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Predictions of Dynamic property for Gas Foil Bearings Based on Multi-physics Three-dimensional Model of Computer Aided Engineering Simulations

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Abstract **-** This paper introduces the dynamic characteristic analysis model of the bump type gas foil bearing. The analysis model is capable of analyzing the interaction between the components and the thin working fluid film based on fluid-structure interaction finite element method when the bearing is operating. In order to make it, researchers can analyze the effect of different bearing foil structure equivalent stiffnesses on bearing operating characteristics, such as the pressure and temperature distribution patterns in the working fluid film, stiffness and damping coefficient of the bearing, etc. The top and bump foils in the foil structure of bearing are modeled as an infinite number of Hookean springs attached to the stiff wall of the housing while the hydrodynamic pressure distributions exerting on the springs are modeled as gas film working in steady state lubrication condition. The complete three dimensional multiphysics model built by commercial computer-aided engineering package, which can do the calculation based on finite element method independently for the fluid and solid domain. After that, the model can transfer the analysis results to each other at the interface between those models to do the simulation until the system reaches a quasi-steady state. Some environment states of bearing during operation will be set as the boundary condition and input to the model. The results of the simulation model are in good agreement with the experimental results of published research papers. In order to verify the various operating characteristics of the bearings and compare the results with the analytical model in the future, an internal experimental test bench has been established also. That test bench has the ability to confirm the working characteristics of bearings at different speeds and bearing loads.

Keywords**:** transient analysis; computational fluid dynamics; fluid structure interaction multi-physics simulations; gas foil bearing.

1. Introduction

Gas foil bearings (GFBs) have been successfully applied to high-speed micro turbomachinery, such as: electric generators, turbochargers and rotor compressors in early years of this century already [1]. It not only can stabilize the shaft in relatively high efficiency during high-speed operation because the friction force is very small compared to traditional bearings but also can take the working fluid as lubrication from the environment directly. Therefore, the system using this kind of bearing does not need sealing and using any oily lubricants. These characteristics have made the GFBs become the most promising bearing technology in high rotational speed, relatively compact and highly efficient systems. Obviously, the main feature of GFBs is the compliant support structure, which can provide load capacity, operating stiffness and damping effect of bearing during shaft rotation. The top and bump foil are usually used as compliant structures (also called foil structure) in GFBs and the rotating shaft will drive the working fluid between the top foil and shaft surface by the shear stress in the thin working fluid film. As a result, the dynamic air pressure can generate the supporting force to support the rotor. Different configurations of the foil structure will affect the dynamic working characteristics of the bearing, such as: the pressure and temperature distribution in the thin film, stiffness and damping coefficient during certain working conditions, etc. Figure 1 illustrates the schematic and main components of a typical bump typed GFBs.

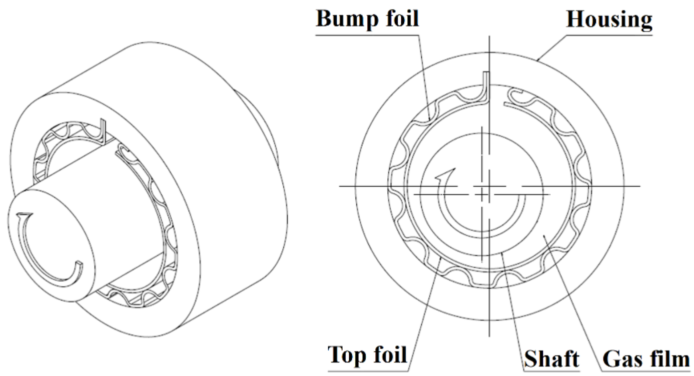

Fig. 1: Three dimensional projective and two dimensional schematic drawings of a bump-type GFBs; major components of GFBs include shaft, top foil, bump foil and support housing in which the clockwise arrow shows the shaft rotational direction.

