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Feasibility Studies on Gas Foil Journal Bearings in Helium Turboexpander

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Abstract

A turboexpander is also referred as rotatory expansion device used in various cryogenic processes such as air separation, cryogenic liquification, etc. The operational objective of a turboexpander is to refrigerate a gas stream, by expanding the gas at the nearly isentropic condition and removal of work from the gas. The high efficiency of cryogenic liquification process is possible at high-speed of the turboexpander. High-speed brings constraints on the selection of bearing. So to meet above requirements gas bearings are found to be suitable for such application. The gases of gas bearings unlike liquid lubricants have an inherently low viscosity, which leads to lower stiffness and damping. Low stiffness and damping are prone to instability at high rotational speed. The gas foil bearings with compliant structure can tailor stiffness and damping. Also, the compliant surface can accommodate the thermal and centrifugal growth of the rotor. In the current research work, a modest attempt has been made to study the feasibility of gas foil bearing for helium turboexpander rotating a 2,55,000 rpm. The feasibility study includes (i) thumb rule for load carrying capacity, stiffness and damping coefficient (ii) aerodynamic analysis of gas foil journal bearings, by solving compressible Reynolds equation and structural equation using Finite Difference Method and (iii) rotordynamic analysis of the vertical rotor. The author believes the detailed steps of the feasibility study will help the researchers around the world to design gas foil bearings for other high-speed turbomachinery.

Keywords: *Gas foil journal bearings, Turboexpander, Finite Difference Method*

Introduction

The static load in a vertical rotor of a cryogenic turboexpander is negligible, but dynamic load can be significant at high rotational speed. The dynamic load is because of the unbalanced masses in the rotor. The unbalanced load in the designed rotor is constrained by a pair of journal bearings. Oil-free journal bearings are gaining its popularity in small and medium rotor because of low maintenance and high reliability. Current research work targets to design a pair for aerodynamic gas journal bearing based on the feasibility study. Aerodynamic gas journal bearing like tilting pad, grooved and gas foil bearings are used in high-speed turbomachinery. Among the mentioned gas bearings, foil bearing has an added advantage because of its compliant behaviour of the bearing surface. Foil bearing is consisting of three elements a bearing sleeve, a compliant foil and a smooth foil (Fig.1).The target of present investigation to study the feasibility of using bump type gas foil journal bearing for the turboexpander designed to be in the indigenously developed helium liquefier at Institute for Plasma Research (IPR), Ahmedabad. The rotational speed of designed helium turboexpander for 75% turbine efficiency about 2,55,000 RPM.

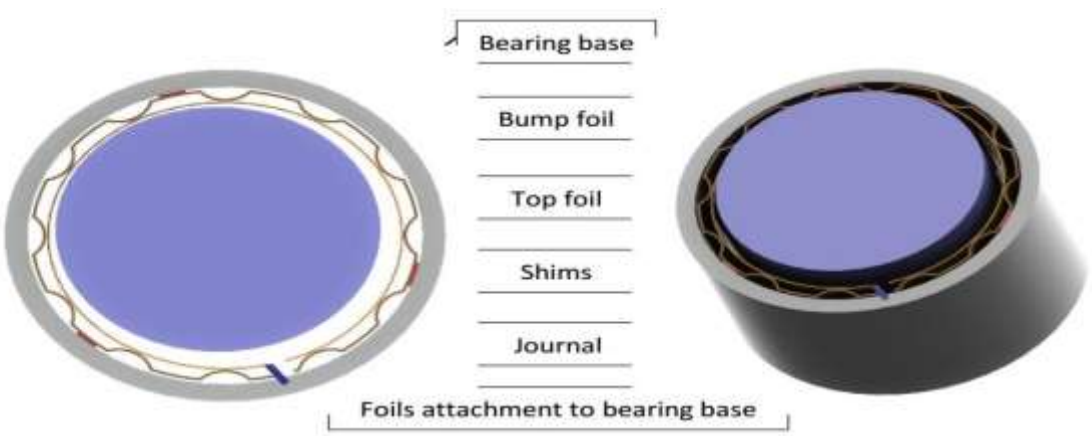

Fig. 1. Schematic diagram of a bump type foil bearings for the vertically oriented rotor.

Thumb Rule for Gas Foil Bearing Design

Simple and reliable performance methods or design guidelines have not yet been developed for foil bearings because of the non-linear structure of compliant structures. So empirical or "Rule of Thumb" (ROT) are used to find load carrying capacity, bearing stiffness and damping, etc. [2]. The ROT is based on experimental data and fundamental first principles and is shown to be remarkably effective in making direct comparisons between bearing designs [2].

