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An Investigation to Find the Effects on Air Foil Bearing by the Variation of Foil's Structural Parameters

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The newest advancement in the realm of bearing technology, Air Foil Bearings (AFB) is a marvel that allows for operation at both incredibly low and high temperatures without fail. Their minimalistic design eliminates the requirement for lubrication and sealing systems, making them not only more efficient but also more eco-friendly. When it comes to speed, these bearings give no quarter - they can handle even the most extreme of conditions with ease. Air foil bearings rely on the structural design of top and bump foils to support and distribute pressure in the air film. To increase bearing capacity, these foils must be thick enough to withstand greater force. It is crucial to explore how varying foil thickness and bump height-pitch ratios may affect the performance of an air foil bearing. The researchers at the ANSYS Fluent lab set out to understand the dynamics of air foil bearings. By adjusting the thickness of the top and bump foils, they were able to observe how stress, stiffness, and air film clearance changed in relation to each other. Their results showed that even minor changes in foil thickness, bump height, and bump pitch had a significant impact on bearing performance. With their discoveries, these engineers have unlocked a new understanding of this complex technology - one that will help guide its continued development into the future. The thickness of the foil may not confer much strength, but it certainly does wonders for reducing stress and maintaining load-bearing capabilities. Its suppleness, however, cannot be denied – a boon for air foil bearings.

Keywords: Bump foil, Foil thickness, Minimum air film thickness, Top foil, Unit stiffness

Introduction

An AFB is a bearing that operates without the use of oil due to air operation. The absence of friction-induced wear, heat generation, and lubrication requirements is one of the main advantages of air bearings. Air bearings are faster than ball or roller bearings when there are no re circulating components involved. The plane elastic circular top foil, the corrugated visco-elastic compliance bump foil (which is the opposite of stiffness), and the sleeve are the three basic components of an air foil bearing. The top foil is smoother and typically more elastic than the bump foil which encircles the object. The smooth top foil is supported by the corrugated bump foil, which also gives the bearing structural rigidity and damping.[1,2] It falls within the category of journal bearing. Instead of lubricating oil, a thin film (between 35 and 70 microns thick) of gas or air creates a frictionless connection between the top foil and the rotating rotor in this non-contact bearing.[3] According to their fundamental foil shapes, AFB are classified as elastically sustained leaf type and bump type AFB. Foil bearings are either aerostatic (externally pressurized) or aerodynamic (self-acting), or a mix of the two.[4,5] Among these three bearings, the aerodynamic air foil bearing has the lowest running cost maintenance cost. The AFBs are also classified into three distinct positions based on structural stiffness changes in the axial and circumferential axes.[6] Foil bearings are further divided based on load direction as thrust and radial air foil bearings. AFB is the pertinent bearing for use in lightly loaded small or midsize turbo-machineries at very low or high temperatures and at very high speeds (> 60,000 rpm). It doesn't require an oil lubrication circuit or a seal. It is less complex and more ecologically friendly. There are various advantages to using an air foil bearing over other types of rotor support journal bearings. The most essential characteristics of AFBs are i) increased dependability, ii) improved misalignment tolerance, iii) getting rid of the lubrication system, and iv) the ability to operate at very high and low temperatures. Low load-bearing capacity and rotor damage from overloading and beginning operations are the two primary drawbacks of air foil bearings.