Because of the growing importance of GFBs in micro-turbomachinery applications in recent years, many research results of that in various fields have also been reported. At the end of the last century, Ku and Heshmat proposed a theoretical model capable of analyzing the working property of GFBs with a compliant deformable structure [2]. In that analytical model, it considered the interaction forces of the bearing components during operation, such as: friction, shaft loading, and thin working fluid film shear stress etc. After that, Dellacorte and Valco presented empirical design guidelines that can assist designers in applying GFBs in turbomachinery [3] Based on the conclusion of the study, the load capacity of GFBs is proportional to the shaft rotational speed. In addition, that study also compared the effect of many other design factors on the bearing load capacity, such as: bearing configuration and size of bearing, etc. Peng and Carpino [4] analyze the damping coefficient and dynamic stiffness of the bearing during various shaft rotational speed based on ideal gas assumption. Peng and Khonsari [5] analyzed the thermohydrodynamic characteristics of a GFBs with shaft diameter 50 mm and the range of working rotational speed starting from 10 to 30 krpm with experimental verifications. Their results indicate that non-isothermal gas assumption gives less loading capacities. San Andrés and Kim [6] reported predictions on the top foil deformation and gas pressure distributions by own dimensional and two dimensional finite element method (FEM) of bearing when it's operating at 30 and 45 krpm. Carpino and Talmage [7, 8] developed a fluid structure interaction analysis model by FEM to predict the pressure and temperature field arrangement pattern and shaft position during bearing is working. After that, Song and Kim [9] presented a new elastic foil structure to build the GFBs and verified its working characteristics by experiment. Their analysis model considers the vibration pattern of the shaft to predict the working characteristics of GFBs. In addition, Kim [10] compared the working characteristics between single and three-pad foil structure GFBs. The results concluded that the bearing geometry and configuration significantly affect the dynamic characteristics of the shaft than the foil structure stiffness. Le Lez et al. introduced both static and dynamic methods to study the characteristics of the foil structure of GFBs, and presented an analysis model that considers the foil structure as a separate spring for predictions of the dynamic characteristics [11-14]. They employed the model for simulations of the imbalance response of GFBs with verifications by experimental data. Concerning the thermal conditions of GFBs, Dykas and Howard analyzed the thermal transfer phenomenon under light loadings and concluded that the dominant factor in the thermal conditions is the configuration of bearings [15]. Heshmat and coworkers studied various applications of GFBs working in extreme temperature environments [16-20].

2. The Basic Equations

Author could analyze the aerodynamic properties of the thin working fluid film between the shaft and the top foil surface based on the governing equation called Reynolds equation [21]. Based on the thin-film assumptions, the clearance of thin film is very small compared to the radius of the shaft. Therefore, researcher can neglect the curvature of the thin film in its circumferential direction. Please see Figure 2 for details. If the axes of the bearing hole and the shaft are parallel, the Reynolds equation can write in cylindrical coordinates as follows form:

$$\frac{1}{R^2}\frac{\partial}{\partial\theta}\left(\frac{\rho h^3}{\mu}\frac{\partial p}{\partial\theta}\right)+\frac{\partial}{\partial z}\left(\frac{\rho h^3}{\mu}\frac{\partial p}{\partial z}\right)=6\omega\frac{\partial(\rho h)}{\partial\theta}+12\frac{\partial(\rho h)}{\partial t} \tag{1}$$

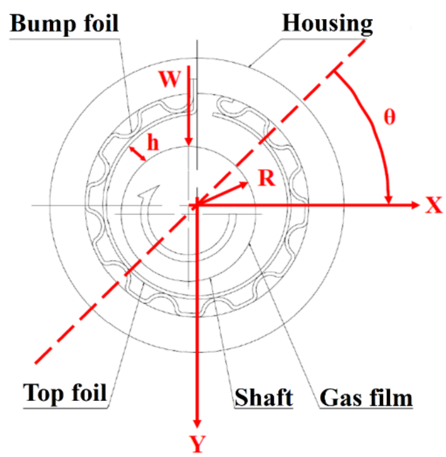

Fig. 1: Gas foil bearing representation.

3. The Comparison of the Result of Simulation Model and the Data of Published Paper

Before the simulation model can be used to do the analysis for GFBs operating characteristics, the FEM analysis model of fluid region needs to be verified first due to the support ability built from pressure charged in the thin gas film mainly. As a result, using the analysis model to do the simulation for a gas rigid bearing (GRBs) and compare the result with the data of published paper can assist researchers to verify the result of the simulation model can be used to study the bearing working performance. To achieve that goal, researchers build a three dimensional (3D) FEM simulation model to analyze the aerodynamic property in the thin gas film of bearing. The working fluid type, diameter, length, average clearance around the shaft, eccentricity, rotational speed and isothermal process assumed analysis temperature of the bearing analysis model is air, 38.1mm, 38.1mm, 50μm, 0.79, 30krpm, 25˚ C. The mesh type and the number of divisions of mesh along circumferential, radial, axial direction of the model is hexahedral, 360, 24 and 56. To save the analysis time, the analysis model is being set in symmetric on the middle face of the bearing. The pattern of how pressure arrangement from the result of simulation model please see Figure 3. Researcher also compare the result of simulation model with presented paper [22] and there is agree to published data well. The comparisons between published data and simulated result please see Figure 4.

