Numerical and Experimental Investigations of Micro Air Bearings for Micro Systems

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Abstract: The paper investigated performance of air bearing system in a micro device. A parametric study is carried out. The dynamic performance of a very short journal bearing \((L/D < 0.1)\) and thrust bearing is studied. The parameters that affect the performance of the air bearing are discussed. The optimum values of the important parameters are explored, and the stability of the thrust bearing is discussed. The prototype and test result are presented.

Keywords: Air bearing, Micro system, Numerical modeling and Dynamic performance

1. Introduction
To supply more efficient and longer lasting power for various movable electric appliances, the fuel-power micro engine is proposed and developed by many researchers. The process of micro gas turbine engines are the same as electricity stations, that is, burning fuel and running it to generate electricity. Due to the very high rotational speed, air bearing has to be used in these micro turbines instead of conventional ball bearings or oil-lubricated fluid bearings [1-2]. Since air bearings in micro systems usually operate in high-speed condition, the air bearings used in these devices should ensure to offer high speed, low wear operations. Many commonly accepted assumptions and design rules that have guided air bearings in conventional machinery have had to be revised due to both the consequences of scaling down as well as the current limitations in micro fabrication technology. Piekos [1] investigated the performance of short air journal bearing in a micro-turbine system. A categorization of nondimensional variables is suggested including loading, geometry and fluid. Savoulides [2] proposed a low order model to analysis the performance for very short hybrid gas bearings. With given stiffness and damping coefficients, the motion stability of the journal bearing was analyzed.

In this paper, a parametric study of air bearing system used in a micro turbine is carried out. The dynamic characteristics of the bearing system, consisting of a very short journal bearing \((L/D < 0.1)\) and a thrust bearing, at various conditions are studied. The parameters that affect the performance of the air bearing system are discussed. The optimum values of the important parameters are explored.
and presented. Using a simplified model developed by Constantin and Galetuse [3-4], the motion stability of the thrust bearing is also analyzed.

2. Governing equation

The governing equation for air bearings is Reynolds equation [5]:

\[
\frac{\partial}{\partial x}(ph^3 \frac{\partial p}{\partial x}) + \frac{\partial}{\partial z}(ph^3 \frac{\partial p}{\partial z}) = 6R\mu \omega \frac{\partial (ph)}{\partial x} + 12p \frac{\partial (ph)}{\partial t}
\] (1)

\[h = C(1 + e \cos \theta) + g(x, z) \quad \text{for journal bearing} \quad (2a)
\]

\[h = C + g(x, z) \quad \text{for thrust bearing,} \quad (2b)
\]

The boundary conditions are:

\[p = p_a, \text{ at } z = 0, z = l & r = r_i, r = r_o \quad (4a)
\]

\[p(\theta) = p(\theta + 2\pi) \quad (4b)
\]

where \(p\) is pressure; \(h\), fluid film height; \(R\), radius; \(\mu\), viscosity; \(\omega\), angular speed; \(C\), bearing clearance; \(e\), eccentricity ratio; \(h_g\), groove depth, \(p_a\), ambient pressure, \(l\), journal bearing length; \(r_i\), \(r_o\), inner and outer radius of thrust bearing, respectively.

At steady state, the second term on right hand side of Eq. (1) is zero, so \(p = P(\omega)\). Let \(\omega^{(n+1)} = \omega^{(n)} + \Delta \omega^{(n+1)}\), \(p^{(n+1)} = p^{(n)} + \Delta p^{(n+1)}\). Eq. (1) is linearized by incremental variational method. Discretizing the linearized equation with Galerkin methods gives following finite element equations:

\[\{K_{ij}\} \{\Delta p_i^{(n+1)}\} = \{D_{ij}\} f^{(n+1)} \quad (5)
\]

Solve Eq. (5) by starting the solution procedure from \(\omega = 0\), increase the speed step by step, until the specified speed is reached so that the pressure distribution is obtained [6].

3. Load capacities of bearing system

Fig. 1 shows the schematic of a micro air bearing to be investigated. Due to dimension limitation of micro devices, the ratio of bearing length over bearing diameter \(L/D\) is usually very small compared with the conventional air bearings. Therefore, the journal bearing in these devices is usually plain journal bearing only. The load capacity of plain journal bearing at two different aspect ratios is investigated and compared here. Fig. 2(a) shows the non-dimensional load capacity \(\Pi\) versus rotational speed of the journal bearing at aspect ratios of \(L/D = 0.0438\), where \(\Pi = W/\bar{W}\), \(W = DLp_a\) and \(p_a = 1.0135 \times 10^5\) Pa. It is observed that the non-dimensional load capacity \(\Pi\) linearly increases with the rotational speed and the effect of air compressibility is not obviously observed. The higher rotational speed, the higher load capacity. Higher load capacity of
Fig. 1 Schematic drawing of air bearing

(a) Load capacity versus speed

(b) Load capacity versus radius of bearing

(c) Load capacity versus radial clearance

(d) Load capacity versus bearing number

Fig. 2 Non-dimensional load capacity and stiffness of journal bearings at different conditions.

the journal bearing can also be obtained by increasing the radius of the journal bearing, or reducing the radial clearance of the journal bearing as shown in Fig 2(b) and (c). To consider the effect of these parameters together, a non-dimensional parameter, bearing number $\Lambda$ is defined as $\Lambda = \frac{6 \rho_0 R c^2}{P_z L}$. Fig. 2(d) shows the load capacity of the journal bearing versus bearing number. It is seen that up to $\Lambda = 40$ the effect of air compressibility is not obviously observed, both load capacity and stiffness linearly increase with the increasing of the bearing number. Furthermore, the simulation shows that the load capacity also increases with the aspect ratio of $L/D$.

