Abstract
With extensive application of foil gas journal bearings in high temperature conditions, the effect of increasing temperature on performance in the bearings have attracted more attention. High temperature can result in significant effects on static and dynamic characteristics and stability in foil gas journal bearings. In-depth understanding about thermal performance of foil bearings is in favor of structural optimization and developing more advanced foil bearings. This paper presents a short introduction about operational mechanisms and advantages of foil gas journal bearings firstly. Then, many works concerning thermal effects in foil gas journal bearings are detailedly reviewed. The problems that need to be improved or developed in the study of thermal effects of foil bearings are also presented, that is, accuracy and reliability of thermal predicting model, cooling methods and details of bearings and solid lubricant coatings which can be applied to a more wide temperature range.

Key words: Foil journal bearings, Thermal effects, Cooling, Solid lubricant coatings

1. Introduction

Compliant foil gas journal bearings are a kind of self-acting hydrodynamic bearings that utilize ambient gas as the lubricating fluid. Figure 1 shows the structure of bump-type compliant foil gas journal bearing (first generation bump foil bearing). The bearings work by building up a hydrodynamic fluid film pressure in the small gap between the rotating shaft surface and the stationary bearing sleeve surface. The pressure is generated by the surface velocity of the rotating shaft that drags fluid into the convergent wedge-shaped gap formed between the two surfaces. The combination of Couette and Poiseulle flows in the gap produce a pressure distribution that works to keep the two surfaces separated. All self-acting hydrodynamic bearings operate with above-mentioned principle.

Fig. 1 Bump-type compliant foil gas journal bearing schematic

The specificity of gas foil bearing (GFB) rests with the compliant inner surface of the stationary sleeve, consisted of several layers of sheet metal foils. A glossy top foil is often supported by a series of corrugated bump foils acting as springs to provide foil bearings compliance. The main advantage of the compliant inner surface is that a film thickness is larger than a geometrically identical rigid gas bearing. The larger gap results in lower power loss due to shearing of the gas film. The thicker gas film and compliant surface make foil bearings less susceptible to damage by ingested dust particles, because the compliant foil surface can move to allow large foreign particles in the fluid to pass. Centrifugal/thermal radial growth and misalignment cause less problem with foil bearings since the compliant foils can accommodate these changes in shaft diameter and position. As a result, compliant foil bearings can operate at higher temperatures and speeds than rigid gas bearings. In addition, foil gas bearings have an inherent advantage when operating...
at elevated temperature environments, because the lubricant, i.e., air, does not degrade with increasing temperature. In contrast, the conventional oil-lubricated bearings are susceptible to oil-coking and degradation at high operating temperatures.

However, foil bearings are not totally immune to high temperature operations because bearing materials tend to soften as their temperatures increase. As a result, the load capacity suffers, the stiffness decreases, and the damping mechanism can be changed under the combination of temperature effect and load condition (Peng and Khonsari, 2006). One major concern is the localized overheating of the foil material due to nonuniform viscous heating within the gas film when the bearing operates at high speed and/or high load conditions. In addition, the increasing viscosity with increasing gas temperature can lead to thermal instability.

There is another characteristic in the foil bearing design that poses a heat transfer problem. Unlike the conventional oil-lubricated bearing, the contact between the top foil and the bump foil in a foil bearing is very narrow, therefore, the path for conducting heat away from the gas film to the sleeve is markedly restricted. As a result, both bearing and journal can be affected. So it is necessary to conduct a systematic research for understanding thermal behavior of foil bearings.

2. Experimental Studies of Thermal Characteristics

DellaCorte, (1997) developed a test rig for evaluating first generation bump foil air bearings which was capable of measuring foil bearing performance at temperatures to at least 700°C and speeds to 70 krpm. Results from the test data showed that the load capacity decreased with increasing temperature. The data from this test facility had provided valuable input for foil bearing development and application. Before long utilizing above-mentioned rig DellaCorte, et al., (2000) conducted tribological performance and durability tests for first generation bump foil bearings operating between 25°C and 650°C. The test bearings were made from uncoated nickel based superalloy foils. The solid lubricant coating was applied to the shaft to reduce friction and wear. It was found that bearing torque increased with increasing load and decreased with increasing temperature. The results also showed that these bearings performed well over a wide range of static loads (10 to 50 kPa) and exhibited good wear lives (about 30,000 to 100,000 cycles) within the range of experimental temperatures.

