

Recent progress on the structural styles of journal foil gas bearings

Guo-Ping Wang*, Shuang Cheng, Hua-Ning Hao

The High-Tech College of Xi'an University of Technology, Ziwu Road No.35,
Chang'an District, Xi'an, Shaanxi Province, P. R. China, 710109

*diaphragmcoupling@163.com

Abstract. With the rapid development of turbo-machinery, foil bearings became a very important type of high-tech mechanical components. Mechanical structure is one of the key influence factors on the progress of foil bearings. Different structure design characteristics of the bearings were described and compared by reviewing published results and patents. Future developments of the patents and models on foil journal bearings were presented to improve the current design structures. Finally, we know what will be done.

1. Introduction

With the development of aeronautics and power industries, gas turbine and other turbo-machinery have attracted much attention of researchers and engineers. Compliant foil journal bearings, supporting the rotor system of gas turbine, are concerned more and more due to its significant influences on the performance of gas turbine. In comparison with conventional rigid gas bearings, the main advantages of the bearing are as follows [1, 2, 3, 4, 5]:

- a). Lower power loss: because of thicker film the shear stresses in the fluid are lower.
- b). Misalignment accommodation: because of the elastic foundation.
- c). Good stability: good damping characteristics.
- d). Resistance of particles: the large film thickness and the compliance of the structure allow ingestion of foreign matter.

In comparison with conventional oil-lubricant self-acting bearing, there are additional advantages as [1]:

- a). Slight weight: devices providing pressure oil are useless.
- b). Higher speed: rigorous operated environment is no more a problem with the bearings.
- c). No pollution: the lubricant is usually air or nitrogen.
- d). Endurance of high temperature and low temperature: gas is lower sensitive to the temperature.

In general, a typical compliant foil journal gas bearing (figure 1. (a).) contains four parts: journal, top foil, bump foil, and housing, which is a self-acting aerodynamic bearing that generates the aerodynamic film by a high rotational speed of the journal plus a wedge clearance between the journal and the top foil. Journal and housing are both rigid metals, which may be coated with specific coating[1, 6] for specific functions, such as decreasing wear, resisting high temperature, and enhancing the damping characteristics. Top foil and bump foil are made of extensible metals, which provide an elastic support foundation with some specific coating or some stick-elastic material layers[7] in optimizing the frictional and damping characteristics and improving operational stability.



Bump foils are usually made into a continuous circular structure or in segments, which can provide an elastic foundation and avoid journal misalignment on bearing performance.

From the archival literatures, it is difficult to find a review paper of compliant foil journal gas bearing. In 1997, Giri, L. Agrawal[8] published a review paper that mainly aimed at application of foil bearing and described the various devices in use and their characteristics. However, it was out of date and need to be updated. This paper presents a full review of the patents and the structural style researches for compliant foil journal gas bearing, these may be useful for more and more scholars to recognize and study the bearings.

