Design and development of bump-type gas foil journal bearings for cryogenic turboexpander

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ABSTRACT –

A cryogenic turboexpander is also referred as rotatory expansion device used in gas processing and cryogenic liquefaction. The operational objective of cryogenic turboexpander is to refrigerate a gas stream, by expanding the process gas in an expansion turbine. A mid-sized cryogenic turboexpander rotates at very high speed for better aerodynamic efficiency. The need for high rotational speed and contamination free operation brings constraints on the selection of appropriate bearings for the turboexpander. Gas bearings is a solution for above requirement. Present work describes on design and development and performance study of bump-type gas foil journal bearing(GFJB) for a turboexpander with 16 mm rotor diameter rotating at 80,000 rpm.

1. INTRODUCTION

Most of the turboexpander for small and medium-sized plants are vertically oriented for easy installation and maintenance. It consists of a shaft with the turbine fitted at the bottom end and the brake compressor at the other end. The major source of the radial load in a vertically oriented rotor is the unbalance load. Above radial load need to be supported by oil-free gas journal bearings to avoid contamination of the process gas. Due to the low viscosity of gas bearings, the stiffness and damping are inherently low. A compliant type gas bearing such as GFJB (Fig 1) has many attractive advantages compared to the rigid gas bearings such as compensation for misalignment, accommodation of thermal distortion, larger clearance, tailored damping, etc. [1]. This paper explains about design and development methodology for a pair of bump-type GFJB for a vertical turboexpander used in nitrogen liquefier operating at 80,000 rpm. The axial bearings for current application is a pair of aerostatic bearings.

The unbalance radial load of the rotor for current application is predicted to be 10 N, due to the presence of unbalance in the order of 100 mg-mm. A factor of 2 is multiplied for current radial bearing design for the possibility of increasing radial load during start up and shut down of the machine. So a GFJB with load carrying capacity of 20 N is essential for current application. The bearings is also designed for minimum vibration level at the designed speed.

A feasibility study for current application is done based on predicted load carrying capacity of the bearing. The load carrying capacity is predicted by solving compressible Reynolds equation, where the film thickness is considered to be a function geometry and bump deflection [1]. The work is further extended to determine bump parameters such as its geometry and material. The structural stiffness of bump foils is calculated based on bending formulations. Precise bump formation being a bottleneck, a forming operation is simulated numerically to design appropriate dies for forming the bumps [2]. Finally, assembly of foil bearings is tested in the turboexpander test facility at NIT Rourkela, India to study its performance.

2. AERODYNAMIC ANALYSIS

The GFJB is self-acting bearing and operates on the principle of aerodynamics [1]. The popular and easy method to analyze GFJB is by solving aerodynamic and structural equation simultaneously based on pioneered work by Heshmat et al. [1]. The dimensionless Reynolds equation is expressed in Eq^n. (1)[1].

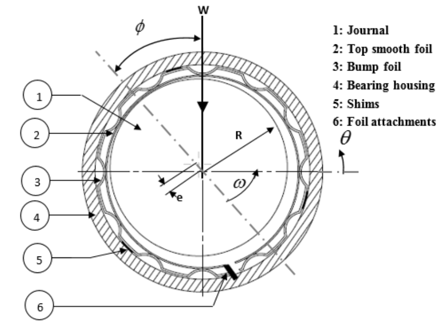

Figure 1 Dimensional nomenclature of GFJB

$$\frac{\partial}{\partial\theta}\left(\bar{p}\bar{h}^3\left(\frac{\partial\bar{p}}{\partial\theta}\right)\right)+\left(\frac{2R}{L}\right)^2\frac{\partial}{\partial\bar{z}}\left(\bar{p}\bar{h}^3\frac{\partial\bar{p}}{\partial\bar{z}}\right)=\Lambda\frac{\partial(\bar{p}\bar{h})}{\partial\theta}\ldots\ (1)$$

The Finite Difference Method (FDM) is used to discretize, and Newton-Rapsons method is used to solve the nonlinear Eq^n. (1). The objective of solving above equation is to determine bump material and its dimensions for desired load carrying capacity. The simulation is performed for the below design parameters:

(a) Load carrying capacity for various feasible foil materials such as Inconel X-750, Phosphor Bronze, SS 302 and Beryllium copper.
(b) Load carrying capacity for various foil thickness
(c) Load carrying capacity for various bump pitch and its half bump length

Table1: Selected bearings parameters

Journal bearing parameters	Dimensions
Diameter of Shaft (2R)	16 mm
Bearing Length (L)	16 mm
Rotational Speed (N)	80,000 rpm
Nominal Radial Clearance (C)	25 μm
Eccentricity ratio(ε)	0.8
Top Foil Thickness (t_t)	0.1 mm
Bump Foil Thickness (t_b)	0.1 mm
Bump Pitch (s)	4.2 mm
Bump Length ($2l_b$)	2.64 mm
Bump Foil Young's Modulus (E)	114 GPa
Bump Foil Poisson's Ratio (ν)	0.35
Grid Size	80 × 80
Viscosity	178.4×10^{-7} N.s/m^2

After extensive numerical analysis, the bump foil parameters are selected based on the availability of material, ease of forming bumps, literature studies, and numerical analysis. The selected bearing parameter is given in Table 1.