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In the year 1953, Blok & Rossum established the basic concept of AFB.[7] The AFBs have advanced significantly during the last 30 years. Since then, several researchers have contributed to the advancement of foil bearing. In his article, Agarwal summarized the sequential progress of foil air bearings over the past fifty years, in which they learnt the basic theory of AFBs, their application, and future improvements as well as the types of patterns that are currently being employed with air foil bearings as well as their relative merits and demerits.[8] Air-foil bearings will benefit greatly from the findings of this comparative study. A hypothetical model of air foil bearing was developed by Ku and Heshmat by describing the corrugated bump foil strip deformation.[9] Heshmat *et al.* investigated the AFBs with bump foils for the first time and incorporated the static load performance of aero bearings.[10] A model of air foil bearing has been developed by Zeszotek & Braun, in order to take into account the correlation between the flow of the deflection of the foil and the working fluid.[11] A method of iteration was used to solve Reynold's equation. Dellacorte & Valco provide a concise strategy for exploring the dynamics of an AFB set on an elastic backing.[12] The researchers employed the Navier-Stokes equation (time-reliant) to analyze the interaction between (i) the journal's motion, (ii) the hydrodynamic impacts of the film of air, and (iii) the deformable foil edge. Formulating a finite element model has been used to describe the resilient properties of the top and bump foils. An air foil bearing is capable of withstanding a load based on simple thumb rules established by Kumar & Kim[13]. The Validation of these thumb rules has been conducted using foil bearings from all three generations. Langlois proposed a more sophisticated and incredibly effective design of the air hydrostatic foil bearings compared to their previous model.[14] In order to estimate the load-carrying capacity of air foil bearings at higher velocities, they built the most modern experimental setup. At low speeds, they also offer efficient hydrostatic levitation while retaining a higher capability to carry the load. Radil *et al.* observed that the coefficient of load capacity of AFBs is impacted by removing air film.[15] Radil & Dellacorte first proposed a 3D power loss effective map for foil bearings by means of a function of speed and load.[16] As a result of investigational outcomes, Arora *et al*. assessed the damping and stiffness of radial air foil bearings.[17] Nielsen and Santos developed a multiphysics model of an AFB incorporated with the partially supported top foil and considering the large sagging effect of the bump foil. The model predicts that the bump foil will cause the top foil to sag, resulting in a decrease in lift.[18] Samanta *et al*. explained a modern analysis of the advancement of the foil bearing technology.[19] Larsen *et al*. found a good relationship between the number of bumps and the stiffness off oil bearing.[20]

As previously noted, numerous computational and experimental investigations have been done to address the features of air foil bearing. According to our knowledge, very few researchers have reported on the relationship between foil thickness, load-bearing capacity, stress generation, and stiffness of air bearing. The study explains how the performance of an aerodynamic air foil changes with the thickness of both the bump and top foils. The different thicknesses of top and bump foils are created in Solid Works and simulated using ANSYS Fluent, which is one of the most popular CFD software. This study can give designers the opportunity to make incredible progress through innovation and also provide the most confidence in results. As pressures to optimize products increase and margins for error become narrower, CFD software is becoming more essential for engineers.

Materials and Methods

When the shaft is stationary, the dead weight between the bearing and the shaft is less. This is because the revolution of the rotor creates a pressure of hydrodynamic in nature across the rotor and the upper foil of the said bearing. It pushes the upper foils to place away from the rotor. As a result, the rotor is fully supported by gas or air. This will occur instantaneously upon start-up, at speeds ranging from 4–5% of the rotor's maximum revolving speed (as seen in a foil-bearing test rig by MiTi). When the shaft is airborne, the frictional loss caused by rotor rotation is significantly reduced. The foils are pushed farther away as the rotor speed increases up to a particular limit. Because of their relative motions, the foils produce coulomb damping. This dampening is critical for the bearing shaft's stability. In terms of operation, airfoil bearings are quite similar to oil-lubricated journal bearings. The top film and the spinning shaft are separated by a thin high-pressure self-generated zone of air film, similar to other hydrodynamic bearings that carry the rotor load. This high-pressure air congregates in the route of rotation because of creating the relative motion between the top film and the rotating rotor. The bearing-load limit of AFBs is primarily determined by the size of the converging zone, the form of the clearance gap and the relative surface speed between the shaft and top foil, the lubricant's viscosity, and the stiffness of the support assemblage. Air is commonly used as a lubricant for air foil bearings (argon, CO_2, and other gases can also be used as lubricants). A foil bearing's distinguishing characteristic is its compliant functioning surface. Depending on the load, thermal deformations, fluctuating speed, etc., this surface changes its profile. By virtue of this compliance, the bearing is able to accommodate misalignment as well as heat evolution levels that would otherwise result in the destruction of the stiff surface of an air foil bearing. Bump films act as structural stiffeners and dampers by transferring the stresses generated by air films between top films and rotors. The bumps deform or flex due to this action and provide Coulomb damping for the bearing.

Construction of AFB

One of the key considerations for the entire foil bearing function is the material selection for the top foil and bump foil. Because of its self-lubricating feature and high mechanical strength, the bump and top foils in this article are made of the nickel-chromium-based alloy "INCONEL X-750." Because of its high strength at temperatures as high as 1300°F and resistance to corrosion and oxidation, the precipitation-hardened nickel-chromium alloy known as INCONEL X-750 is employed. The top and bump foils' and rotor's material characteristics could be found in Table 1. Although the drawback of air foil bearing is its relatively lower load-holding capacity. Its speed ranges from 60,000 rpm to 150,000 rpm which makes it appropriate for high-speed turbo-machinery operations, notably in microturbines. The foil bearing's "lift-off speed" is ultimately another key feature. In this regard, minimizing the lift-off speed is a key objective of air foil bearing designers.