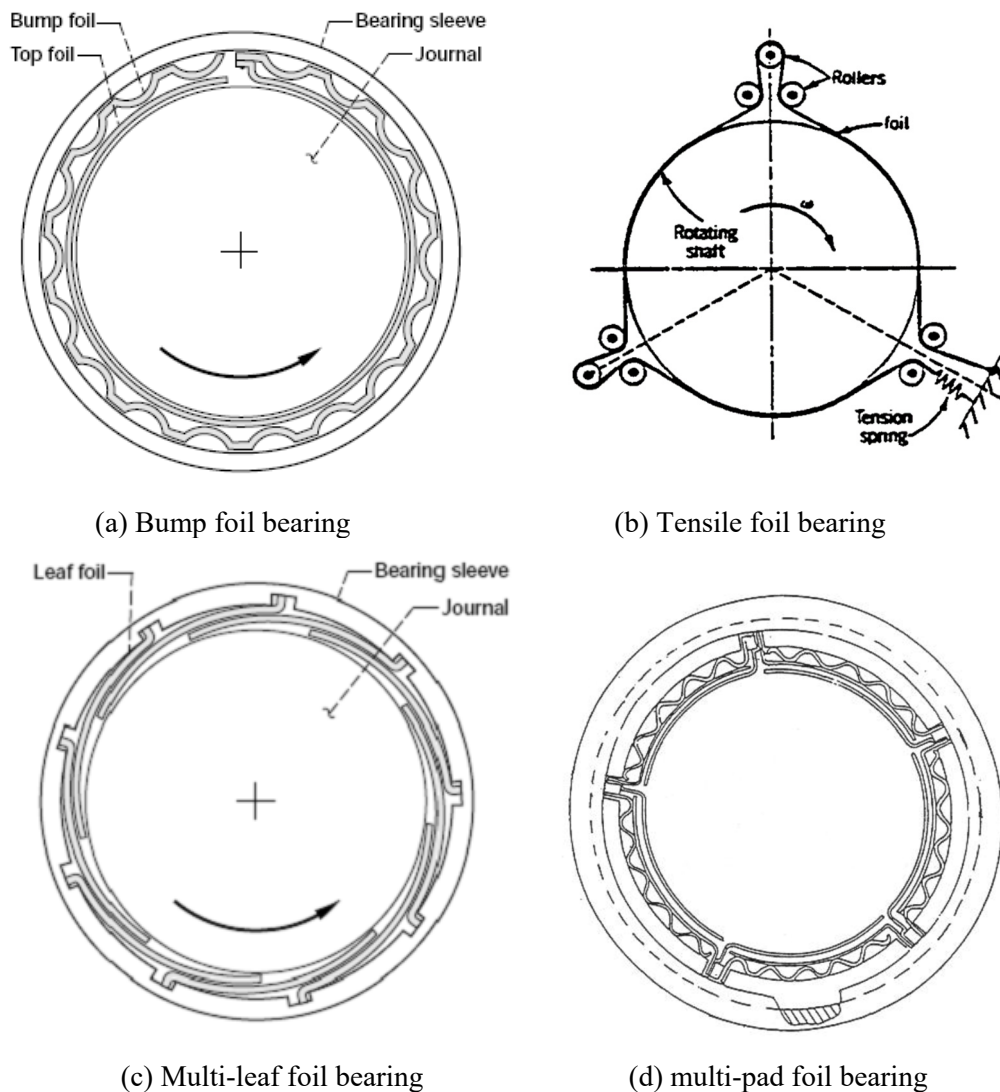


Figure 1. The first generation foil gas bearing

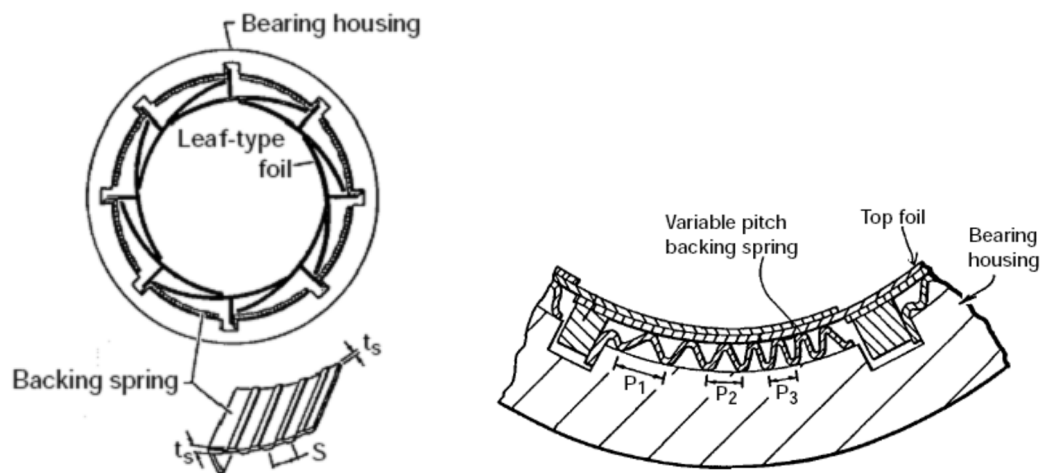
2. Variations of journal foil gas bearings' structure style