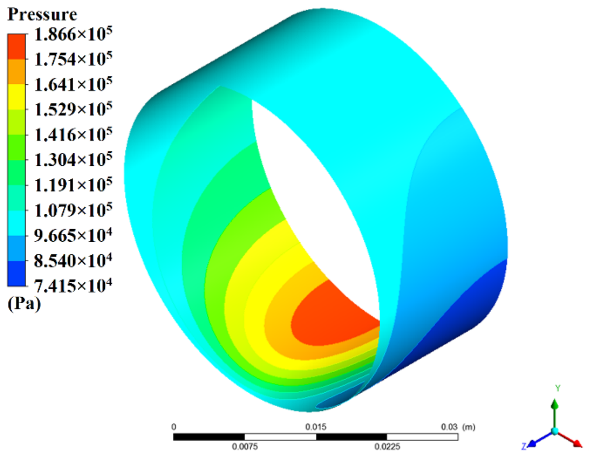

Fig. 3: Simulated pressure distribution on surface of shaft in gas rigid bearing operated at 30 krpm with eccentricity is 0.79.

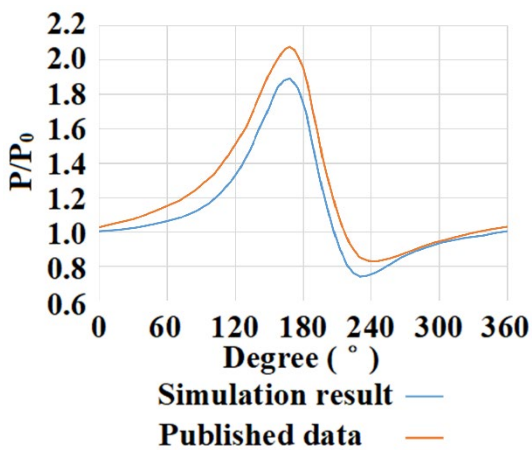

Fig. 4: Comparisons of gas film to ambient pressure ratio between published data and simulated result; the blue line is the simulated results and the orange line represents results previously published in reference [22].

4. Fluid-Structure Interactions Model

Because the working principle of the GFBs is based on the resultant force generated by the pressure distribution in thin air film between the rotating shaft and the top foil along the circumferential direction, it's worth noting that the center of the shaft must be in an offset position of the bearing hole to provide support force to balance the load of the shaft. In addition, when analyzing the working characteristic of the rotating shaft in the hole of GFBs, the final stable operating position of the rotating shaft will be defined by a factor called eccentricity. That parameter can describe the ratio of the distance between bearing center and shaft center to the working fluid film clearance of the bearing. Based on the above description, it is necessary to establish an analysis model based on fluid-structure interaction (FSI) multiphysics coupling method. Since a commercial computer aided engineering (CAE) package, namely copyrighted by Ansys Inc., USA, is now bonded with multi-physics simulation programs, this paper uses that program to solve the aerodynamic characteristic in the working fluid film and uses the elastic model to do the transient stress analysis for the foil structure based on the computational fluid dynamic (CFD) lubrication model. The purpose of this analytical model is to simulate the dynamic operating characteristics of a GFB with a given bearing specification by doing the transient analysis of bearing until the model reaches the quasi-steady state. Figure 5 illustrates three connected regions of different physical domains, where FSI is used for dynamic simulation of GFBs during the analysis process. In order to simulate the operation characteristic of GFBs, the 3D geometric and the mesh model of each component of bearing is established.

The shaft diameter and length are both 18 mm and the uniform working fluid thickness around the shaft is 14 μm is assumed when there is no load on the shaft. In the initial state during whole simulation process, the position of the shaft is assumed at the center of the bearing hole. The mesh type and the number of divisions of the mesh of shaft along the circumferential, radial, axial direction of the model is hexahedral, 36, 1 and 11. For foil structure is 36, 2 and 11. Table 1 lists the related parameters of simulation of GFBs in simulation model, with the environment conditions being set at 30 °C and 1 Bar (E-4 GPa). In the table, the equivalent stiffness of the homogeneous material assumed foil structure is set at 0.1 GPa and researcher defined that based on thin plate theory. The same method is adapted in bump-type foil equivalent structure calculation related working study published by Heshmat et al. also [23]. Additionally, that value of equivalent foil structural stiffness of bearing is used to do the simulation of GRBs performed by K. Feng and S. Kaneko [24]. The foil structure was made by a material with a Poisson ratio and Young's modulus of 0.3GPa and 214 GPa, respectively. Figure 6 shows the corresponding layout of the foil structure of bearing used in the simulation model of this paper. To do the analysis for the bearing during various working conditions to allow researcher can understand how bearing working, the outside surface around the foil structure can be set as fixed, the axis of shaft and the bearing hole will always parallel.

