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Assessment of thermal effects on the levitation speed of bump foil bearings made of low cost spring steel

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ABSTRACT

The demand for higher speeds and torque capacity from micro turbines, heat pumps and turbochargers has necessitated the development of high temperature resistant foil bearings. This paper focuses on investigating the effects of successive thermal cycles on the levitation speed of bump foil bearings made up of low cost spring steel. Bump foil bearings were designed for high stiffness of 1.64 MN/m^2. Rotor dynamic analysis indicated highest frequency of 4790.5 Hz corresponding to second flexure mode of rotor bearing system up to which it remained stable. The bump foil bearing fabrication procedure was established and rotor was tested under suitably designed bearing rig. The orbital analysis indicated that levitation speed decreased with increase in temperature. During second and third thermal cycle, at lower rotor speeds drastic variations in amplitude of vibrations and uneven waveforms were indicative of unbalance condition of rotor. With further increase in rotor speeds, the rotor - bump foil bearing system attained the balanced state indicative of safe design.

1. Introduction

Gas foil bearing technology was developed to support high speed shaft systems that do not operate with conventional oil bearings or rigid geometry gas bearings because of contamination, speed and thermal stability requirements [1–3]. Foil bearings have been developed as "proof-of-concepts" for diesel engine turbochargers, auxiliary power units (APUs) and hot section bearings in gas turbines [4–6]. The foil bearings are generally formed from compliant surface in order to provide the damping effect and one or more layers of top foil surfaces. The three configurations of compliant surface include tape-type, bump-type and leaf-type as shown in Fig. 1(a)–(c). Generally, tape and leaf type of foil bearings are tension dominated and bump type foil bearings are bending dominated [7]. Further the bump foil bearings are classified into Generation I, II and III based on the arrangement of bump layer.

Some of the researchers have developed and analyzed foil bearings without and with coatings adopting various material systems. Kulkarni et al. [8] developed and assessed the performance of foil bearings made up of Be Cu alloy. The authors reported that discrete and continuous bump foil bearings showed levitation at speeds above 14,000 rpm and 9000 rpm respectively. DellaCorte et al. [9] employed novel tooling technique for fabrication of Generation I and II bearings made up of Inconel X 750 and analyzed for load capacity and power loss. The authors observed that Generation I bearings exhibited lesser load capacity than Generation II bearings. Also higher power loss was observed in Generation I bearings compared to Generation II bearings.

Heshmat et al. [10] investigated the effects of various coatings such as PS304 plasma sprayed, hard chrome, dense chrome and Korolon on Inconel X-750 foil bearings and Inconel 718 disks in order to analyze the friction coefficient and surface roughness. The authors reported that Korolon coatings exhibited minimum friction coefficient of 0.1 during startup and shutdown periods and hard core chrome coatings were found with high surface cracking. Satanford and DellaCorte [11] investigated Cu-4Al coated foil bearings applied by ion diffusion technique. The authors found that Cu-4Al coated bearings supported higher loads than uncoated ones. Also wear rate for coated journals at 650 °C was higher than that of uncoated bearings. Laskowski and DellaCorte [12] investigated the friction and wear properties of nickel based alloys (Rene 41, Inconel X-750 and Inconel 713C), iron based alloys (MA956 and Inconel 909) and alumina ceramic at elevated temperatures. The authors found that Ni-Cr oxides formed on Inconel X-750, Inconel 909, and Rene 41 reduced friction and wear at 500 °C and 800 °C. However, the alumina forming materials (Inconel 713C, MA956,

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Nomenclature

K_e	air stiffness per unit width	L	width of bump sheet
K_f	foil stiffness per unit width	n_b	number of bumps
K_a	equivalent stiffness per unit width	d_c	bearing housing inner diameter
G	flexural stiffness per unit width	s	standard deviation
r_b	radius of bump	m	mean
E	Young's modulus of spring steel	Uc	experimental uncertainty
t_b	bump sheet thickness		
γ	Poisson's ratio of spring steel		

and MA956-Oxide) did not show reduction in friction until 800 °C is reached.