2.1. General description of structural characteristics

Since 1920s compliant foil journal gas bearing has been proposed firstly by A. A. Pollock in Thomson Houton Corporation in British. It wasn't concerned enough for a long time until 1953 when the bearing was studied by Bloc, H. and Van Rossom, J. J. on theoretical and testing aspects of the first time. It was improved to use in tape recorder devices, turbo-generator and other turbo-machinery successfully. Its structure schematic view is shown in figure 1. (b). The bearing comprises of several

cylindrical guide bars and a foil strip which wraps around the surface of the bars. The foil strip is fastened at one end and free at the other end. The free end will be enforced to make sure the generation of wedges between the journal and foil trip [3, 9, 10]. When the rotor speed is up to or exceeds a certain value, the hydrodynamic gas film will be produced to separate the journal with supporting structure. With large starting torque of the bearing and the limited strength of the foil, such foil bearing is easy to be fatigue failure.

A new structure of the foil gas bearing was developed in the late 1960s by Allied Signal Aerospace Corporation (ASAC) which was supported by NASA and the US military. It was used for high speed turbo-machinery, especially in aeronautics and aerospace, high speed rotating machinery, such as DC-10, Boeing 727, 757, 767 etc. [3, 8]. It was called a multi-leaf style foil bearing (figure 1. (c)). The configuration of such a bearing consists of a hollow cylinder, the inside of which contains a layer of thin, compliant, metallic, overlapping foils that wrap around the journal. Each overlapping foil is equally spaced within the housing and constructs a wedge between the leaf foil and the journal [9, 11, 12]. The overlapping foils act as springs, which deflect when loaded and the journal will be separated from leaf foils when the rotating speed of journal reaches the lifting speed.



(a) multi-leaf foil bearing with backing springs (b) The bump foil bearing

Figure 2. The second generation foil gas bearing

In the early 1970s, another kind of foil bearing was also realized, named as bump foil style foil bearing (figure 1. (a)) which was developed by Mohawk Innovative Technology Incorporation (MITI) supported by the US Department of Energy (USDOE) and National Aeronautics and Space Administration (NASA). It contains 360 degrees single tile style (figure 1. (a)) and multi-tile style (figure 1. (d)) [13, 14, 15]. In this paper all of the above bearings are named as the first generation foil gas bearing whose structure are essentially uniform in both the axial and circumferential directions. Obviously the structural stiffness of the bearing in circumferential, radial and axial direction is approximately uniform [1, 5]. They all have relatively simple structure, good damping characteristics and endurance for misalignment, but their load capacity limited their application. So more complicated foil gas bearings were presented, with more refined and appropriate design. It had variable pitch (variable stiffness) both in radial and circumferential directions, and was named as the second generation foil gas bearing (figure 2). Compared with the first generation multi-leaf foil bearing, the second generation (figure 2. (a)) just changed a little. Some additional backing springs with the same number as that of the leaf foils and are positioned between the foils and the bearing housing to increase the structural stiffness [16]. Spacer keys restrict the circumferential motion of the foil, while allowing it to move radially [12]. The second generation bumps foil bearings (figure 2. (b)) adopted

the multi bump strips and layers to achieve variable stiffness in radial and circumferential directions [1, 4, 17].

In the late 1990s, high load capacity foil bearings were found from some US patents [18, 19, 20]. Such kind of foil bearings has the characteristics of tailoring the foil support structure stiffness in axial, circumferential and radial directions. It was defined as the third generation foil bearing (figure 3). Its bump foils are split and staggered along the axis also with multilayer and variable pitch [1, 18]. According to the published literatures, this bearing has not been applied to the industry yet and just on the testing stage.

