aerostatic thrust bearing is mainly caused from gas chamber, where compressible gas can be stored. However, the damping chamber, which is similar to the damping chamber inside the pneumatic vibration isolator, can increase the bearing stability. The gas chamber and the damping chamber play opposite effects on the stability of aerostatic thrust bearings.

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