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Influence of Foil Thickness and Bump's Height-Pitch Ratio on Airfoil Bearing- an Analytical Approach

Bivash Chakraborty[1], Prasun Chakraborti[2]
*[*1] Department of Automobile Engineering, Tripura Institute of Technology, Agartala*
[2]Department of Mechanical Engineering,National Institute of Technology, Agartala
Corresponding Author: Bivashtit2008@gmail.com

Abstract
One of the recent advances in bearing technology is airfoil bearing, which can be operated at very high and low temperatures with extremely high speed. It is an entirely oil-free and air-operated bearing. Top and bump foils are two crucial structural design parameters of an airfoil bearing as the top foil distributes the created pressure in the air film. In contrast, the bump foil props up the top foil by providing structural stiffness and damping to the bearing assembly. To increase the load-bearing capability, the foils must be able to carry more loads. Consequently, it is essential to study the effects of the variations in foil thickness and bump's height-pitch ratio on airfoil bearing. The current work explores the unit stiffness and stress generated in the top and bumps foils by varying the thicknesses of these foils. It has been found that changing the foil thickness and the height-pitch ratio of the bump has a substantial impact on the stiffness and stress generation of the system.
Keywords: *Airfoil Bearing, Bump foil, Top foil, Film thickness.*

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I. INTRODUCTION

An airfoil bearing is an air-operated, completely oil-free bearing. It has three main parts: a smooth elastic encircling top foil, a visco-elastic corrugated compliant bump foil, and a sleeve (Figure 1). The encircling top foil is smooth and generally more elastic than the bump foil. The corrugated bump foil provides backings to the smooth top foil, and it also provides damping and structural stiffness to the bearing. It is a subsection of journal bearing. In this non-contact bearing, a thin film (35µm to 70µm) of air or gas provides a frictionless interface between the top foil and the revolving rotor instead of lubricating oil. According to their basic foil configurations, the airfoil bearing may be subcategorized as elastically supported bump type AFB and leaf type AFB. The Foil bearing is generally aerodynamic (Self-acting), aerostatic (externally pressurized), or a hybrid of aerostatic and aerodynamic. Airfoil bearings are also categorized into three generations based on the modification in the structural stiffness in the circumferential and axial directions [1]. According to the load direction, the foil bearing is also further classified as radial and thrust air foil bearing. AFB is the best-suited bearing used at very high or low temperatures with very high speed (more than 60,000 rpm) in lightly loaded small or medium turbo-machineries. It does not need an oil lubrication circuit and seal. It is less complex and better for the environment because of the smaller quantity of elements needed and no sealing or lubrication systems.