Howard, et al., (2001a) collected high temperature stiffness and damping data of bump foil air bearings using a high temperature displacement measurement system. They found that as the temperature increased the damping shifted from a viscous type to a frictional type. The damping tended to respond to high load inputs by shifting into the frictional damping domain where more energy could be dissipated from the system. The stiffness dropped as the temperature increased from startup to operating conditions. However, the impact of the stiffness drop was likely to be unimportant according to the fact that the frictional damping tended to increase at higher temperatures to help stabilize the system. In the same year, they measured steady-state stiffness of bump foil air bearings at high temperature (Howard, et al., 2001b). It was found that the steady-state stiffness decreased in general as temperature increased from 25°C to 538°C. They also found that load capacity dropped slightly with temperature. An experimental investigation was presented by Salehi, et al., (2001) about the thermal characteristics of bump foil air bearings. A 100 mm diameter foil bearing operated at speeds up to 30 krpm employing cooling air across the bearing between top foil and bump foil. It was found that the temperature rise slope during the rotor speed coast down was bigger than the slope during the rotor speed up.

Radil, et al., (2004) performed a series of tests to determine the internal temperature profile in a bump foil air bearing operating at room temperature under various load and speed conditions. Tests were conducted at loads from 9 to 222 N and speeds ranged from 20 to 50 krpm. The results showed that both speed and load had an effect on thermal generation, and the speed was the more significant role. The temperature distribution was almost axial symmetric about the bearing center at 20 and 30 krpm, but at 40 and 50 krpm it became slightly skewed toward one side. The maximum temperatures occurred in the middle of the bearing. Thermal gradients were strongest in the axial direction from the middle of the bearing to its edges. Compared with it circumferential thermal gradients were negligible. Their temperature data provided a reference for validating analytical model and employing any active cooling techniques. Lee, et al., (2006) experimentally investigated dynamic characteristics of the bump foils under the high temperature environment up to 680°C. The results demonstrated that the stiffness characteristics of bump foil bearings decreased linearly and the damping effect of bump foil decreased suddenly when the bump foils were heated up. Simultaneous, the results of theoretical analysis were obtained by Finite Element Method (FEM) for comparing them with the experimental results. The compared results suggested that the FEM program could reflect the real system well. Tests were performed by Radil,
et al., (2007) to evaluate three different methods of utilizing air to provide thermal management control for bump foil air bearings. Air volumetric flows was 0.06, 0.11, and 0.17 m$^3$/min at approximately 150°C to 200°C. Figure 2 shows the direct cooling method that a guide tube delivers the preheated air to the inner surface of journal. Figure 3 shows the indirect cooling method that the straight guide tube was directed at the back end of the journal, where the air would impinge and then flow axially out of the journal. The last cooling method (shown in Fig. 4) is the most common approach that air flow is axially through bearing support structure. The results indicated that the last cooling method had a greatest effect on the bulk temperature for each air flow, and the thermal gradients could be influenced by the directionality of the air flow. Both direct and indirect journal cooling had a uniform cooling effect on bulk temperatures and thermal gradients, but the effective of indirect cooling method was lower.

Kim, et al., (2009) conducted experiments to estimate the structural stiffness of a test bump-type GFB for increasing shaft temperatures up to 188 °C. A 38.17 mm inner diameter GFB was mounted on a nonrotating hollow shaft and a cartridge heater inserted into the shaft provided a controllable heat source (shown in Fig. 5). They found that thermal expansion of the GFB housing was larger than that of the shaft causing a significant increase in radial clearance, which produced a obvious reduction of structural stiffness in the bearing. They also tested dynamic stiffness, viscous damping and dry-friction coefficient with single frequency periodic loads. The results demonstrated that the dynamic stiffness decreased by a third as the shaft temperature risen to 188°C. The viscous damping was inversely proportional to shaft temperature. The dry-friction coefficient decreased with increasing shaft temperature. Andrés, et al., (2011a) experimentally assessed the effects of shaft temperature on the structural stiffness and mechanical energy dissipation parameters of a second generation bump foil gas bearing (shown in Fig. 6). A hollow shaft warmed by an electric heat was loaded dynamically by an electromagnetic shaker. The results showed that the foil bearing structural stiffness and
viscous damping increased as the shaft temperature increased. The foil bearing structural loss factor or its dry friction coefficient decreased slightly with shaft temperature. The data demonstrated identified loss factor at the highest temperature (263°C) was just 27% less than the magnitude for tests at room temperature. Radil and Batcho, (2011) experimentally evaluated a thermal management technique for a third generation bump foil air bearings (shown in Fig. 7). The technique was based on injecting air directly into the internal circulating fluid-film to reduce axial thermal gradients and bulk temperatures. The experiments were performed at room temperature with the bearing operating at speeds from 20 to 40 krpm and supporting 222 N. It was found that this kind of air injection approach was a viable thermal management technique which was capable of controlling axial thermal gradients and bulk temperatures. Andrés, et al., (2011b) presented test data for a test rotor-GFB system operating hot (157°C maximum rotor outer diameter temperature). A hollow test rotor (38.1 mm OD, and 25.4 mm ID) was supported on two second generation gas foil bearings. An electric cartridge fitted loosely inside the hollow rotor heated the rotor unevenly. In tests they found that the rotor peak motion amplitude decreased as the system temperature increased while the bearing system traversed critical speed at about 13 krpm. The effect of the outer cooling flow which was turbulent in character was most effective at the highest heater temperature. However, the cooling flow demonstrated a very limited effectiveness at a lower heater temperature condition.