Table 1: List of parameters employed for the transient simulations of GFBs.

Parameter Definition	Parameter Values and Unit
Working fluid	Air (ideal gas model)
Initial Gas Film Pressure	1.0 (Bar)
Initial Gas Film Temperature	303 (K)
Environment Pressure	1.0 (Bar)
Environment Temperature	303 (K)
Foil Structure Stiffness	0.1 (GPa)
Shaft Rotational Speed	5, 5.5, 6, 7, 8, 9, 10, 15, 20 (krpm)
Heat transfer coefficient of surface of shaft and GFBs	100 ($W \cdot m^{-2} \cdot K^{-1}$)
Temperature of surface of shaft and foil structure	303 (K)
Shaft Load	5.0 (N)
Shaft Mass	0.5102 (kg)
Shaft diameter	18 (mm)

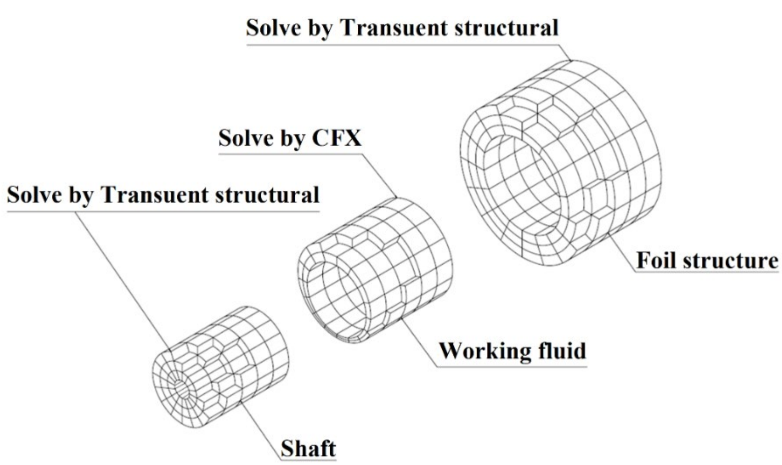

Fig. 5: 3D schematic drawings for showing the three connected regions of the physical domain employed for the GFBs simulations.

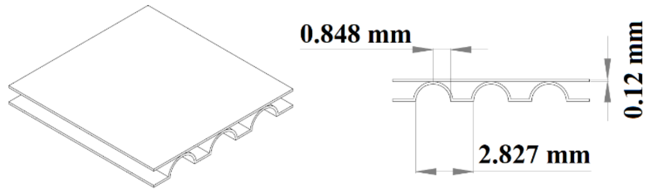

Fig. 6: Schematic of the measurements and the layout of the foil structure used in the GFBs simulation process.

The motion trajectory and position of the shaft will be fully analyzed in the simulation model from when it starts to move from the center of the bearing hole until it reaches a stable working position somewhere in the bearing hole. That phenomenon can be confirmed by observing that the trajectories of the shaft from the result of the model reach to the quasi-steady state. Therefore, researchers can understand the various characteristics of the bearing when it operates during different conditions, such as: aerodynamic state in working fluid gas film, eccentricity and the attitude angle in different working conditions. Figure 7 is showing the shaft displacement trajectory of the shaft during the whole analysis process within the different rotational speed. The final position of the shaft during difference rotational speed (7, 8, 9, 10, 15, 20 krpm) plotted in Figure 9. After that, Table 1 lists some parameters used in the simulation model, and the environmental conditions are set as 30 ˚ C and 1 bar.

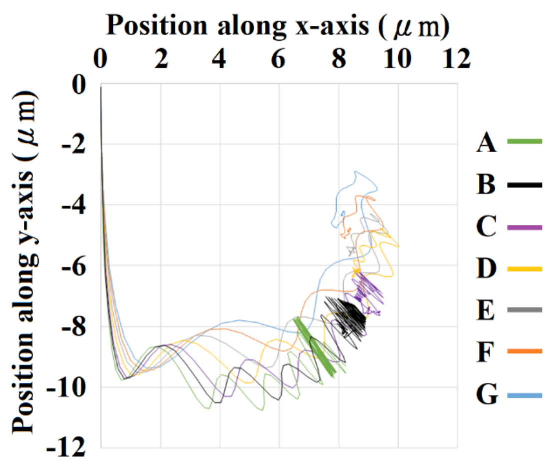

Fig. 7: Composite plots of transient position of shaft with various rotational speed; A represents 5, B represents 5.5, C represents 6, D represents 7, E represents 8, F represents 9, and G represents 10 krpm.

