Aerodynamic and Thermal Behaviour of Helium Lubricated Gas Foil Journal Bearing for High-Speed Cryogenic Turboexpander

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Abstract

Gas Foil Bearings (GFBs) are used for several high-speed applications such as cryogenic turboexpander and turbochargers in order to achieve desired load carrying capacity with better stiffness and damping characteristics. The present work deals with the aerodynamic analysis of helium lubricated bump-type gas foil journal bearing of 16 mm diameter at a design speed of nearly 240krpm. The numerical model is developed by using the non-linear compressible Reynold's equation and structural equations. Both the equations are coupled to predict the aerodynamic pressure, film thickness and load carrying capacity. The coupled equation is discretized in second order using the finite difference method and solved using successive over-relaxation (SOR) method for quick convergence. A detailed comparison is made between a rigid and compliant journal bearing to verify the advantages of GFBs and its feasibility in the current application. The effects of varying eccentricity on the aerodynamic characteristics are also presented along with mid-plane normalized pressure profile and film thickness. The work is further extended to predict the temperature distribution over gas foil journal bearing using energy equation.

Keywords: Gas Foil Bearings, Journal Bearing, Turboexpander, SOR.

Introduction

With recent development in high speed turbomachinery gas lubricated bearing are preferred over the liquid lubricated bearing as it avoids the contamination issue by using the same process gas as lubricant. Also, GFBs are compact in size, reduce power loss and have endurance to foreign matter and high temperature. There are two types of load generated by the rotor of the turboexpander, axial and radial load, which are supported by thrust and journal GFBs respectively. GFBs comprise of a pair of corrugated foil (bump foil) and smooth top foil, which deforms under the application of pressure. The use of gas foil bearings is restricted due to low load carrying capacity. However, with recent development in the design of the gas foil bearings, the load carrying capacity of the gas foil bearings has been improved which in turn has improved its scope of application. In 1994, Heshmat has done ground-breaking improvement on the design of foil bearings. They did an investigation on dynamic analysis which achieved a load-carrying capacity of 6.7 bar at a rotational speed of 59.7krpm [2]. In 1983, Walowit studied the hydrodynamic behaviour of gas foil bearing, where they used the Newton Raphson method to solve the non-linear compressible Reynolds equation [3]. Since that time, many models have been developed to calculate the load performance of bump type foil bearings. In 2000, Dellacorte & Valco derived an empirical formula to estimate the load carrying capacity [4]. Series of investigations have been done to predict bearing performance due to variation in parameters like radial clearance, bearing speed, compliance, etc. and reported in [2, 5 and 6]. There are several experimental and theoretical investigations which show that the foil gas bearing is more stable as compared to the rigid gas bearing [2, 4]. In 1993, J.-P. Peng & Carpino derived an equation to determine the foil bearing's dynamic characteristics. In 2004, Z.-C. Peng & Khonsari developed a model to predict the elastohydrodynamic behaviour of the foil bearing [7].

This paper aims to model and simulate the Gas Foil Journal Bearing (GFJB) taking into account the complaint behaviour of the foil. Numerical method is developed to predict the thermohydrodynamic behaviour of helium lubricated gas foil journal bearing (GFJB) which supports the radial load generated by the rotor of turboexpander used in cryogenic liquefaction cycle, operating at speed of 240krpm.

Aerodynamic model

The configuration of GFJB is shown in Figure 1 [1]. This GFJB contains the top foil and corrugated bump foil which are attached with a bearing sleeve.

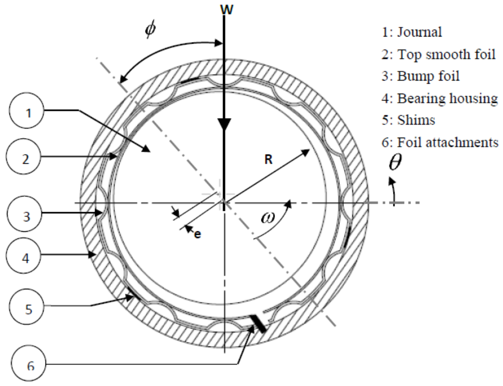


Figure 1. Schematic Geometry of Gas Foil Journal Bearing (Behera, 2018)

To predict the aerodynamic pressure profile of GFJB, a non-linear normalized Reynolds equation is used [7].

$$\left(\frac{\partial}{\partial\theta}\left(\bar{p}\bar{h}^{3}\frac{\partial\bar{p}}{\partial\theta}\right)\right)+\left(\frac{D}{L}\right)^{2}\frac{\partial}{\partial\bar{z}}\left(\bar{p}\bar{h}^{3}\frac{\partial\bar{p}}{\partial\bar{z}}\right)=\bar{\mu}\Lambda\frac{\partial}{\partial\theta}\left(\bar{p}\bar{h}\right) \tag{2}$$

