Proceedings of WTC2005
World Tribology Congress III
September 12-16, 2005, Washington, D.C., USA

WTC2005-63398

GAS FOIL BEARINGS: LIMITS FOR HIGH-SPEED OPERATION

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ABSTRACT

Commercial oil-free micro turbomachinery relies on gas foil bearings (GFBs) for reliable performance with improved efficiency. However, GFB modeling is still largely empirical, lacking experimental validation. An analysis of simple GFBs operating at large shaft speeds (*infinite* speed number) follows. The bearing ultimate load and stiffness coefficients are derived from simple algebraic equations for the gas film pressures at the equilibrium journal position and due to small amplitude journal motions, respectively. GFBs without a clearance or with assembly interference are easily modeled. The underlying elastic structure (bump foil strip) determines the ultimate load capacity of a GFB as well as its stiffnesses, along with the limiting journal displacement and structural deformation. Thus, an accurate estimation of the actual minimum film thickness is found prior to performing calculations with a complex computational model, even for the case of large loads that result in a journal eccentricity well exceeding the nominal clearance, if applicable. An initial assembly preload (interference between shaft and foil) increases the GFB static stiffness at both null and infinite rotor speeds. At *infinite* speed, cross-coupled stiffnesses are nil; and thus, GFBs are impervious to hydrodynamic whirl instability.

INTRODUCTION

Gas foil bearing (GFB) technology needs reliable prediction tools and design guidelines for its widespread use in oil-free turbomachinery and micro gas turbine engines [1]. GFBs are (self-acting) hydrodynamic bearings with a compliant surface comprised of a thin (top) foil and a series of bump strip layers. GFBs offer distinct advantages over rigid surface bearings for operation at high speeds; in particular tolerance to misalignment and rotordynamic stability [2].

The literature detailing GFBs applications in rotating machinery is extensive. Heshmat [2] demonstrates operation of a GFB supporting a large load, specific pressure 6.8 bar (100 psi), at a top speed of 132 krpm. Salehi et al. [3], in a micro rotor-bearing, show GFB operation to speeds close to 1 million rpm. Some references, notably [4], state that GFBs have load capacity unbounded by rotor speed. DellaCorte and Valco [1] dispel this notion and reveal that GFBs have a limiting load capacity at "high" shaft speeds. Most GFB analyses are based on thin film lubrication principles, a few including the foil mechanics [5]. Refs. [6, 7] validate GFB computational predictions to test data for load and film thickness data [8]. In spite of recent efforts [9, 10], experimental rotordynamic force coefficients are yet to appear.

Peng and Khonsari [11] introduce a unique analysis for the ultimate load capacity of GFBs at *infinite* speed number operation. The clearance and underlying stiffness of the foil support determine this load. In practice, however, either by design or due to inaccurate manufacturing, GFBs have no actual clearance. For mechanical integrity, GFBs are usually preloaded (assembly interference), with the journal diameter being larger than the foil's. The preload ensures even contact at the static condition (no shaft speed) with uniform pressures pushing on the elastic structure. Radil et al. [12] find a strong correlation of GFB measured load capacity to the assembly clearance. In operation, the journal grows due to thermal and centrifugal effects, thus exacerbating the issue of the largely unknown "actual" clearance.

This paper retakes the analysis in [11], includes the effect of an assembly preload, and provides simple formulae for estimation of load capacity, minimum film thickness and stiffness coefficients at large shaft speeds, *infinite* in theory. The results are compared to the structural stiffness and elastic deformation for the contact condition between shaft and foil, i.e. without journal rotation [13].

ANALYSIS

The relationship between hydrodynamic pressure *(P)* and film thickness *(h)* follows from the limiting form of Reynolds equation at *infinite* speed number, i.e. very high journal speeds, $\Omega\rightarrow\infty$ [11]:

$$\frac{\partial (Ph)}{\partial \theta}=0 \;\; or \; (Ph)_{(\theta)} = P_a \, h_{(\theta=0)} \tag{1}$$

where θ is the circumferential coordinate, P_a is ambient pressure, and

$$h=\left(c-r_p\right)+e_X \cos(\theta)+e_Y \sin(\theta)+\frac{1}{K_f}\left(P-P_a\right) \tag{2}$$

c and r_p are the radial clearance and assembly preload, and $e_{X,Y}$ are the journal eccentricity components. K_f is the stiffness per unit area of the foil support structure. It is simple to show that a static load *(W)* applied along $\theta=\pi$, renders a pressure field and film thickness symmetric about this angle, and thus $e_X=e$ and $e_Y=0$. Thus, a GFB has no cross-coupling since the journal static eccentricity (*e*) is parallel to the load direction.

