Abstract of Dissertation
論文の内容の要旨

Title of Dissertation
Prediction of Static and Dynamic Performance and Thermohydrodynamic Analysis of Gas Foil Bearing

（フォイル軸受の静特性、動特性及び温度特性の解析手法に関する研究）

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Several advantages, including lower weight and smaller size, better performance at high rotational speeds and high temperatures, and higher reliability, can be gained with the usage of gas foil bearings as compared to conventional oil bearings. The achievements of gas foil bearings in recent 30 years enhance their applicants in high-speed turbo machinery, such as aircraft gas turbine engines, auxiliary power units, micro gas turbines, and hybrid fuel cell-turbine power systems. However, major technical hurdles impeding the application and widespread use of gas foil bearings are the lack of enough load carrying capacity and damping due to the low viscosity of air and the high temperature performance. Therefore, several designs of gas foil bearings have been proposed, which resulted in significant improvements in the performance of gas foil bearings. In order to reduce time and financial cost of design, this research introduces theoretical models for the performance prediction of gas foil bearings, based on two types of gas foil bearings, multiwound foil bearings (MWFBs) and bump-type foil bearings (BTFBs). With the developed models, the static and dynamic performances as well as the temperature dependent characteristics of gas foil bearings are predicted, and the calculated results from the models are compared with published experimental data to ensure the correctness.

Due to the incidence relation between the air film and the foils, the performance prediction models need couple the air pressure to the elastic deflection of the compliant foil structure. The pressure field within the air film is solved with the Reynolds' equation using the finite difference method and Newton-Raphson technique. However, the solution of the foil deflection is not so easy and it is still the main challenge for an accurate performance prediction of a gas foil bearing. In the model of MWFBs, the triply wound foil is separated into three layers, top foil,

middle foil and bottom foil. A finite element plate model is presented to compute the deflections of the top foil and the middle foil. The bottom foil is assumed to have no deflection because of the supporting of the housing. The deflections of the top foil and the middle foil are both added to the air film thickness to take into consideration the effects of the foil local deflections. On the other hand, a link-spring model, replacing each bump with two rigid links and a horizontally spaced spring, is proposed to simulate the corrugated bump structure in the model of BTFBs. The equivalent vertical stiffness in each link-spring structure is calculated with the Castigliano' theorem. A finite element shell model is presented to describe the elasticity of the top foil. The obtained equivalent vertical stiffnesses of bumps are appended to the stiffness matrix of the top foil at appropriate positions. Finally, the deflection of the top foil is calculated with the direct matrix method and coupled to the air film thickness for iterative calculations. The advantage of this model is that the horizontal spring, which is parallel to the bump strip, makes it easy to account for the effects of the interaction forces and the friction forces within the foil structure. With this model, the bump elasticity, the interaction forces and the friction forces within the foil structure, and the local deflection of the top foil are all taken into consideration. Both the presented models of MWFBs and BTFBs are validated with published experimental data. Furthermore, based on the developed models of gas foil bearings, an approach with the perturbation of journal with respect to a small displacement about its equilibrium position is used for the prediction of the dynamic coefficients of gas foil bearings.

Predicted results from the model demonstrate that the load capacity and the torque of MWFBs will decrease if the effects of foil deflection are taken into account. However, since the deflections of foils create a space for the shaft eccentricity, which can increase up to a value much lager than the nominal clearance, MWFBs can also support a heavy load. According to the analysis of BTFBs, the elasticity of bumps is noted related not only to the geometry of bumps but also to the deflection of bumps and the friction forces within the foil structure. The predicted results demonstrate that the bearing radial clearance and the friction forces significantly affect the performance of BTFBs. An optimum clearance of BTFBs for the largest load carrying capacity is noted in the calculation of the load capacity, and the optimum value decreases as the journal speed increases.

Thermohydrodynamic models based on the two types of gas foil bearings are also presented. The simulations of the foil structures follow the ways in the above analysis. The thermal Reynolds' equation for the air film pressure and the energy equation for the temperature field of air film are simultaneously solved. The Lobbato point quadrature algorithm is utilized to reduce the effort of computation. An iteration procedure is conducted between the two equations and the calculation of foil deflections until the convergence is achieved. The THD model accounts for the compressibility and viscosity-temperature characteristic of air. In the model of MWFBs, the temperature of the air at the inlet is estimated from the mixture of fresh air and the recirculating flow. The shaft is assumed to be isothermal. However, for the temperature prediction for BTFBs, the developed model is improved for more accurate results by taking into consideration more factors, such as effects of the cooling air, thermal expansion of the bearing components and the change of the bump foil elasticity due to the increase in temperature. Furthermore, the calculation of the fluid flow within the air film is also modified, because the top foil is recognized to detach from the bump strip in the region of the subambient pressure. The predicted results of both the two types of gas foil bearings show good agreement with published experimental data.

The calculated temperature profile shows that the highest temperature in the air film occurs a little downstream of the minimum film thickness and closer to the top foil than the shaft along the radial direction. An obvious increase of the predicted bearing load is noted if the bearing temperature is taken into account during the calculation. And the predictions also show that the effects of journal speed, rather than the bearing load, is more significant on the temperature increase of bearings. The ambient temperature affects the bearing performance mainly by changing the radial clearance of foil bearings through the thermal expansion of components.

Finally, parametric studies of the number of bumps, the size of bumps, the thickness of foils, and the material of foils are performed on the prediction of the bearing load and the nonlinear orbit simulations. The results demonstrate that more bumps provide much higher load capacity, but lower threshold speed for instability. In general, we can advance the performance of bump-type foil bearings with larger length ratio of the segment and the bump (l_s / l_o), thicker foil thickness (t_f), higher bump height (h_b) and larger elastic modulus (E), although the threshold speed for instability will slightly decrease.