Theoretical Study on the Radial Error Motion of High-precision Aerostatic Rotary Tables

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Abstract

Owing to the increasing demands on the accuracy of rotary tables supported on air bearings, an optimised design of these systems is necessary. This paper models the radial error motion of an aerostatic journal bearing with inherent restrictors in function of the bearing's design parameters and the form (manufacturing) errors of the components. Based on a modified finite-difference model of gas film behaviour, the influence of several manufacturing errors on the radial error motion is investigated first. Then the optimal design parameters are defined in order to reduce the influence of manufacturing errors on the accuracy of the rotary table. Finally an orbit model, based on the ADI-method, is developed to analyse the influence of the rotational speed on the error motion.

1 Analysis and results

An in-house developed finite-difference model of gas film behaviour [1], is modified to analyse the influence of various manufacturing errors and feedhole configurations on the radial error motion of the rotor. In order to validate the results of this steady-state model and to analyse the influence of the rotational speed on the error motion, an orbit model is developed.

1.1 Steady-state analysis

The compressible viscous (isothermal) flow between rotor and stator of the air bearing is modelled using the time-independent Reynolds equation. If one assumes that the rotor moves to the position of static equilibrium when there is no external load applied to it, the displacements are small and the bearing characteristics are linear, the equilibrium position can be calculated by: $\varepsilon = K^{-1}W$

where K is the stiffness coefficient matrix defined as $K = \begin{pmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{pmatrix}$ and W is the load acting on the rotor, defined as $W = (W_x, W_y)^T$. The equilibrium position of the rotor of an aerostatic journal bearing was calculated for several angular positions of the rotor between 0 and 2π for determining the radial error motion with respect to several manufacturing errors.

1.1.1 Manufacturing errors

In literature there are very few reports on the effects of manufacturing errors on the performance of air bearings. One of these reports is that by Stout and Pink in 1980 [2]. The most significant manufacturing errors which have a detrimental influence on the radial error motion of an aerostatic journal bearing are the form error on rotor and stator and also deviations in feedhole diameters. The form error used in the analysis resembles measured form profiles of a rotor and stator of an existing air bearing setup. The deviations in feedhole diameter are not uniformly applied to all feedholes. A way to describe the variation between the feedhole diameters is the coefficient of variation (CV), which is chosen to be 0.05 in the following analysis. Figure 1 shows the effect of each manufacturing error on the radial error motion of the rotor. It clearly illustrates that there is almost no difference between the radial error motions, ranging from 148 nm for an aerostatic journal bearing with only a form error on its rotor to 168 nm for an aerostatic journal bearing with a form error on its rotor, stator and deviations in feedhole diameters. From this figure, one can conclude that the radial error motion of an aerostatic journal bearing is mainly influenced by the form error of the rotor.

1.1.2 Influence of the feeding parameter

The major contributor to the error motion of the rotor is identified. If one wants to mitigate the influence resulting in a reduction of the error motion, one can improve the form accuracy of the rotor. However, if the production limits are reached and the error motion of the rotor is still too high, the influence can further be mitigated by appropriate film-geometry modifications. The complete characterisation of the feeding geometry of an aerostatic journal bearing is fulfilled with three dimensionless parameters, these are L/D, R_f and Λ_f (see nomenclature). The influence of film-geometry modifications on the error motion can thus be analysed with respect to the feeding parameter Λ_f R_f, which is in turn function of the feedhole radius (r_f) and the clearance (c) of the air bearing. This is depicted in Figure 2 together with the direct dimensionless stiffness K_{xx}. One can clearly notice that the error motion decreases if the feeding parameter is also decreased. Also, the error motion increases drastically if the value of the feeding parameter is greater than that corresponding to the optimum direct stiffness.

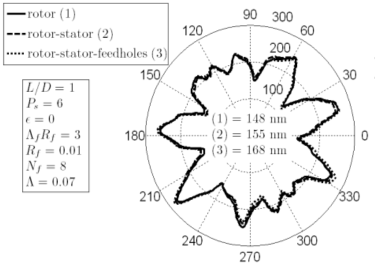

Figure 1: Influence of several manufacturing errors on radial error motion of an aerostatic journal bearing.