Small amplitude journal motions about the equilibrium position, $e_X=e+\Delta e_X$ and $e_Y=0+\Delta e_Y$, render changes in the film pressure, i.e. $P=P_0+ P_X\Delta e_X + P_Y\Delta e_Y$. From eqn. (1) follows that

$$P_{0_{(\theta)}}=\frac{P_a\,(c-r_p+e)}{h_{0(\theta)}};h_{0(\theta)}=c-r_p+e\cos(\theta)+\frac{\left(P_0-P_a\right)}{K_f} \tag{3}$$

$$P_{X_{(\theta)}}=\frac{P_a-P_{0(\theta)}\cos(\theta)}{h_{0_{(\theta)}}+P_{0(\theta)}/K_f};\;\; P_{Y_{(\theta)}}=\frac{-P_{0(\theta)}\sin(\theta)}{h_{0_{(\theta)}}+P_{0(\theta)}/K_f} \tag{4}$$

The solution of quadratic eqn. (3) is

$$P_{0_{(\theta)}}=\frac{K_f}{2}\left[-A_1+\left(A_1^2-4\;A_2\right)^{1/2}\right] \tag{5}$$

where $A_1=(c-r_p)+e\;\cos(\theta)\;-\;P_a/K_f$; $A_2=-\;(c-r_p+e)P_a/K_f$ as in [11], except for the included preload (r_p). Integration of the pressures, equilibrium and perturbed, on the bearing surface (*LD*) renders the reaction force and stiffness coefficients $(K_{i,j}\}_{i,j=X,Y}$, i.e.

$$\begin{Bmatrix} W \\ 0 \end{Bmatrix},\begin{Bmatrix} K_{XX} \\ K_{YX} \end{Bmatrix},\begin{Bmatrix} K_{XY} \\ K_{YY} \end{Bmatrix}=-\frac{D}{2}L\int_0^{2\pi}\left\{\left(P_0-P_a\right),P_X,P_Y\right\}\begin{Bmatrix} \cos\theta \\ \sin\theta \end{Bmatrix}d\theta \tag{6}$$

As expected, $K_{YX}=K_{XY}=0$. Incidentally, damping force coefficients are nil at *infinite* speed operation [14].

RESULTS AND DISCUSSION

An example of ultimate GFB force performance follows. The bearing length (*L*) and diameter (*D*) are 38 mm, c=0.032 mm, with foil support stiffness K_f=4.74 GN/m^3 [8], and P_a=1.01 bar. Dimensionless load (W') and direct stiffnesses (K'_{XX}, K'_{YY}) relate to (P_aLD) and (P_aLD/c), respectively. Engineered GFBs must have W'>1, i.e. specific pressure (W/LD) > P_a. The clearance (*c*) is referential only.

Figure 1 shows the journal eccentricity ($\varepsilon=e/c$) versus load W' at increasing speed numbers, $\Lambda=(6\mu\Omega/P_a)/(R/c)^2$, as obtained from [7]. The journal displacements lie between the limit at *infinite* speed, $\Lambda=\infty$, and the structural deformation at null shaft speed, $\Lambda=0$ [13]. Thus, the simple formulae, eqn. (3-6), in conjunction with [13], facilitate the estimation of the actual GFB eccentricity at a finite shaft speed.

Figure 2 depicts the effect of an increasing preload (r_p) on the limit journal eccentricity and minimum film thickness at both null and *infinite* shaft speeds. $r_p = c$ denotes an effective null clearance, and $r_p=2c$ a positive interference. $e> (c-r_p)$ ensures a gas film with generation of hydrodynamic pressure. As W' increases, the journal displacements approach the deflections of the support structure. The film thickness tends to similar magnitudes, irrespective of the preload. A GFB cannot exceed the elastic load limit from its support structure.