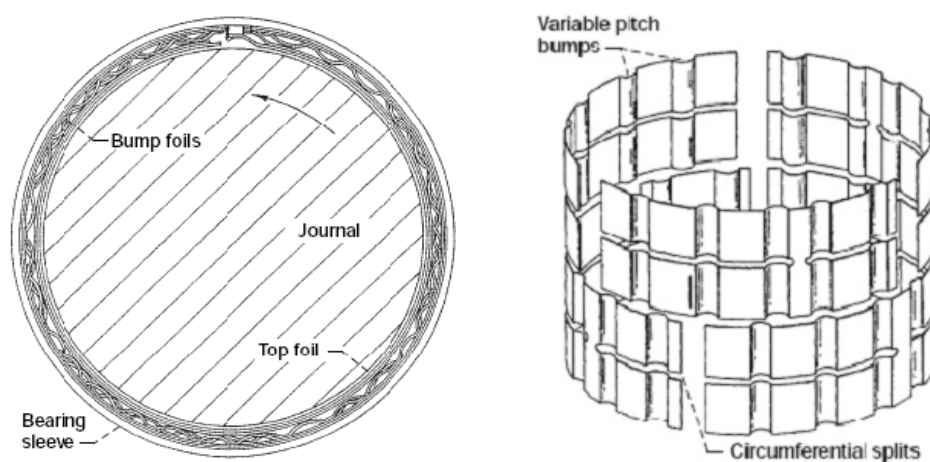


Figure 3. The third generation foil bearing

In recent years, 4th Generation compliant foil bearings are introduced on the website of MiTi (Mohawk Innovative Technology, Inc.)[21]. The net tells that the foil bearings have unlimited speed potential, high load carrying capacity, can operate under temperature extremes from cryogenic to 650°C, have a low power loss and long life, and are handmade to a high level of precision by skilled craftsmen in accordance with their rigorous engineering designs and uncompromising standards. The bump strips are custom designed to provide the correct amount of stiffness and damping for smooth operation, even when external vibrations occur. The bumps also allow the bearing to accommodate large shaft growth due to thermal or centrifugal effects. Bearing sizes range from 6 mm to 200 mm in diameter. Actually the 4th generation compliant foil bearings are developed for the micro gas turbine, their special merits are stronger wear-resisting and high temperature-resisting metal coating and preloaded assembly technology [6, 22, 23]. But there is no the next step researching literatures to be found.

2.2. Recent patents on foil journal gas bearings

Foil air bearings were first commercialized in the 1970s in air cycle machines used for aircraft cabin pressurization. Since then, new applications in cryogenic turbo-expanders, turbo-alternators, and turbochargers have been demonstrated [24]. Owing to the difficulty of modeling, the nonlinear coupling between the structure and gas fluid, and the complicated interactions among the elements of foil bearing, it relied on an experimental development sequence, and many new patents on the foil journal gas bearings were disclosed, which mainly aimed at improvements of the dynamic characteristics by designing the new structure. Besides wear-resistant coatings and hybrid bearings were also used.