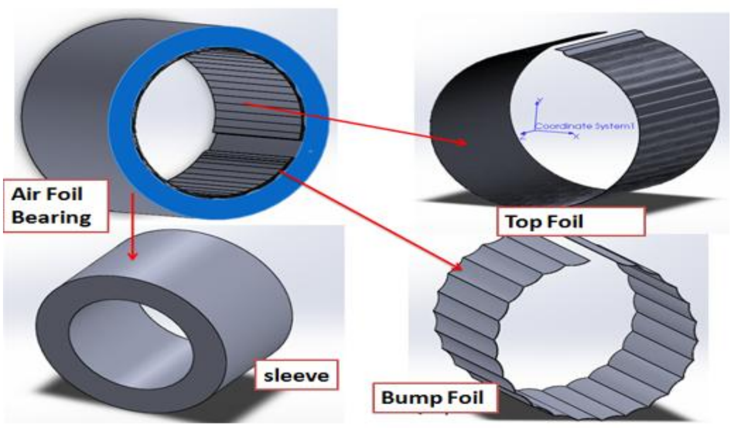

Figure 1: Components of Airfoil Bearing

In 1953,Block, H. established the fundamental conception of airfoil bearing [2]. During the last 20 to 30 years, airfoil bearings have made significant progress. Since then, many investigators have been contributing to the improvement of foil bearing. Agarwal G.L.[1] summarises the chronological progress of foil air bearings during the last 50 years from which we come to know a basic concept of airfoil bearing, its uses, and future developments and types of designs of airfoil bearing used in recent times and their comparative advantages and disadvantages.Describing the corrugated bump foil strip deformation,W. E. Langlois [3] has established a hypothetical model of airfoil bearing. By explaining the bearing's static load performance,Heshmat A Walowit [4] analyses bump foil type AFBs for the first time. Branagan et al. [5] reported a contemporary and very effective design of hydrostatic airfoil bearings compared to their earlier model. They built up the latest experimental setup for calculating load bringing ability of airfoil bearings at higher velocities.Guo et al. [6] ensure the efficient hydrostatic levitation aspect at lesser speeds with high load-bearing capacity and investigate the influences of air film clearance on the load-bearing capacity coefficient of AFBs.

II. WORKING PRINCIPLE OF AIRFOIL BEARING

When the shaft is at rest, less amount of dead load is in between the bearing and shaft. By the rotation of the rotor, a hydrodynamic pressure has been generated between the rotor and the top foil of the bearing that pushbacks the top foils away from the rotor, which will make the rotor completely gas/airborne. This matter occurs immediately during start-up, i.e., at about speeds of 4% to 5% of the maximum revolving speed of the rotor (when experienced by MiTi in a foil-bearing test rig) [7]. The frictional loss due to rotor rotation is quite less when the shaft is airborne. As the rotor speed increases, the foils get pushed farther away for a certain limit. The foils provide a coulomb damping due to their relative movement. This damping is vital for the stability of the bearing shaft. Airfoil bearings are very similar to the working principle of oil-lubricated journal bearings. Like other hydrodynamic bearings, the rotor load is upheld by a self-generated zone of a thin layer of high-pressure air film between the top foil and the rotating shaft. This high-pressure air converges in the way of rotation due to the relative motion between the top foil and the revolving rotor. The limit of bearing-load of airfoil bearing that can be sustained is mostly a function of the area of the converging region, the relative surface speed, the shape of the clearance space between the top foil and shaft, the viscosity of the lubricant, and the support assembly stiffness. Commonly for airfoil bearings, the air is used as a lubricant (Argon, CO_2, etc., also be used as a lubricant). The compliant operating surface is the unique feature of a foil bearing. This compliant operating surface adjusts its profile in response to load variation, thermal deformations, variation of speeds, etc. This compliance permits the bearing to adjust levels of misalignment and thermal evolution that would demolish a stiff surface of the airfoil bearing. When the top foil transfers the stresses formed by the air film between the top foil and rotor to the bump foil, then the bump foil offers structural stiffness and damping-like springs. There has a relative motion between the bump and contact surface. This activity initiates the bump to deform or bend, and the bearing goes under Coulomb damping.

III. CONFIGURATION OF AIRFOIL BEARING

Choosing materials for top foil and bump foil is one of the most significant for the overall foil bearing operation. In this current paper, a nickel-chromium-based alloy 'Inconel X-750' has been used to make thebump and top foils. The Poisson's ratio (υ) and modulus of elasticity (E) of Inconel X-750 are 0.29 and 220 GPa at 300 K, respectively [8]. The material properties and parameters of the airfoil bearing are shown in Table I & Table II.