As a thumb rule, the static load capacity of foil bearing is determined by dividing rotor weight (or preload load for a vertical rotor) by projected area. Typically, a design value of 1 to 5 psi is used for gas foil journal bearing [4]. For current research work, this value is 2.6 psi for journal bearing. Also, an empirical relation is developed from experimental data and fundamental first principles to find load carrying capacity as [2]:

$$W = w_j * (LD) * (DN) \tag{1}$$

Where L and D are length and diameter of the journal bearing and N is the designed rotational speed. w_j is bearing load capacity coefficient is taken from literature [2] for current analysis of journal foil bearing. Using equation (1) static load carrying capacity is within the range of 92.6N to 127.4N. Similarly, the stiffness and damping of the bearing were determined using ROT [3].

Load carrying capacity, stiffness, and damping calculated using ROT was found to be satisfactory for the current requirement of the journal bearing. Therefore, from ROT, gas foil journal bearing is a feasible solution for small high-speed turboexpander.

Aerodynamic Analysis of Gas Foil Journal Bearing

The aerodynamic pressure developed varies with operating speed and has a significant influence on the deformation of the foils. Hence, the film thickness is a function of aerodynamic pressure and the elastic properties of the foils [5]. An elasto-hydrodynamic analysis should account for the above parameters and the compressibility of the lubricant [6].

The standard non-dimensional Reynolds equation neglecting the time variant, constant viscosity, considering a bearing with finite length is given as [6]:

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

$$Where, \Lambda = \frac{6\omega\mu_0}{p_a}\left\{\frac{R}{C}\right\}^2$$

In case of a foil bearing since the bushing is compliant, the film thickness is a function of the eccentricity ratio and aerodynamic pressure, which deforms the top and lower bump foils.

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

$$where,\ \bar{h}=\frac{h}{C},\ \bar{p}=\frac{P}{P_a},\ \varepsilon=\frac{e}{C}\ \ and\ \ \alpha=\frac{2P_a s}{CE}\left[\frac{l}{t}\right]^3\left(1-\nu^2\right)$$ (Nomenclatures are given in Table 1)

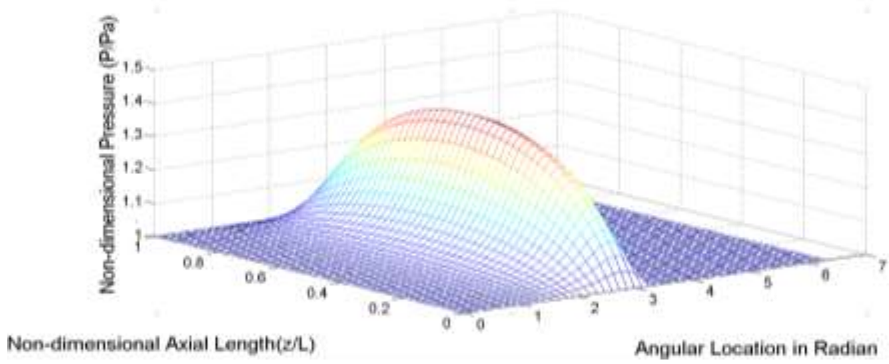

Fig. 2. Pressure distribution of 360^0 1st generation bump type gas foil journal bearing.

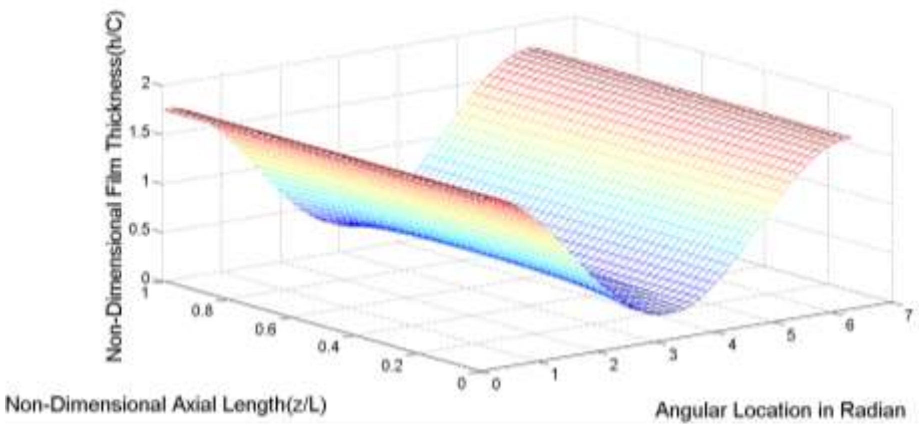

Fig. 3. Film Thickness profile for 360^0 bump type gas foil journal bearing.