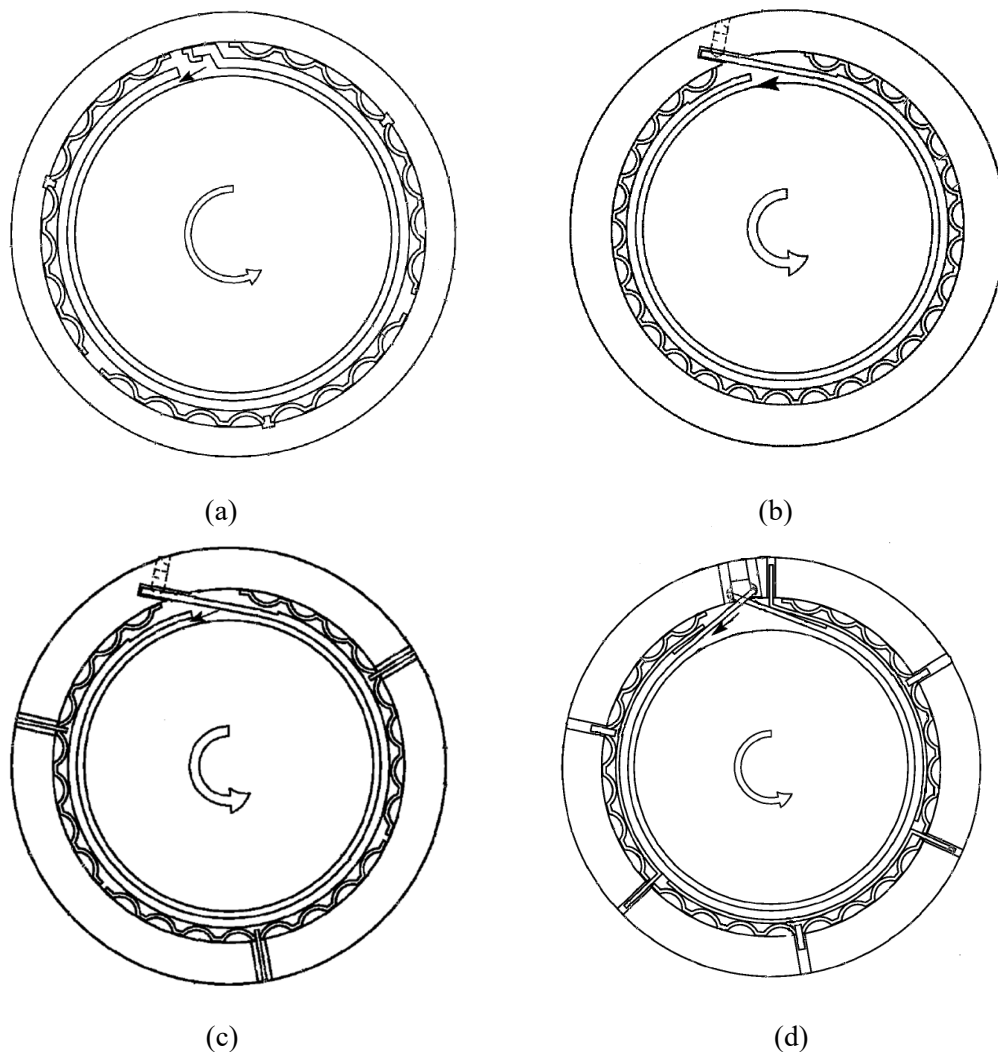


Figure 4. The newest structural styles I of the foil journal gas bearings

Influenced factors on dynamic characteristics of the foil bearings are the stiffness (load capacity) and damping. Structure style designs of the bump foil and top foil are crucial to improve the stiffness and damping capacity. So the improvement of structural style design is the leading development direction for the compliant foil bearings. Omori Naomichi [25-30] invented a series of radial foil bearings, as figure 4. The bearings structural variations are as follows: 1). The numbers, fixed styles or positions on the housing of bump foil pieces are adjusted; 2). Assembly method of the top foil is changed; 3). Multi top foil layers are used. In the figure 4, drawings (a), (c) and (d) have 3 bump foil pieces, and fixed points are located in the middle of the piece, so they have better uniform distribution of stiffness and stronger load capacity compared with the drawing (b); drawings (b), (c), (d) have the top foil without fold at the fixed end, won't bring irregular bend to affect up/down operation, can improve the dynamic characteristics. Drawing (d) has two top foil layers, it can enhance the load capacity and damping property notably. Yoshino Masato [31] designed foil gas bearing with a new top foil structure, as figure 5. The top foil can slide in a bigger scope to decrease the damping when the forces act on its surface. Kang Sun Goo [32] disclosed a patent to improve the system dynamic performances of the foil journal gas bearings. The author designed multi back bump foils and multi top foils (as figure 6). the stiffness and damping were improved well.