Table 1 — Material properties of air foil bearing[12]

Properties of Material	Value
Free-fixed-end bump stiffness	0.876 MN/m
Material density	7830 Kg/ m3
Free-free end bump stiffness	0.256 MN/m
Rotor modulus of elasticity	193 GPa
Coefficient of friction	0.3
Bump modulus of elasticity, E	213 GPa
Poisson's ratio of foil material	0.29

Research Methods

A major factor in the deviation of the upper and lower film is the generated air pressure and its distribution between the upper film and the rotor. As the rotor turns, the top foil creates a geometry in the form of a tube. Due to this, the rotor is surrounded by a flat edge, which makes it less likely that the moving parts would break. A corrugated bump foil is an essential component of the construction of an air foil bearing. Among the three basic elements of bump foil, height, thickness, and pitch, these three components have a significant effect on the steady-state and transient response of the foil bearings. The dynamic action of the rotating rotor causes a thin film of compressed air to form between the revolving rotor and the top foil of an aerodynamic air foil bearing. The air film that develops at low shaft rpm is insufficient to float the rotor, hence there is no "lift-off" of the rotor. In this manner, the top foil and rotor make their initial contact. The rotor may circle without coming into contact with the top foil, though, due to its rapid speed and the air film that it produced. The thickness of the air film is crucial for air foil bearing. The rotor starts to rotate without any contact with the top foil as soon as the proper air film forms, which reduces start-up wear and tear. This indicates that the air layer thickness affects the load-bearing capacity. Not all radial tracks have the same air film thickness; it is maximal in the low-pressure zone and minimal in the loaded and high-pressure areas. Therefore, one of the important considerations while designing air foil bearings is the minimal air film thickness. To effectively support loads and reduce start-up wear, an air foil bearing must generate a minimum air film thickness quickly and satisfactorily. The three main elements that greatly affect the operation of the AFBs along with the transient and steady-state responses are the bump foil's shape, thickness, and pitch. Researchers may easily estimate the single bump foil stiffness (K) of AFBs using Timoshenko's simply supported beam theory.[17] The equation of stiffness is,

$$K=\frac{E t_B}{2s(1-\mu^2)l^3} \quad \ldots (1)$$

Here, the bump foil's pitch is indicated by s, the thickness of the bump foil is shown by t_B, the Poisson's ratio is indicated by μ, and E signifies the bump foil's material's elastic modulus. The film clearance of air is affected by the bearing load, rotor speed, thickness and stiffness of the bump and top foils, compliance characteristics, and the coefficient of friction adjacent to bump and top foils, top foil and rotor, and bump foil and bearing sleeve. The stiffness of the system is in turn based on the structural properties of the bump foil (ratio between bump height and bump pitch). To determine the results of the bearing capacity and air film thickness, the film thickness is varied. SolidWorks software is used to model a film bearing in this work. At first, five separate air-foil bearing models are created in SolidWorks using foils that have five different thicknesses (160, 140, 120, 100, and 80 μm). Both bump and top foils are taken at the same thickness. The dimensions of the bearing parameters are listed in Table 2. Utilizing the FLUENT tool of ANSYS WorkBanch16, these five designs of air foil bearing are investigated. For CFD analysis, ANSYS WorkBanch16 is utilized to do the fine meshing of the whole assembly of an air foil bearing model. Researchers determine the clearance volume between the rotor and top foil in the CFD study after determining the output and input sections of the airflow in the models of air foil bearing. The rotor speed limit is specified as 80 Krpm, and the fluid characteristics of air are chosen from the record of options in ANSYS version-WorkBanch16. The velocity at which the pressurized film of air develops is known as the lift-off speed; at this point, the top foil and the rotor are not in touch as the rotor begins to revolve in the air film (airborne). Before the lift-off velocity, both the friction between the top foil and rotor and the bearing drag torque are greater. The torque rapidly decreases as it approaches lift-off speed.[15] In Fig. 1, the stress analysis is presented.