Howard et al. [13] investigated the influence of temperature and load on steady state stiffness coefficients of foil bearings made of Inconel X-750. The authors reported that stiffness remained constant till 538 °C and gradually decreased thereafter. Stiffness increased with increase in load and decreased with speed. Della-Corte et al. [14] evaluated a performance map for bearing friction which described operating regimes, performance safety margins, limiting factors and the effect of load on performance of foil bearings. The researchers observed an asymmetric parabolic curve characterized by two distinct load regimes namely, high and low, occurring at low and high values of Sommerfeld number respectively. However, both regimes yielded an equivalent bearing power loss. Kim et al. [15] reported the influence of nominal clearance, supply pressure, bump stiffness per unit area and orifice diameter on rotor imbalance response of bump foil bearings. Increase in onset speeds of instabilities were found at lower nominal clearance and higher supply pressure. San Andres [16] investigated the static and dynamic load responses of gas foil bearings by integrating top foil model with bump strip layers. Staggered bump strip layers improved the bearing load capacity as well as dynamic forced performance of gas foil bearings by reducing the sagging of the top foil between the adjacent bumps.

Lack of high temperature start/stop durability of the bump foil bearings is a major shortcoming [13] that necessitates the design and analysis of high temperature resistant bearings demanding higher speeds with minimal power loss. From the review of literature [1–16], it was found that researchers have focused on design and development of bump foil bearings adopting high cost nickel based alloys. The studies are limited for analyzing mechanical behavior of bump foil bearings by considering load carrying capacity, damping, friction and stiffness as major parameters. The effect of temperature on levitation speeds of bump foil bearings made of low cost material systems such as spring steel is not yet reported. This paper presents experimental studies measuring levitation speeds with varying temperatures in bump foil bearings made of low cost spring steel [EN42J], an alternative to high cost nickel alloys. The test rig consisting of rotor, bearings and temperature sensors was fabricated to analyze the performance of bump foil bearings at higher temperatures. Rotordynamic analysis of shaft bearing system was performed in order to evaluate the vibration characteristics such as critical frequency and mode shapes using ANSYS 14.0 finite element package. The stability of the foil bearings was assessed based on the Orbit and Bode plots.

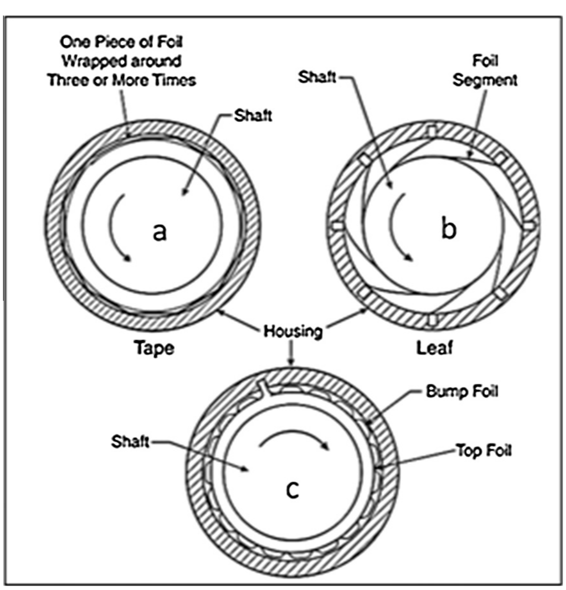

Fig. 1. Types of foil bearing. (a) Tape, (b) leaf and (c) bump [7].

2. Design of foil bearings

2.1. Selection of material system and coating

The characteristics of bearing material include self lubrication, ease of heat treatment, high stiffness, good corrosion resistance, low thermal expansion, high thermal conductivity, availability, cost and reliability [17]. Based on the availability of conditions pertaining to temperature, self lubrication, friction and heat treatment processes, some of the candidate materials for bump foil bearing design are as shown in Table 1. Even though nickel alloys (Rene 41, Inconel X-750, Inconel 713C, MA956 and Inconel 909) and MAX phase alloys had superior properties [18] [19], they are scarcely available and are of high costs. Hence spring steel [EN42J] was adopted for the fabrication of foil bearings, the material properties of which are presented in Table 2. Molybdenum disulfide was adopted as coating material for the rotor.

2.2. Design of bump foil bearing

Design of foil bearing depends on identification of bearing geometry for the required load carrying capacity at desired speed [7]. Load carrying capacity is the function of equivalent stiffness involving bump stiffness and air film stiffness acting in series and can be calculated from Eq. (1) [7]:

$$\frac{1}{K_e} = \frac{1}{K_f} + \frac{1}{K_a} \tag{1}$$

The bump stiffness was evaluated as function of flexure stiffness, bending moment, radius of curvature and elastic strain [20]. The simplified equation is given by (2):

$$K_f = \frac{6G}{r_b^3} \tag{2}$$