In order to operate the bearing system stably, it is very important to analyze the hydrodynamic characteristics of the working fluid film of the bearing during the design process. Theoretically, the distribution pattern of the pressure in the thin working gas film will affect the load capacity a lot. On the other hand, the working film temperature will affect the thermal management strategy of the bearing during operation also. The FSI simulation model based on FEM presented in this paper not only has the ability to analyze the structural deformation of the bearing but also can simulate the aerodynamic state of the working gas film of the bearing. As a result, researcher can estimate the performance of the bearing by doing the series analysis of the bearing. Figure 8 is showing the pressure and the temperature distribution pattern around the shaft of the bearing and deformation of foil structure surface during the rotational speed of shaft is 10 krpm when it reaches to the quasi-steady state.

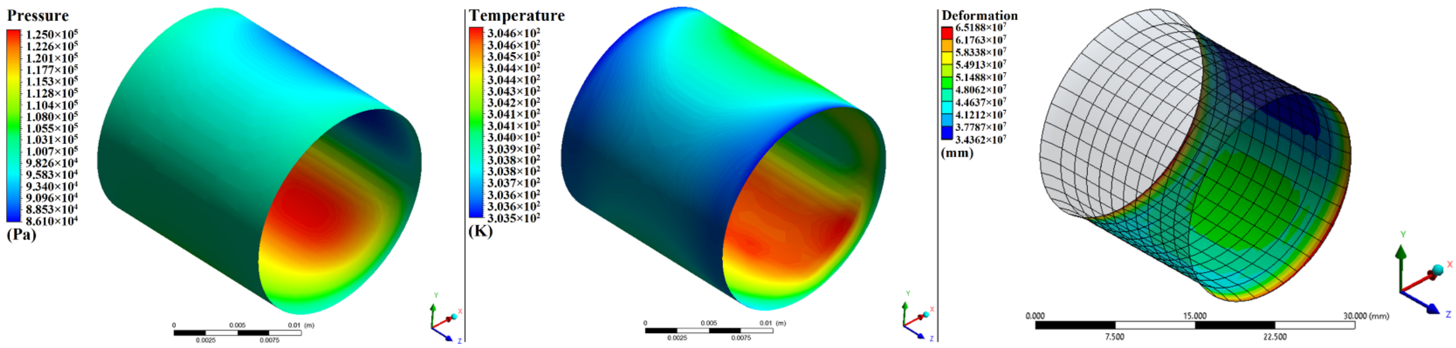

Fig. 8: Simulated pressure, temperature distribution on surface of shaft and the deformation distribution on surface of foil structure operated in gas foil bearing at 10 krpm with load of 5 N.

5. Simulation Results of GFBs in Various Working Conditions

Since the GFB is driven from standstill, dry friction force resists shaft rotation so it will cause relatively high torque. When a thin working gas film is formed between the rotating shaft and the bearing to create the supporting force to bear the rotating shaft, the rotating shaft will be lifted up and start to run stably. That phenomenon can be seen from the comparison of transient analysis process series during various rotational speeds in Fig. 7. As the rotational speed increases, the load capacity increases proportionally. As a result, the eccentricity of the shaft decreases. Before the rotation speed of the shaft isn't fast enough to create enough support force in the working gas film around the shaft to bear the shaft operating, the shaft will continue to vibrate somewhere in the bearing hole to increase support force. That phenomenon in the analysis model can be directly observed in Figure 7. The last part of the continuous moving path of the shaft solved by the transient analysis process during 5, 5.5, and 6 krpm all have that kind of phenomenon. Based on that, researchers can predict that the kicked off rotational speed of this bearing will be about 6 to 7kpm. After that, the bearing can create enough supporting force and damping effect to maintain the shaft operating stably. That phenomenon can also be directly observed in Figure 7 and Figure 9, such as: the transient analysis shaft moving paths during 7, 8, 9, 10 krpm. As the speed increases, the support force of the bearing will also increase and the eccentricity will decrease. Meanwhile, the attitude angle of the shaft will also change to adapt to different pressure distribution patterns. However, the attitude angle of the shaft will begin to change slightly after the rotational speed of the shaft reaches a certain value, such as: the final center position of the shaft during 7, 8, 9, 10, 15, 20 krpm. Related phenomena can be observed in Figure 10. It is noteworthy that after the rotational speed of shaft higher than 15 krpm, although the eccentricity of the bearing still decreases obviously but the attitude angle during operating just has a small change. Based on this phenomena, researchers can predict the working state of the shaft for higher shaft rotational speeds reasonably. That prediction of bearing working position during higher rotational speed please check the dashed red line in Figure 19 please.