Table 2 — Measurement of the bearing parameters

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

Results and Discussion

The thicknesses of the top foil and bump foil are particularly essential when building air foil bearings. Five alternative air foil bearing models of various possible foil thicknesses (80, 100, 120, 140, and 160 m) are used for CFD study in ANSYS Varsion-Workbench 16. At different foil thicknesses, it is observed that the minimum air film thickness changes with rotor speed. In Fig. 2 the rotor speed vs minimal air film thickness for the five distinct versions of an AFB at varying foil thicknesses are depicted. The thicknesses of the top foil and bump foil are particularly essential when developing AFBs. In five alternative AFB models of various possible foil thicknesses (80, 100, 120, 140 m, and when zero rotor speed is present), the least film thickness of air is likewise zero, i.e., the top foil and rotor come into contact in the leading segment with no air gap. The growing speed of the rotor generates hydrodynamic pressure, which pulls the foils apart from the rotor and also leads the rotor to become completely

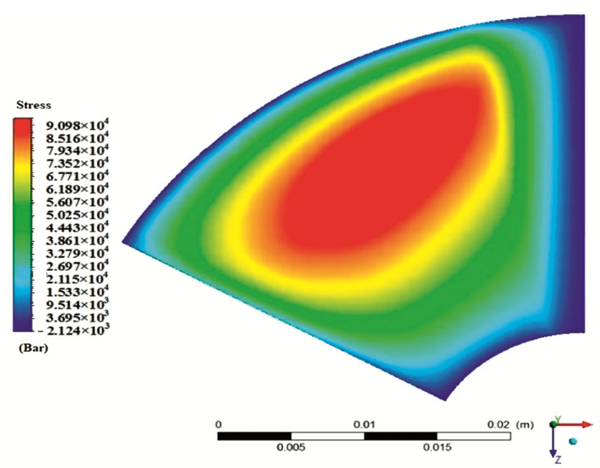

Fig. 1 — Stress analysis of top foil

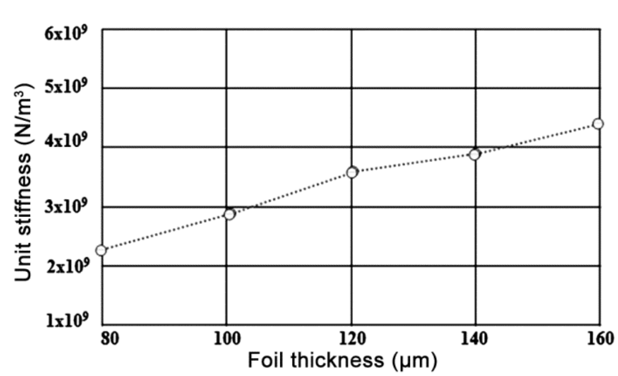

Fig. 2 — CFD analysis was employed to investigate the air film generated in an a/f bearing

airborne/gas. This lift-off trend occurs immediately upon start-up, with speeds ranging from 4 to 5% of the rotor's maximum spinning speed. The static load is held constant at 400 N in these studies, and a constant pressure profile is used. The minimal air film thicknesses at each rotor speed are greater at a foil thickness of 80 µm, as can be shown in Table 3. However, 160 µm thick foil produces the worst results. The shortest possible film thicknesses of air in AFBs are typically between 35 and 70 µm. As the rotor spun faster, the thin film of air that separated it from its surface grew thinner and thinner. The foil's thickness decreased as the air layer became more ephemeral, a transparent veil between them. The rotor lift-off velocity also propels the rotor into the air before the anticipated minimum air film thickness occurs. The air enters the sleeve perimeter through a few of the incredibly small holes and leaves tangentially through the other holes. As a result, the pressure is lower along the edges and highest in the middle. Air drift is always coming in and going out. An airbed in compressed is created between the rotor and the top foil by the rushing air. As a result, the rotor will be in the air and there will be very little friction between the top layer and the rotor. Therefore, the rotor speed of the air foil bearing has no theoretical upper limit.

Impact of Foil Thickness on Stiffness

As the foil thickness grows, so does the system's stiffness. Smooth compliance top foils are often more elastic than bump foils. This bump foil offers dampening and structural rigidity to the bearing while supporting the upper foil. The bump foil also compensates for shaft expansions and misalignments. The graph of the unit thickness of the bearing to the foil thickness is shown in Fig. 2

Effect of Stresses on Top Foil

The same techniques are used in the aforementioned five models of various foil thicknesses in ANSYS Workbench-16 to conduct investigations of stress, strain, strain energy, and deformation. Two picks of crumpled bump foil are sandwiched between the thin top foil, which sags. From the graph, it can be seen that the tension produced at various rotor speeds is lower for 160 m of foil thickness. But when it comes to foil thickness, 80 m produces the worst outcome. It is evident from Fig. 3 that as foil thickness increases, the amount of tension created decreases.