Table 1: Material Properties of Airfoil Bearing

Material Properties	Value
Bump modulus of elasticity, E	213 GPa
Poisson's ratio of foil material	0.29
Material density	830 Kg/ m3
Coefficient of friction	0.3
Rotor modulus of elasticity	193 GPa
Free-fixed end bump stiffness	0.876 MN/m
Free-free end bump stiffness	0.256 MN/m

Table 2: Parameters of Airfoil Bearing

Name of Bearing Parameters	Dimensions
Bump Height, h	0.5mm
No. of Bumps	26 bumps
Bearing outer dia. D	100mm
Bearing inner diameter, d	61.34 mm
Thickness of bump foil, t_b	160, 140, 120, 100, and 80μm
Air film thickness, t_{af}	35μm to 70μm
Top foil thickness, t_t	160, 140, 120, 100, and 80μm
Bump Length, L_b	4.6mm
Bump Pitch, p	4.3mm
Eccentricity	0.02mm
Bearing Length, L	45mm
Rotor diameter, inner	40mm
Rotor diameter, outer	60mm

III. METHODOLOGY

In aerodynamic airfoil bearing, a thin layer of compressed air film (thickness varies from 35μm to 70μm) is produced between the top foil and the revolving rotor due to the dynamic action of the rotation of the rotor. At low rpm of the shaft, the air film generated is not so adequate to float the rotor, i.e., no "lift-off" of the rotor. So, start-up friction between the rotor and top foil occurs. But at the high speed of the rotor, the air film created is adequate to float the rotor, and the rotor turns without any connection with the top foil. So, the air film thickness is a significant factor for airfoil bearing. As early as the adequate air film produces, the rotor begins to revolve without any connection with the top foil, and as a result, start-up wear and tear will be going down. From this, it can be said that the load-bearing ability depends on the air film thickness. This air film thickness is not equal in all radial tracks. It is minimum in the loaded and high-pressure area, whereas in the low-pressure region, it is maximum. So, the minimum air film thickness is one of the key factors for designing air foil bearing. So, a satisfactory and quick minimum air film thickness generation is essential for an airfoil bearing for effective load-bearing capacity and minimizes start-up wear. The corrugated bump foil is the root component of the AFBs. The bump foil's thickness, pitch, and geometry are three key factors that have a huge impact on the working of the AFBs as well as on the steady-state and transient responses. By using the simply supported beam theory of Timoshenko, we can produce a simple estimation of a single bump foil's stiffness [9]. This analysis uses a linear elasticity theory for the estimation of bump stiffness. The air film clearance is the factor of rotor speed, bearing load, Bump and top foil's thickness and stiffness, compliance characteristics, coefficient of friction between top and bump foil, between the rotor and top foil, and in between bearing sleeve and bump foil. Again, the stiffness of the system depends on the structural behaviors of the bump's height-pitch ratio [10]. So, an inspection is done to see the results of air film thickness and load-bearing capacity by varying the foil thickness and the bump's height-pitch ratio. In this paper, SolidWorks software is used for the modeling purpose of foil bearing. At first, five different air-foil bearing models are drawn in SolidWorks by taking different thicknesses of foils (i.e., 160μm, 140μm, 120μm, 100μm, and 80μm). Identical foil thicknesses are taken for both tops and bump foils. Then these five models of airfoil bearing are analyzed by using ANSYS WorkBanch16. The FLUENT tool of ANSYS WorkBanch16 is used for CFD analysis, and the model geometries available in SolidWorks are selected for CFD analysis. The fine meshing of the complete assembly of the airfoil bearing model is done by using ANSYS WorkBanch16 software. In CFD analysis, after identifying the input and output portions of airflow in the airfoil bearing models, we calculate the clearance volume between the top foil and rotor. Fluid properties of air are selected from the available list of ANSYS WorkBanch16, and the rotor speed limit is given (80 Krpm). Other required input parameters for CFD analysis are also provided, i.e., the material of the rotor, foils, and bearing sleeve, their coefficient of friction, etc., in the ANSYS datasheet.