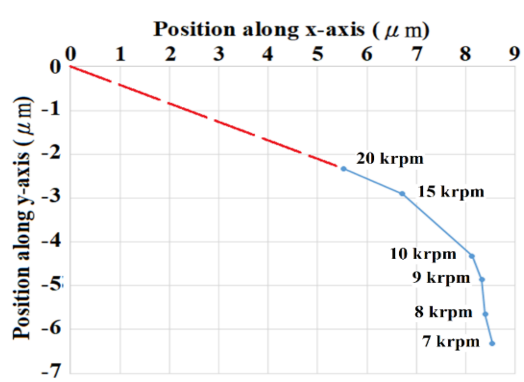

Fig. 9: Plots of final center position of the shaft during various working rotational speed. The dashed red line presents the final bearing working position during higher rotational speed.

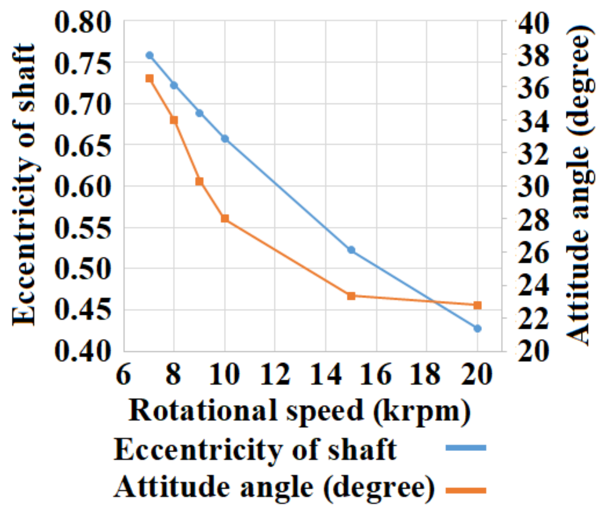

Fig. 10: Plots of eccentricity and attitude angle of the shaft during various working rotational speed.

6. Conclusions

An analysis model based on multiphysics 3D CAE simulation method is reported in this paper to estimate the start-up speed, operating characteristics and property of GFB. The model capable to analyze the working characteristic of bearing based on system coupling module of CFD and mechanical analysis, it will create a FSI model which can analyze the working gas film and foil structure by lubrication theory and homogeneous assumed elastic material model to assist designer to estimate the performance of the bearing within various working conditions. The commercial FEM program has been well developed in recent years in various research areas, the CAE package being adapted in this paper copyrighted by Ansys Inc., USA, is a program now bonded with multi-physics simulation function. To confirm the result of the analysis model, the comparison of the data of published papers and the simulation model has been confirmed also. Some critical design factors are included in the model, such as: environment pressure, temperature, heat dissipation conditions, rotational speed of shaft, foil structure stiffness and loading. Therefore, the working property can be observed by doing the transient analysis until it reaches the quasi-steady-state. Conclusively speaking, the proposed CAE method could help GFTB design engineers comprehend the dynamic performance of GFBs, and illustrates the possibility of implementation of GFBs into digital twin machine architectures.

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Nomenclature

The following nomenclature is used in this manuscript:

Abbreviations

3D	Three-dimensional
CAE	Computer aided engineering
CFD	Computational fluid dynamic
FEM	Finite element method
FSI	Fluid structure interaction
GFBs	Gas foil bearings
GRBs	Gas rigid bearings

Notation

h	Film thickness, m
p	Aerodynamic pressure, Pa
R	Bearing radius, m
t	Time, s
W	Static load, N
X,Y	Shaft center coordinates, m
z	Bearing axial coordinate, m
P	Working fluid pressure, Pa
P0	Ambient pressure, Pa

Greek symbols:

θ	Bearing angular coordinate, rad
μ	Dynamic viscosity, Pa-s
ρ	Lubricant density, kg/m^3
ω	Rotational speed, rad/s

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