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**Fig. 5** A rigid test shaft and cartridge heater in bump foil gas bearing system

**Fig. 6** Schematic of a second generation bump foil gas journal bearing

**Fig. 7** Schematic of the test bump foil journal bearing (third generation) showing location of inlet hole for air injection

Kim, et al., (2012) performed temperature measurements of a bump-type GFB floating on a hollow shaft (60 mm OD, and 40 mm ID) for various operating conditions. They also found that GFB temperatures increased as the shaft speeds and static load increased. The temperatures in the loaded zone was higher than those in the unloaded zone. The highest temperature appeared at the location where a highest hydrodynamic pressure built up. Ryu and Andrés, (2012) conducted comprehensive measurements of bump foil bearing temperatures and shaft dynamics utilizing a hollow rotor supported on two GFBs. The hollow rotor was heated from inside to reach an outer surface temperature of 120°C. It was found that...
the cooling effect of the forced external flow was most significant when the rotor was hottest and operating at the highest speed, and cooling flow did not affect the amplitude and frequency of the rotor motions. It was also found that the test system critical speeds and modal damping were almost invariant for increasing rotor temperatures and cooling flow rates. Ryu and Andrés, (2013) conducted a test again for above-mentioned rotor-GFBs system operating with a heated shaft at a speed of 37 krpm. No forced cooling air flow was supplied to decrease temperature. The experiments proceeded without incident until the rotor temperature reached 250°C. When seizure occurred they found a remarkable reduction in bearing clearance as the rotor temperature increased. Sim, et al., (2014) performed an experimental investigation of the dynamic force performance of bump-type GFBs at high temperatures. The highest test heater temperatures were 400°C and the highest excitation frequencies were 180 Hz. The test rotating speed and static load were 12 krpm and 30 N. The test results demonstrated that as the shaft temperature increased, the direct stiffness coefficients decreased by about 8%, and the direct damping coefficients decreased by approximately 30%.

3. Theoretical Studies of Thermal Characteristics

Salehi and Heshmat, (2000) discussed the fluid flow and thermal analysis of advanced compliant foil bearings (CFB) and compliant foil seals (CFS). The steady-state governing Reynolds equations of a compressible gas for the pressure and film thickness were solved simultaneously using a numerical method which was a combination of the successive over-relaxation and iteration method. A thermal model was applied using the modified Couette approximation. Using the results of the flow analysis the energy equation was solved to obtain the temperature rise in a CFB or a CFS. Through analysis they found that, the major portion of the heat was carried through conduction. The more compliant seal due to larger film thickness had more leakage which leaded to more heat transfer, therefore the maximum temperature was lower in a more compliant seal. This predicted result of temperature could be useful in the design of compliant foil seals and foil bearings. An analytical investigation was done by Salehi, et al., (2001) about the thermal characteristics of bump foil air bearings with cooling fluid. In parallel, an experimental program was performed. The experimental temperatures were compared against the analytical predictions and over-prediction of 8%-19% was obtained. From the theoretical analysis it was deduced that 75%-85% of heat energy was carried away by conduction, leaving about 10%-15% to be convected by side leakage. The Couette Approximation used in their analysis provided a reasonable tool for the temperature approximation. Peng and Khonsari, (2006) considered the effect of temperature field on the dynamical characteristic in bump foil air bearings based on their previous study (Peng and Khonsari, 2004). A simultaneous solution to the Reynolds equation and the energy equation with the appropriate boundary conditions was attained. The results showed that thermal gradients were smaller in the axial direction and bigger in the circumferential direction. Temperature had a weak effect on load-carrying capacity of bearings at low speeds, but the effects were stronger with speeds up.