IV. INFLUENCE OF THE FOIL THICKNESS ON AIR-FILM

The top foil and bump foil thicknesses are more important for designing air foil bearing. Five different models of airfoil bearing of different feasible foil thicknesses (i.e., 160μm, 140μm, 120μm, 100μm, and 80μm) are taken for CFD analysis in ANSYS Workbench 16. It can be observed that the minimum air film thickness varies with the rotor speeds at different foil thicknesses. Figure 2 provides the graph of the minimum air film thickness versus rotor speed for the five different models of airfoil bearing at different foil thicknesses. It has been noticed that when the rotor speed is zero, the minimum air film thickness is also zero, i.e., the rotor and top foil get in touch, no air gap between them in the leading segment. A hydrodynamic pressure is created due to the increasing speed of the rotor that drives the foils away from the rotor and causes the rotor to be gas/airborne.

This trend of lift-off happens immediately during start-up, i.e., at about speeds of 4 to 5% of the maximum rotating speed of the rotor. In these analyses, the static load is kept unchanging at 400N, and a constant pressure profile is followed.

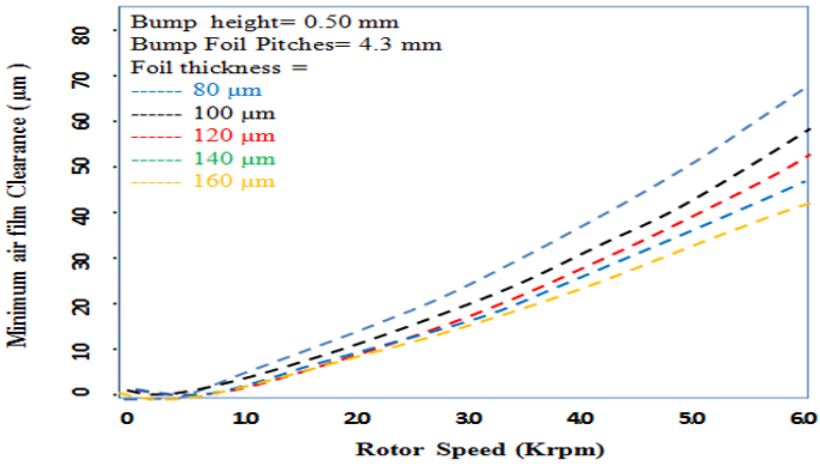

Figure 2: Graph of Minimum Air Film Clearance Vs. Rotor Speed

From figure-2, it has been observed that at foil thickness of 80 µm, the minimum air film thicknesses are more at every rotor speed. On the other hand, 160 µm thick foil gives the poorest result. Generally, the minimum air film thicknesses in airfoil bearing are about 35µm to 70µm. It is distinct from the graph that as the rotor speed rises, the minimum film thickness of air is also growing. The air film thickness decreases as the foil thickness increases. As early as the expected minimum air film thickness develops, the rotor lift-off speed also makes the rotor airborne. The air is inflowing through some of the very tiny holes on the sleeve and exits tangentially from the sleeve through the perimeter. So, the pressure near the perimeters is less, and the midway portion is maximum. The air drift is continuously flowing in and out. The running air generates a compressed airbed between the top foil and the rotor. So, the rotor is going to be airborne, and the friction between the top layer and rotor minimizes significantly. So theoretically, there is no limit to the rotor speed of the airfoil bearing.

V. INFLUENCE OF BUMP'S HEIGHT-PITCH RATIO

The height and pitch ratio of bump foil also has a significant role in the design of the airfoil bearing. The structural stiffness of the system is also changed if the bump's height-pitch ratio is altered. By keeping the bump thickness constant at 120 µm, a graph of unit stiffness versus bump height and pitch ratio has been outlined by varying the bump's height-pitch ratio (Figure-3). The applied bearing load has been kept constant at 400N. It has been observed that the unit stiffness of the bump structure is also increasing marginally as the ratio of bump height and pitch rises. The number of bumps is directly proportional to the bump's height-pitch ratio, and in science, this ratio is rising, and the number of bumps is also growing. As a result, the stiffness of the system increases.