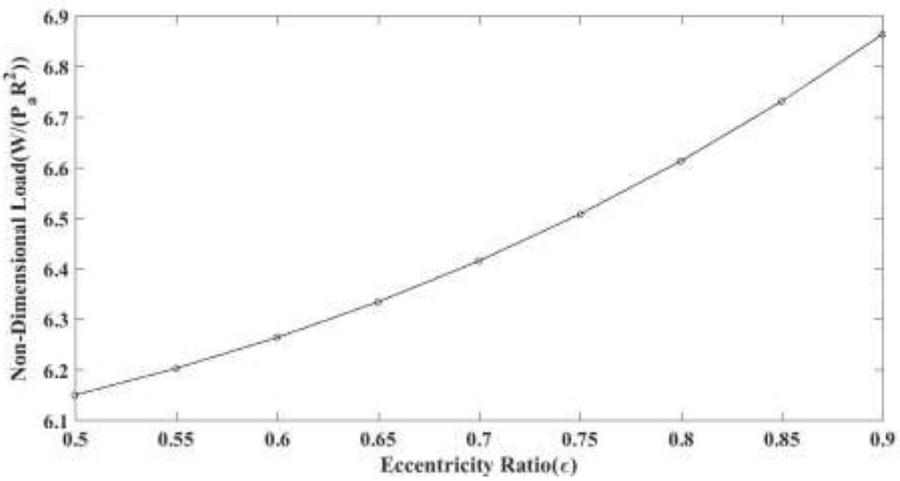

Fig. 4. Load Carrying Capacity for 360^0 bump type gas foil journal bearing.

The Reynolds equation (Eq. 2) is solved using Finite Difference Approximations written in MATLAB language. The analysis was done to find pressure profile (Fig. 3), the static film thickness (Fig. 4) and load carrying capacity variation with eccentricity (Fig. 5). An extensive analysis is done to select best possible foil materials based on numerical analysis and availability in the market. Similarly, the bearing geometries are selected based on rigorous numerical analysis for various values of bump pitch, bump length and foil thickness. The selected bearing geometry values used to solve Reynolds equation is given in Table 1.

Table1: Designed bump foil bearing data

Diameter of Shaft(D), mm	16
Bearing Length (L), mm	16
Top and bump Foil Thickness (t), mm	0.1
Foil material	Inconel X750
Bump Pitch (s), mm	4.2
Half bump Length (l), mm	1.125
Radial clearance(C) mm	0.03
Foil Young's Modulus(E)N/mm^2	214E+03
Bump Foil Poisson's Ratio (v)	0.31
Coefficient of viscosity (□)(N-s/mm^2)	19.6E-12

Speed (N)(RPM)	2.55E+05

Rotodynamic Analysis of Rotor-Bearing System

For every rotor-bearing system, there exist an infinite number of discrete natural frequencies of lateral vibration. When there exists an externally impressed periodic force with a frequency equal to one of the natural frequencies, the vibration amplitude increases significantly. In a rotating shaft, such periodic forces can arise due to a variety of causes, one among them being the shaft imbalance. The corresponding speed of rotation of the shaft is called a critical speed. Although theoretically there are infinite numbers of natural frequencies but in practice, only the first four are the interest of study. Transfer matrix method (Myklestad – Prohl method) was used to find the first four natural speeds and mode shapes at all four critical speed. Third and fourth are also called first and second bending critical speed. At the critical bending speed, the rotor does not vibrate, but rather is bowed into the mode shape associated with the particular natural frequency, and whirls about its bearing centreline. The prototype cryogenic turboexpander rotor was modelled with 19 stations (Fig. 5).

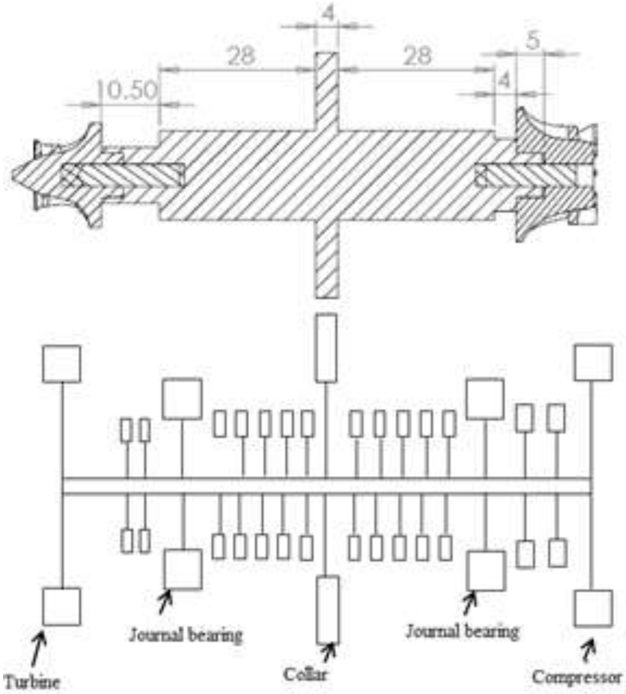

Fig. 5. The lumped inertia model of the prototype turboexpander rotor.