While, the non-dimensional film thickness accounting for both the structural and aerodynamic behavior is:

$$\bar{h}=1+\varepsilon\cos(\theta)+\alpha(\bar{p}-1) \tag{3}$$

Where, α and Λ is compliance number and bearing number respectively.

$$\bar{h}=\frac{h}{C},\quad \alpha=\frac{2p_0 s}{CE}\left(\frac{l}{t_b}\right)^{3}\left(1-\nu^{2}\right)\ \text{and}\ \ \Lambda=\frac{6\omega\mu_0}{p_0}\left(\frac{R}{C}\right)^{2}$$

The boundary condition for the governing differential equation is given below

$$\bar{p}(\theta=0)=\bar{p}(\theta=2\pi)=1,\quad \bar{p}=1\ \text{at}\ \bar{z}=\pm1$$
$$\frac{\partial\bar{p}}{\partial\bar{z}}=0\ \text{at}\ \bar{z}=0 \tag{4}$$

Thermodynamic model

The thermodynamic analysis is carried out to predict the temperature effect on GFJB. The normalized form of equation (5) is given as

$$\left(\bar{u}\frac{\partial\bar{T}}{\partial\theta}+\bar{w}\frac{\partial\bar{T}}{\partial\bar{z}}\right)=k_2\left(\frac{\partial^{2}\bar{T}}{\partial\bar{z}^{2}}\right)+k_3\left(\bar{u}\frac{\partial\bar{p}}{\partial\theta}\right)+\frac{k_4\bar{\mu}}{\bar{h}^{2}}\left[\frac{\partial\bar{u}}{\partial\bar{y}}\right]^{2} \tag{5}$$

Where

$$\bar{T}=\frac{T-T_0}{T_0-T_{ref}},k_2=\frac{kR}{\rho_0 c_p C^{2}},k_3=\frac{p_0}{\rho_0 c_p \tau_0},k_4=\frac{akUR}{\rho_0 c_p C^{2}},\bar{\mu}=\frac{\mu}{\mu_0}=a(\bar{T}+1)$$

The boundary condition for the Energy equation are mentioned below.

$$\bar{T}\left(0,\bar{y},\bar{z}\right)=\bar{T}_i \qquad\qquad \bar{T}\left(\theta,\bar{y},1\right)=\bar{T}_s$$

$$\gamma \left.\frac{\partial \bar{T}}{\partial \bar{z}}\right|_{\bar{Z}=0} = -\bar{T} \qquad\qquad \gamma \left.\frac{\partial \bar{T}}{\partial \bar{z}}\right|_{\bar{Z}=0} = -\bar{T} \tag{6}$$

Results and Discussion

Table 1 shows the bearing parameters of GFJB

Table 1. Dimension for gas foil journal bearing.

Parameter	Value
The radius of the shaft (R)	8 mm
Length of bearing	16 mm
Radial Clearance (C)	25 μm
Bump Foil Thickness (t_b)	0.1 mm
Pitch of Bump (s)	4.2 mm
Length of Bump (2l)	2.64 mm
Young's Modulus (E)	200 GPa
Poisson's Ratio (v)	0.272
Viscosity of He (μ_0)	19.6×10^{-12} Pa-s
The speed of the shaft (N)	2,40,000 rpm
Eccentricity Ratio (ε)	0.8

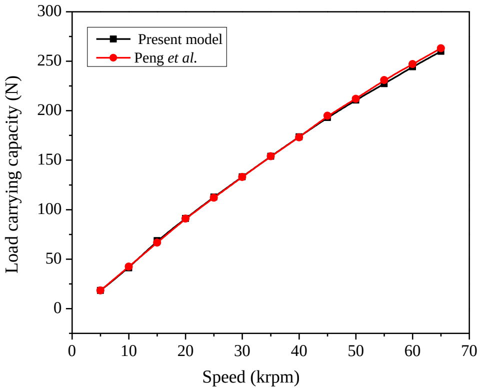


Figure 2. Validation of present work with (Z.-C. Peng & Khonsari, 2004) [7]