The pressure distribution and gas film thickness over the journal bearing surface are shown in Figs. 2 and 3 respectively. Integrating pressure profile calculates the load carrying capacity over the bearing surface. The load carrying capacity predicted for the various eccentricity ratio is plotted in Fig 4.

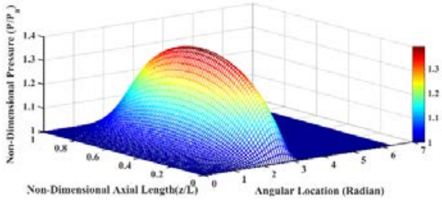

Figure 2: Pressure profile over bearing surface

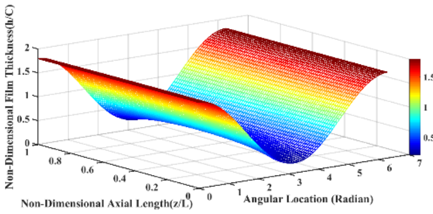

Figure 3: Film thickness with designed data.

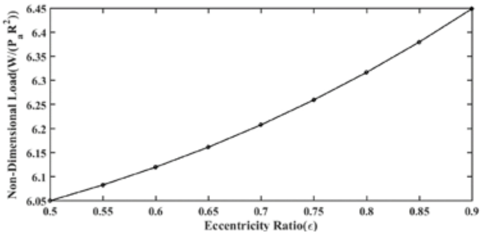

Figure 4: Load carrying capacity

3. DIES FOR BUMP FORMATION

The gas bearings with a radial clearance of 25 microns need a precise fabrication methodology. Maintaining uniform bump height in a bump type GFJB is very much essential for reliable performance. The designed die is simulated in DEFORM 3D to study the process of forming operation such as (a) displacement of bump foil, (b) stress during forming operation, (c) spring back on load removal,(d) possible damage during forming. Fig 5 shows the stress distribution over the bump foil during forming operation.

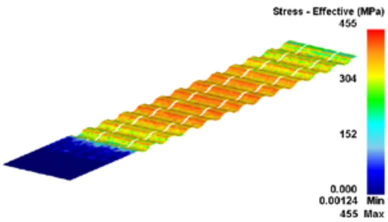

Figure 5 Stress distribution during bump formation.

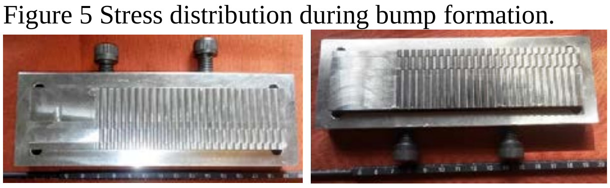

Figure 6: Upper and lower dies for bump formation.

The upper and lower die fabricated for bump formation is shown in Fig. 6. The fabricated top foil, bump foil and assembly of these foils with bearing base is shown in figure 7. An experiment shows less than 10 % deviation on the stiffness of the fabricated bump foil with the predicted stiffness.

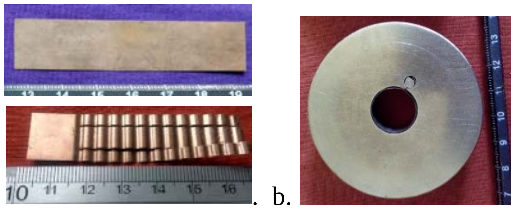

Figure 7 a. Top and Bump foil b. Assembly of foils with bearing base

4. VIBRATION ANALYSIS OF PROTOTYPE TURBOEXPANDER

Detailed performance analysis is carried out to study the behavior of the turboexpander at its stable operation. The signal from the accelerometer near journal bearing is recorded on a storage type oscilloscope during test runs.

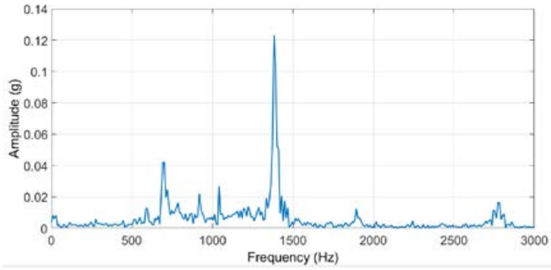

Figure 8 Vibration of bearing housing at upper journal bearing

The obtained signals are converted to acceleration and FFT of the vibrational spectrum at 80,000 RPM is shown in Fig. 8. The vibrational spectrum at 1X, 2X and 0.5X are studied carefully near lower journal bearing, and they are compared with the results of vibration analysis using tilting pad bearings in one of the earlier studies at NIT Rourkela [3]. The comparison prevails 25% reduction of the vibration level near lower journal bearing. The detailed vibration analysis shows enhanced rotor stability.

5. CONCLUSIONS

The work presented in this paper is a modest attempt to implement the gas foil journal bearings to a high-speed turboexpander used in nitrogen liquefier. The dies for bump formation is designed using FEM analysis for forming operation. This analysis rectifies many major issues of the bump formation with a uniform height. Finally, from the vibration signature, the level vibration is found to be significantly reduced near both the journal bearings. This indicates gas foil bearing is an alternate solution to the previously developed tilting pad journal bearings. The author believes that the structured design and fabrication methodology for bump-type gas foil journal bearings will be useful to the tribologists working for other high-speed applications.

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