Table 3 — Variation of minimum air film clearance (µm) w.r.t rotor speeds for various foil thicknesses

Rotor speed	Different foil thickness (µm)				
(Krpm)	80	100	120	140	160
10	5.59	4.12	3.19	2.85	2.17
20	15.56	13.54	10.18	9.63	8.42
30	22.35	20.17	18.95	15.12	14.25
40	35.89	33.12	30.15	28.78	27.05
50	51.23	49.21	47.03	45.87	43.01
60	68.18	60.45	58.58	55.04	50.24

Validation and Reliability

The analytical results are verified using some information from a prior significant thesis and with some common data, and its validity is discussed. With the use of data from Ruscitto *et al*. and Kumar *et al*. the rate of the least feasible film clearance of air vs 120 m of rotor speed thick foil is confirmed.[6] The analytical values are found to be closer to the expected curves in Fig. 4. The rotor must rotate smoothly and aloft with a minimum air film thickness of 35 to 70 micrometers. The analytical findings fall within the specified range

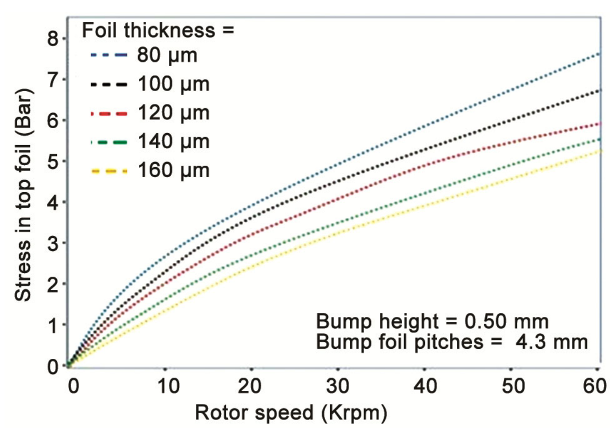

Fig. 3 — Deviation of stress in top foil against rotor speed

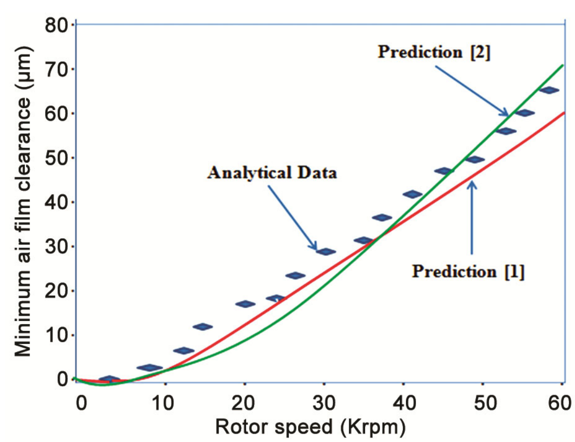

Fig. 4 — Confirmation of minimum air film thickness with the prediction

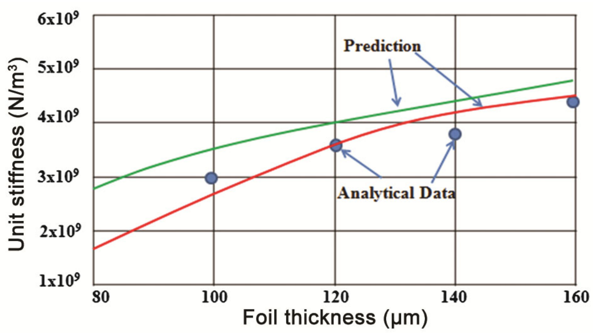

Fig. 5 — The unit stiffness verification by testing the thickness of its foil

as well. The validity of the values will thus soon be taken into account. The unit stiffness of the foils similarly raises the foil thicknesses. Additionally, the data of Ruscitto *et al.* and Kumar *et al.* are used to confirm the unit stiffness data. It has been discovered that the stiffness values in Fig. 5 provide virtually trustworthy results and are slightly close to the projected curve.