The dynamic characteristics of the thrust bearing is studied followed the journal bearing. Fig. 1(b) shows a typical spiral grooved pump-in thrust bearing and its parameters used in the paper. The effect of different parameters on the load capacity of the thrust bearing is shown in Fig. 3 (a) – (d). It is observed that the load capacity of the thrust bearing linearly increases with the increase of bearing number $\Lambda$ as shown in Fig. 3(a). Fig. 3(b) shows that load capacity also increases with the number of grooves ($N_g$). From $N_g = 6$ to $N_g = 15$, the load capacity increases very fast with the increasing of grooves; further increasing the number of grooves, the increase of load capacity slows down and gradually becomes almost flat. The effect of changing the values of groove angle $\alpha$ and groove depth ratio $G_d$ on the load capacity is shown in Figs. 3(c) and (d), respectively, where $G_d = h_g/A_c; \alpha_g =$
\( W_g/(W_g+W_r) \); \( A_c \) stands for the axial clearance. The variation of stiffness with these parameters has a similar trend as the load capacity (not shown in Fig. 3).

4. Motion stability of thrust bearing

The motion stability is a critical problem for the application of air bearing in micro devices. Here, motion stability of the thrust bearing is analyzed with a simplified formula developed by Constantinescu and Galetus [3-4]. A non-dimensional parameter called compressibility number
\[ \Lambda = 3\mu \alpha r_e^2 \frac{A_c}{(r_{re} A_c^2)} \]
is used to determine the stability of thrust bearings. When \( \Lambda_c \) is smaller than a critical value of \( \Lambda^* \), the thrust bearing is considered as working in stable condition, otherwise, it is unstable. Figs. 4(a) – (d) show the results of stability analysis. Fig. 4(a) shows that the critical compressibility number \( \Lambda^* \) against the groove depth ratio \( G_d \) at different groove angle \( \alpha \). The smallest \( \Lambda^* \) occurs at different value of \( G_d \) for different value of \( \alpha \). For \( \alpha = 9^\circ \), the minimum \( \Lambda^* \) is 10.94 at \( G_d = 4.5 \). With the increase of \( \alpha \), the minimum \( \Lambda^* \) appears at a smaller value of \( G_d \). By comparing Fig. 4(a) with 4(b), it is noticed that the minimum \( \Lambda^* \) almost occurs at the point where the maximum load capacity is achieved. Figs. 4(c) and (d) show the result of \( \Lambda^* \) versus ratio of groove width \( a_g \) and ratio of grooved area \( R_m \) \( (R_m = r_m/r_e) \). It is shown that \( \Lambda^* \) simply decreases with the increase of \( a_g \) but has saddle point for different value of \( R_m \) at different value of \( \alpha \). Similar to the situation of Figs. 4(a) and (b), the maximum load capacity always occurs at the point where the minimum value of \( \Lambda^* \) is found, that is, the stability and load capacity have contradictive requirements on the parameters that determine the groove pattern.

Fig. 3 Dynamic load-carrying capacity of thrust bearing against various parameters
Based on the above observations, a set of optimum parameters is recommended for the micro device investigated. They are: $\lambda = 0.5$, $N_g = 15$, $\alpha = 14^\circ$, $G_d = 3.5$, $a_g = 0.5$ and $R_m = 0.7$, where $\lambda = r_i/r_e$. With the recommended optimum parameters, at 1,000k rpm and axial clearance $A_c = 10$ $\mu$m, the thrust bearing has following dynamic characteristics: $W = 0.63$ (N), $K = 2.12\times10^5$ (N/m), $D = 0.95$ (N.s/m), $P = 6.19$ (W). The stability analysis shows that with the recommended parameters, $\Lambda_c = 9.61 < \Lambda^* = 16.57$, therefore, the thrust bearing is at stable working condition.

The prototype of air bearing system based on the simulated optimum parameters is designed and fabricated. Fig.5 shows the setup for testing the turbine rig and the measured result shows the rotation speed and motion stability of the air bearing.

5. Conclusions
The paper investigates the performance of an air bearing in a micro device. It is found that the dynamic performance of a very short journal bearing ($L/D < 0.1$) is different from the conventional air journal bearing; the load capacity of very short journal bearing almost linearly increases with the increase of bearing number, and the compressibility on the load capacity of the journal bearing is not obvious due to the small aspect ratio of $L/D$. Increase the value of $L/D$, the load capacity of journal bearing is also increased. For the dynamic thrust bearing, the load capacity and stability have a contradictive requirement on the parameters that determines the pattern of grooves on thrust bearing. It is possible that a higher load capacity design will result in an unstable working condition of the thrust bearing. Therefore, both load capacity and stability requirement should be considered and compromised to select a set of suitable parameters.

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