Figure 3 shows the stiffness, K'_{XX}, at null and *infinite* speeds for three preloads (similar K'_{YY} not shown for brevity). As W' grows, the GFB stiffness approaches its corresponding structural value, which is largest for the configuration with an assembly interference, $r_p=2c$, and smallest for one with a finite clearance, $r_p=0$. Note that the structural stiffness is piece-wise linear depending on the contact area for a given load and assembly preload [13].

CONCLUSIONS

The paper presents a simple analysis to estimate the limiting journal eccentricity, minimum film thickness and stiffnesses of a GFB operating at *infinite* shaft speed. The predictions demonstrate the ultimate load of a GFB can not exceed that of its underlying elastic structure. The GFB combines in series the gas film and structural stiffnesses. The structural stiffness is much softer than the gas film stiffness, and thus it is the commanding one in the actual operation of GFBs supporting significant loads.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Grant No. 0322925. The support of the Turbomachinery Research Consortium is gratefully acknowledged.

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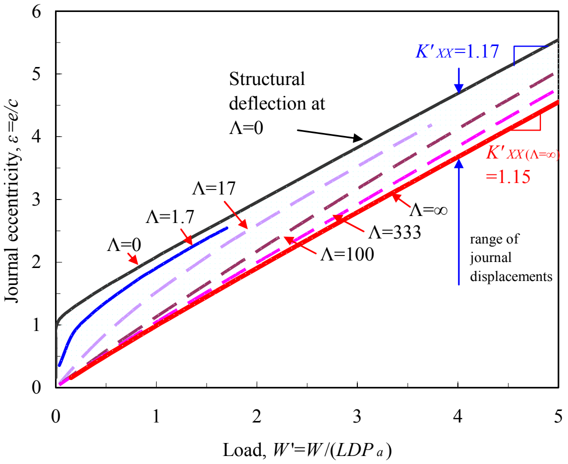

Fig. 1 Journal eccentricity vs. static load. Limiting values and numerical results for various speeds. GFB with no preload (r_p=0)

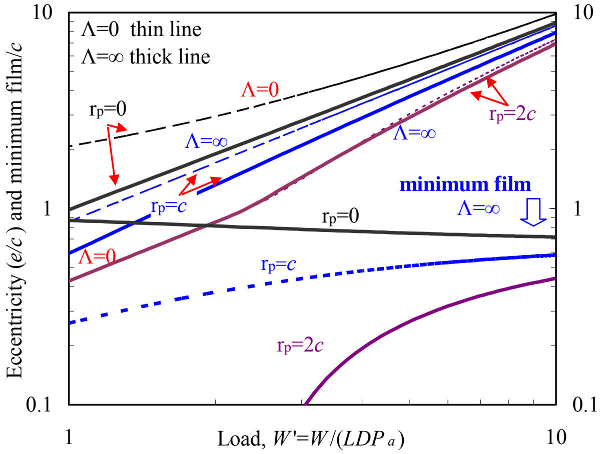

Fig. 2 Ultimate journal eccentricity and minimum film thickness (Λ =∞), and structural deflection at null speed (Λ =0) versus load for GFB with various preloads (r_p)

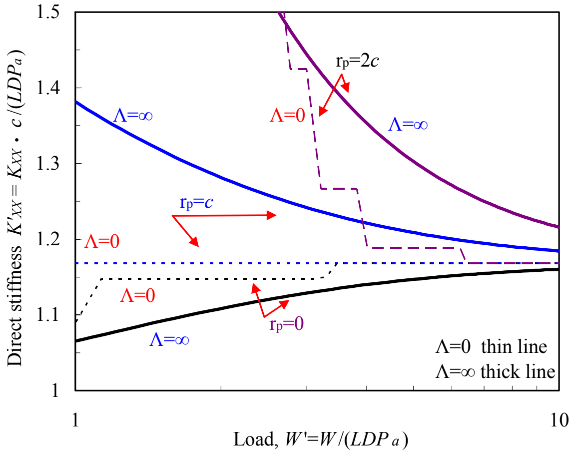

Fig. 3 Ultimate stiffness K'_{xx}, GFB and structural, versus load for various preloads (r_p), Null (Λ=0) and infinite (Λ=∞) speeds