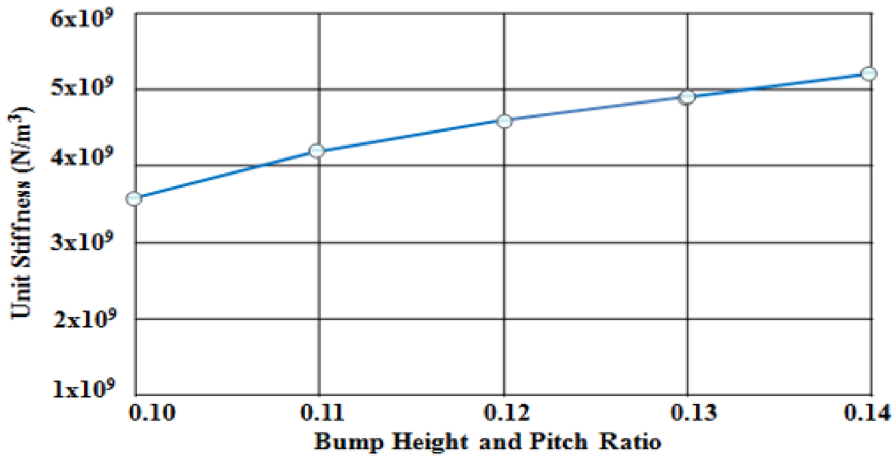

Figure 3: Graph of Unit Stiffness Vs. Bump's Height-Pitch Ratio

VI. INFLUENCE OF FOIL THICKNESS ON STIFFNESS

The stiffness of the system increases as the foil thickness increases. The smooth Compliance top foil is usually more elastic than the bump foil. This bump foil supports the top foil. It also provides damping and structural stiffness to the bearing. The corrugated bump foil also adjusts the shaft misalignments and expansions. In figure-4, it is shown that the unit stiffness of the bearing assembly changes with foil thickness.

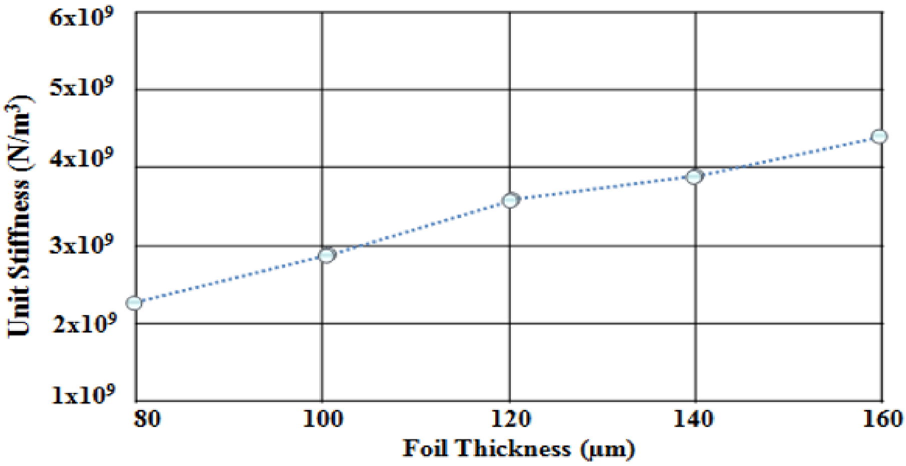

Figure 4: Graph of Unit Stiffness Vs. Foil Thickness

VI. CONCLUSION

It has been found that the bump foil height and pitch and foil thicknesses perform a significant role in the design of an airfoil bearing. It is distinct from the above discussion that the stresses develop on foils, air-film thickness, lift-off speed, and stiffness of the system depend on the bump foil height and pitch ratio and both top and bump foil thicknesses. From the observation and investigation, it can be concluded that

- The minimum air film gap or thickness decreases as the foil thickness increases.
- As the foil thickness increases, the unit stiffness of the airfoil bearing system increases
- The stresses generated on both the foils increase with increasing rotor speed at constant static load, and the stress-induced is more in thinner foil.
- As the height and pitch ratio of the bump increases, the unit stiffness of the bearing system also increases.

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