Feng and Kaneko, (2008) reported a thermohydrodynamic (THD) analysis of Multi Wound Foil Bearing. This kind of foil air bearing consists of a cylinder and a strip of triply-wound foil with small hemispherical projections distributed across the surface (shown in Fig. 8). They utilized lobatto point quadrature to accelerate the iteration process with a sparse mesh across film thickness. A three-dimensional temperature profile of air film was presented and a comparison of THD to isothermal results was made. They found that the highest temperature in the air film appeared adjacent to the minimum film thickness and closer to the top foil than the shaft surface along the axial direction. The torque and load capacity of foil bearings became larger if temperature was included and the differences were obvious. The temperature of foil air bearings increased with bearing load as well as rotational speed, and the latter effected more significantly.

a. Structure of Multi Wound Foil Bearing
Kim and Andrés, (2010) presented a model for the thermal energy transport in a rotor-GFB system operating at high temperature (up to 132°C) with typical inner and/or outer cooling flows. It was found that, an outer cooling stream which flowed through the thin film region and underneath top foil to remove heat was more effective to control the operating temperature than inner stream which flowed through a hollow shaft, about 82% of the energy was taken away by the outer cooling stream. The coast down tests showed the critical speed increased slightly as the temperature increased. In addition, they analysed paths of thermal energy by conduction and convection to help the design and troubleshooting of foil bearing systems operating hot. Lee and Kim, (2010) developed a thermohydrodynamic analysis model for bump foil air bearings with a detailed thermal model of bump foil structures and rotor. Figure 9 shows the cooling channels formed by bump foils which can be divided into primary and secondary channels. They found that the axial temperature profiles of air film, rotor, and top foil were similar to each other. But, bump foil and channel temperatures were affected intricately by cooling flow rates and thermal boundary conditions on the outer surface of the bearing sleeve. The main heat transfer to the secondary channel was a convection from the bump foil, rather than from the top foil. The maximum thermal growth of the foil structure contributed clearance to decrease less than 1% of nominal clearance, compared with it maximum rotor thermal and centrifugal growths contributed to almost 20% decrease of nominal clearance. Andrés and Kim, (2010) presented a thermohydrodynamic model for predicting bump-type GFB performance which included thermal energy transport in the gas film region and cooling gas streams. The analysis also accounted for material property changes and expansion of the bearing components due to temperature increased. The predicted results showed that film peak temperature occurred just downstream of the maximum gas pressure. The journal speed had a greater effect on the increase in film temperature rather than applied static load. The THD model attained a smaller journal eccentricity, larger minimum film thickness, and larger drag torque than those obtained from an isothermal flow model.

A bump-type GFB with axially fed flow was modeled by Ryu, (2012) as a bearing with gas pressurization at one end. The axial cooling gas stream flowed through the inner and outer gaps between the rotor and the top foil and between the top foil and the bearing housing. The results demonstrated that laminar flow was dominant in the inner film gap. For the outer cooling flow, laminar flow translated turbulent flow as the cooling flow rate increased. Large cooling flow rate and consequential turbulent flow conditions did not offer a obvious advantage to reduce the rotor and bearing temperatures. Sim and Kim, (2012) developed a THD model for bump foil air bearing including energy transport in air film, heat conduction of shaft, thermal resistance of bump layer, and heat conduction in bearing housing. What made the model distinctive was that it incorporated analytical models for inlet flow mixing and bump thermal contact to improve the predictive accuracy.

4. Effect of Solid Lubricant Coatings On High Temperature Operation

Robert, et al., (1984) presented PBGF (Polyimide-bonded graphite fluoride) and SBGC (Silicate-bonded graphite/cadmium oxide) used to coat foil surface as the solid lubricant for GFBs from 25 to 315°C. Robert, et al., (1985) presented PS200 coating used for rotor surface. The main composition of PS200 is silver and barium fluoride/calcium fluoride eutectic in a metal-bonded chromium carbide matrix. Maximal used temperature of the coating was 650°C. The test results showed that PS200 had good performance on lubrication and wear-resisting. However, its manufacturing cost was very high. In addition, in high temperature Cr$_2$C$_3$ would be oxidized so as to affect performance of the coating.