Conclusions

The top and bump foil thicknesses have been discovered to have an important influence on the design of an AFB. The stresses that occur on air-film thickness, foils, system stiffness, lift-off speed, and load-bearing capacity are all affected by the thickness of the bump and top foils, as discussed above. Based on the observations and investigations, it is possible to deduce the following:

1. As the foil thickness decreases, the minimum air film thickness increases, and the load-bearing capability of the air foil bearing increases.
2. The air foil bearing system's unit stiffness diminishes with decreasing foil thickness, which is not a good sign for the stability of the bearing.
3. With continuous static load, the stresses formed on each foil rise with increasing rotor speed, and the stress caused in thinner foils is minimized, resulting in higher load-bearing capacity.

The drawbacks of air foil bearing are its low capacity for carrying loads as well as rotor and top foil deterioration from overloading, starting, and halting. To minimize these effects, coatings on foils and rotor and solid lubricants are being used nowadays and experiments are going on for further improvement of the coating.

References

1 Daejong K, Parametric studies on the static and dynamic performance of air foil bearings with different top foil geometries and bump stiffness distributions, *J Tribol*, **129(3)** (2006) 354–364.
2 Paouris L I, Pantelis G N & Dimitrios A Simulation of the static performance of air foil bearings using coupled finite element and computational fluid dynamics techniques, *J Eng Gas Turbine Power*, **136** (2013) 129–136.
3 Nalepa K, Paweł P & Grzegorz Z, Development of the foil bearing technology, *J Tech Sci*, **12** (2009) 229–240.
4 Qi S, Ho Y S, Haipeng G & Lie Y Theoretical prediction of the lift-off speed in aerodynamic compliant foil journal bearings, *J Struct Dyn*, **6** (2010) 175–188.
5 Walowit J A, Anno J N & Hamrock B J Modern developments in lubrication mechanics, *J Lubr Technol*, **99** (1977) 304–305.
6 Ruscitto D, Gray S & Mc Cormick J, Hydrodynamic air lubricated compliant surface bearing for an automotive gas turbine engine, *J Bearing Perf*, **2** (1978) 365–379.
7 Blok H & Van Rossum J J, The foil bearing – a new departure in hydrodynamic lubrication, *J Lubr Eng*, **9** (1953) 316–320.
8 Agrawal G L, Foil air/gas bearing technology — an overview, *J Aircr Eng Mar Turbomach*, **1** (1997) 145–159.
9 Ku Roger C P & Heshmat H, Compliant foil bearing structural stiffness analysis: theoretical model including strip and variable bump foil geometry, *J Tribol*, **114** (1992) 394–400.
10 Heshmat H, Walowit J A & Pinkus O, Analysis of gas-lubricated foil journal bearings, *J Lubr Technol*, **105** (1983) 647–655.
11 Zeszotek M & Braun M J, An experimental investigation into the temperature profile of a compliant foil air bearing, *Style Tribol Tran*, **47** (1992) 470–479.
12 Dellacorte C & Valco M J, Load capacity estimation of foil air journal bearings for oil-free turbo machinery applications, *J Tribol Trans*, **43** (2000) 795–801.
13 Kumar M & Kim D, Static performance of hydrostatic air bump foil bearing, *Tribol Int*, **43** (2010) 752–758.
14 W E Langlois, Iterative solution of finite width foil-bearing problems, *Comput Methods Appl Mech Eng*, **14** (1978) 249–258.
15 Radil K, Samuel H & Brian D, The role of radial clearance on the performance of foil air bearings, *Tribol Tran*, **45** (2002) 485–490.
16 Radil K C & Dellacorte C, A three-dimensional foil bearing performance map applied to oil-free turbomachinery, *Tribol Trans*, **53(3)** (2010) 771–778.
17 Arora V, Vander H & Boer A, Identification of dynamic properties of radial air-foil bearings, *Int J Mech Mater Design*, **6(2)** (2010) 305–318.
18 Nielsen B B & Santos I F, Transient and steady-state behaviour of elasto–aerodynamic air foil bearings, considering bump foil compliance and top foil inertia and flexibility: A numerical investigation, *Proc I Mech E Part J: J Eng Tribol*, **231** (2017) 1235–1253, doi:10.1177/13506501 17689985
19 Samanta P, Murmu N C & Khonsar M M, The evolution of foil bearing technology, *Tribol Int*, **135(2)** (2019) 305–323, doi.org/10.1016/j.triboint.2019.03.021
20 Larsen J S, Hansen A J T & Santos I F, Experimental and theoretical analysis of a rigid rotor supported by air foil bearings, *J Mech Ind*, **16(1)** (2015) 214–226.