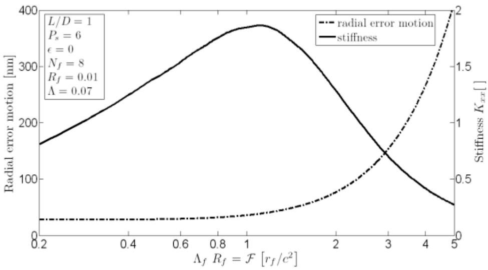

Figure 2: Radial error motion and dimensionless stiffness K_{xx} for an aerostatic journal bearing with a given form error on rotor and stator as a function of the feeding parameter Λ_f R_f.

1.2 Orbit analysis

The aforementioned definition of the equilibrium position for the steady-state analysis does not account for the influence of the dynamics on the radial error motion of the rotor. In order to validate the steady-state results and to analyse the influence of the rotational speed on the radial error motion, an orbit model is developed. To obtain the orbit data of the rotor centre, the time-dependent Reynolds equation and the equations of motion are marched through in time simultaneously. This integration is done in a semi-implicit way by an alternating direction method namely the ADI-method owing to its numerical stability and computational efficiency. Figure 3 compares the trajectory of the rotor centre of an aerostatic journal bearing having a given form error during one cycle of the rotor calculated with the steady-state and with the orbit model. The agreement between the two models is very good, the small difference can be attributed to the different calculation technique used and/or the contribution of the dynamic effects to the system already noticeable at 10 rpm. The orbit model thus provides a theoretical tool to analyse the effect of the rotor speed ω on the radial error motion of the rotor. Such results are shown in Figure 4, where it can be observed that the radial error motion will reduce if the rotor speed is increased. This can mainly be attributed to the increased dynamic stiffness at higher perturbation frequencies as the rotor speed increases [3].

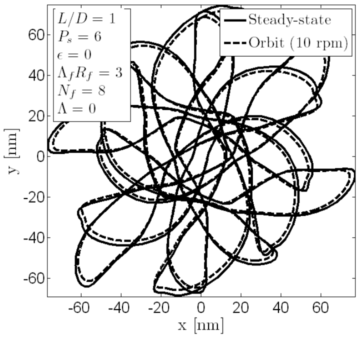

Figure 3: Comparison between the trajectory of the rotor calculated with the stead-state and orbit model.

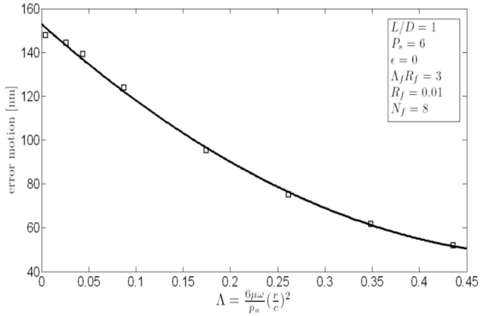

Figure 4: Influence of the rotor speed ω on the radial error motion.

2 Conclusions

(1) The modified finite-difference and orbit model can be used to calculate the bearing characteristics and the radial error motion of the rotor in relation to air film geometry and the machining accuracy.

(2) The error motion of the rotor is mainly influenced by the form error of the rotor, while the form error of the stator and feedhole deviation are of secondary importance.

(3) The error motion increases drastically if the value of $\Lambda_f R_f$ (feeding number) is greater than that corresponding to the optimum direct stiffness. The error motion decreases if $\Lambda_f R_f$ is also decreased and if the rotor speed ω is increased.

3 Nomenclature

L = journal bearing length

D = journal bearing diameter

N_f = number of feedholes

$R_f = \frac{r_f}{r}$

P_s = normalised supply pressure

ε = journal bearing eccentricity ratio

$\Lambda_f = \frac{12\mu r}{p_a c^2}\sqrt{\frac{2\kappa\Re T_s}{\kappa - 1}}$

$CV = \frac{\sigma}{d_f}$

References:

[1] T. Waumans. “On the design of high-speed miniature air bearings: dynamic stability, optimization and experimental validation”. PhD thesis, KU Leuven 2009.

[2] Stout KJ, Pink EG. Orifice compensated EP gas bearings: the significance of errors of manufacture. Tribology Int 1980;13(2):105-11.

[3] F. Al-Bender “On the modelling of the dynamic characteristics of aerostatic bearing films: From stability analysis to active compensation”. Precision Engineering, Vol. 33, p. 117-126, 2009.