DellaCorte and Edmonds, (1996) developed PS300 coating based on PS200 for solving the weakness of PS200. PS300 is a plasma sprayed, NiCr bonded, chrome oxide based coating with Ag and BaF$_2$/CaF$_2$ lubricant additions. Cr$_2$C$_3$ in PS200 was substituted for Cr$_2$O$_3$. The advantage of PS300 was less manufacturing cost and better lubricant performance of high temperature operation. Though PS300 had good friction performance, its coefficient of thermal expansion was obviously different from substrate material so that PS300 was easy to fall off when temperature varied alternately. Therefore, they optimized composition proportion of PS300 and presented famous PS304 coating in 1998. PS304 contains 60wt% NiCr binder, 20wt% Cr$_2$O$_3$ hardener, and 10wt% Ag and 10wt% BaF$_2$/CaF$_2$ lubricants. The coating had very good performance verified by experiment. The main weakness of PS304 was poor performance at room temperature that it has serious wear to foils. However, DellaCorte, (2000) thought that the operating time at room temperature was little that can be ignored. After developing PS304 successfully DellaCorte and Edmonds pursued more
excellent coatings on performance. They presented PS400 coating again prepared by plasma spraying (DellaCorte and Edmonds, 2009). The composition of metal binder in PS400 is Ni, Mo and Al for better stability. Cr$_2$O$_3$ is still wear-resistant component, but the solid lubricants (Ag and BaF$_2$/CaF$_2$) are reduced to increase its intensity in high temperature and improve its surface quality after polishing. Experiments showed that PS400 had quite excellent high temperature performance, but its performance at room temperature was poor yet. The series of PS had this problem generally.

Heshmat, et al., (2005) researched coatings and the match of coatings in foil bearing. They tested a series of Korolon™ coatings on foil surface and tested PS304, Korolon™1350, dense chrome and hard chrome on rotor surface. The composition and performance of several Korolon™ series coatings are shown in Table 1. The tests demonstrated that Korolon™ coatings had excellent friction performance meeting operating requirements of high temperature and high speed for foil bearings. The best performance was obtained when Korolon™1350 or Korolon™800 was coated on foil surface and dense chrome was coated on rotor surface.

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<th>Table 1: Wear-resistant, low-friction Korolon™ coatings</th>
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<td>Chemical composition</td>
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Jahanmir, et al., (2009a, 2009b) evaluated the performance of diamond like carbon (DLC) film for application in foil bearings. By coupling pair they tested DLC film, hydrogen free DLC film, chromium coating and Korolon™900. The results showed that DLC didn’t provide good lubricant performance for foil bearings at high temperature. The main lubricant effect was provided by Korolon™900. DLC as wear-resisting material only protected based material.

Though foil bearings have a wide range of operation temperature, the solid lubricants as coatings have obvious range of applicative temperature. Therefore, developing different solid lubricant coatings is necessary for different working conditions. The series of PS coatings is representative for solid lubricant applied in high temperature working conditions and the condition that most of the working time is high temperature. The series of PS coatings is not suited and economical at moderate temperature working conditions. The series of Korolon™ coatings belongs to a kind of moderate temperature coatings. The lubricant performance of Korolon™ coatings is usually better than that of PS coatings in moderate temperature working conditions.

5. Conclusions

With more and more application of oil-free turbomachinery in high temperature conditions, the effect of increasing temperature on performance in foil gas journal bearings cannot be neglected. Therefore, many researchers are becoming engaged in thermal studies for understanding thermal behavior of foil bearings. They have carried out extensive works about thermal effects in terms of change of static and dynamic characteristics, effect of cooling flows and choice of lubricant coatings, and acquired a series of achievement. In addition, more theoretical studies of thermal effects of foil bearings are developed, various thermohydrodynamic models are presented, and rapid and simple computational methods are applied, which reduce extensive trial-produced and experimental works, save the cost and shorten the research cycle.

However, there are many problems which need to be further developed. For example, high accuracy and reliability of thermal predicting model, optimization of cooling methods and details, lubricant coatings which apply to a more wide temperature range. Therefore, it will still attract attention to improve performance of foil gas journal bearings operating at high temperatures.

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