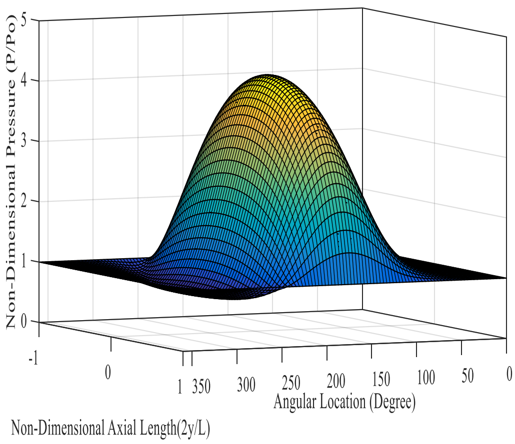
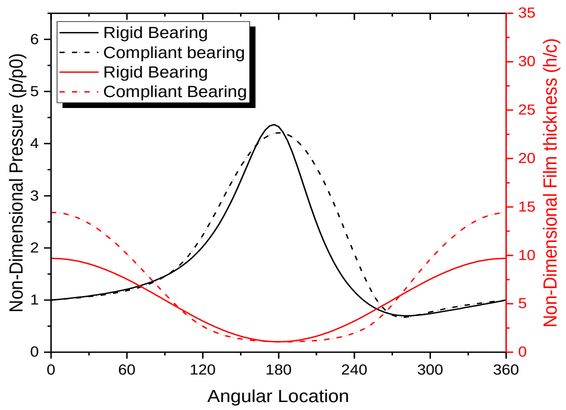


Figure 3. 2-Dimensional pressure distribution along angular (θ) and axial (z) direction.

Figure 2 shows the validation curve of present work with a deviation of 1.17%. Validation of present work is done by comparing the load carrying capacities of Z.-C. Peng & Khonsari, 2004 [7]. Figure 3 shows the variation of normalized pressure along the angular and axial direction. The pressure, along angular direction, is maximum at θ = 180°. The pressure gradually increases from z = 1 ($p = p_0$) reaching maximum at z=0 (mid-plane of the bearing) and decreases till z = -1 ($p = p_0$). Figure 4 shows the midplane pressure distribution and film thickness about the circumferential direction of GFJB. It is observed the pressure distribution and minimum film-thickness of complaint bearing spread over a large area as compared to the rigid bearing due to its compliant property, resulting in increased load carrying capacity, which is evident in figure 5. Also, figure 5 shows the difference between the load carrying capacity of compliant and rigid bearing increases with increase in speed. The variation of temperature over the circumference at the mid plane is represented in Figure 6. Temperature variation is shown from 3.6° to the cavitation angle 256.3° after which fresh Helium gas starts entering. The pressure gradient highly increases from an angle of 50° and the start decreasing at 180° due to which compression and expansion of gas result in temperature rises and fall respectively.



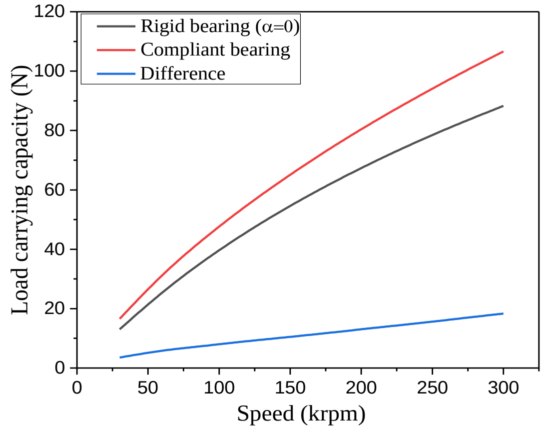


Figure 4. Mid-plane Non-dimension pressure distribution and Non-Dimensional film thickness of GFJB at speed of 240krpm	**Figure 5.** Load carrying capacity of GFJB with a variation of the speed

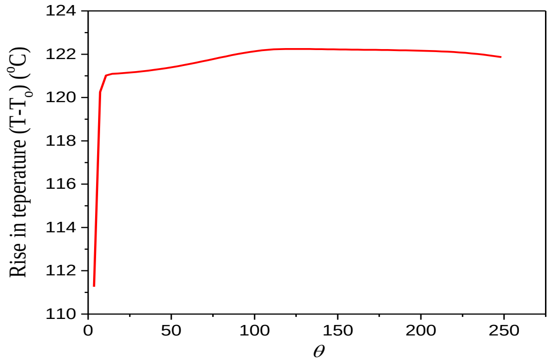


Figure 6. Mid-plane rise in temperature of the middle of the film thickness profile

Conclusion

A thermohydrodynamic analysis for helium lubricated gas foil journal bearing with consideration of compressibility of lubricant and compliant property of bearing is presented. The analysis shows that load carrying capacity of the foil bearing is more compared to the rigid bearing. The pressure in foil bearing is distributed over a larger area compared to rigid bearing, improving the stability of the bearing. The minimum film thickness(5µm) is greater than the surface roughness of the contact surfaces.

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