A MATLAB code was used to find critical speed and bending mode shapes. The 1st bending critical speed is found to be 4,50,325 RPM, which much above our designed speed of turboexpander(Fig. 6). The transfer matrix method is further extended to find the imbalance response of the rotor at compressor and turbine ends; it was observed to be maximum vibration amplitude of 1.8 microns at the turbine end at 2,55,000 RPM(Fig.7). This is because of the large overhang of the turbine. However, vibration amplitudes are under permissible range.

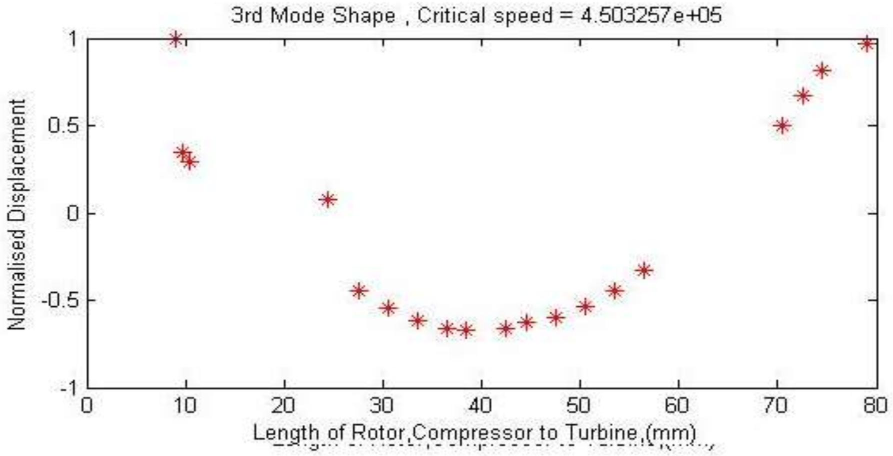

Fig. 6: 1st bending mode shape (3rd mode shape) of the prototype turboexpander rotor.

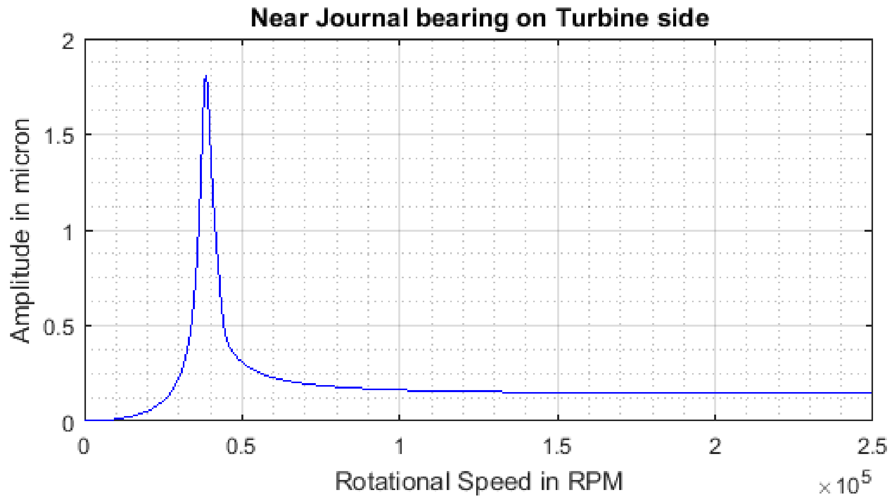

Fig. 7: Imbalance response at turbine side

Conclusion

This paper presented feasibility of bump type journal foil bearing for a vertically oriented turboexpander for helium liquefier. The thumb rule, aerodynamic analysis and rotodynamic analysis on foil journal bearing confirm the load carrying capacity, critical speed and imbalanced response within the range of requirements. This indicates foil journal bearing can be an alternate solution to high-speed turboexpander for the cryogenic application. This feasibility study is very important steps in the design of foil journal bearing for turboexpander used for the cryogenic application. Authors hope that these steps of a feasibility study on gas foil bearings will be useful to researchers around the world.

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