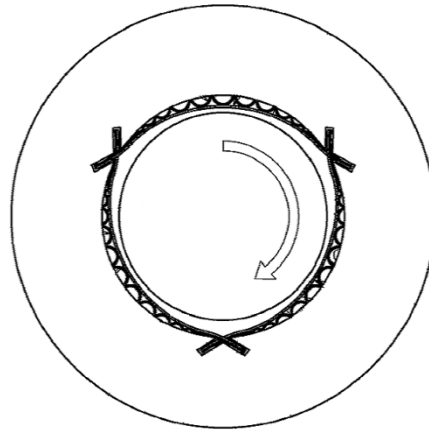


Figure 5. The newest structural styles II of the foil journal gas bearings

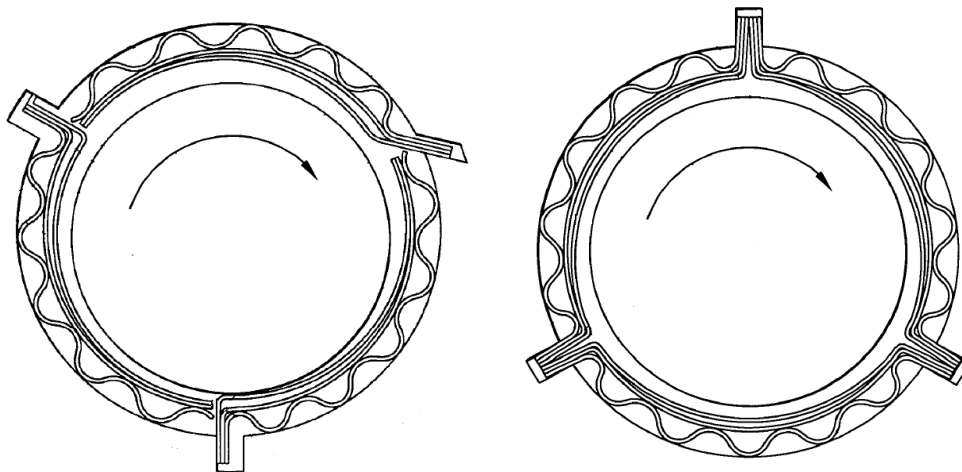


Figure 6. The newest structural styles III of the foil journal gas bearings

In the otherwise, increasing coating or spacer layer made of special materials into the foil bearing is also an effective method to improve dynamic characteristics. Adams, Robbie J. [33,34] presented two patents based on the 1st generation foil bearing (as figure 4. (a).). The author provided three structures: 1). Increasing a wear-resistant coating on the outside surface of the top foil; 2). Increasing two wear-resistant coating layers on the outside surface of the top foil; 3). Increasing one wear-resistant coating on the outside surface and inside surface of the top foil respectively. These structures are beneficial to the damping and endurance of high temperature. Rocchi Jerome[35] invented a foil journal gas bearing with a viscoelastic spacer layer between the housing and the bump foil. This measure also increased the damping and decreased the vibration.

As the difficulties of theoretical researches and dynamic characteristics estimations on the foil gas bearings, the strict requirements of the coating of the foil during startup and shutdown, hybrid bearing technology was studied and used to develop new products. The most representative patents [36,37] are hybrid foil-magnetic bearings. The hybrid bearing includes a magnetic bearing means, which comprise a stator wound with coils to create a magnetic field, and ferromagnetic lamination on the rotor to interact with the stator magnetic field to affect the movement of the rotor radially in the direction in which magnetic field applies force for movement of the rotor. The active magnetic control can solve the startup and the shutdown problem effectively. The magnetic force and elastic supporting force of the bump foil share the anti-force of the rotor, which can improve the load capacity of the foil bearing.

3. Current and future developments

From the prior research and development of the foil gas bearing to date, the foil gas bearings have experienced almost 60 years, lots of patents were disclosed, made a great of efforts to improve dynamic characteristics by designing new structures, using various coatings and some else technologies, and achieved a series of extremely important application in aeronautics, traffics, and power devices, such as air cycle machines for airplanes, engines for trains or ships, turbo machinery for power plants. All these applications rely on experimental and testing researches, the shortages of theoretical research have limited the more extensive applications and hindered the development of foil gas bearing. With the development of computational technology, CAD/CAE and additional advanced technology, solutions of the difficult problems for foil gas bearing became available. At present, people have made a great progress on a number of key problems, but it still falls behind the experimental researches far away, new parents still need to be developed to try on different designs, and there are still lots of work to do, which are:

- a). Due to the nonlinear characteristics of the bump foil structure, there have not been a uniform theoretical model.
- b). Almost no paper takes the inertial terms into account in the Reynolds equation no matter the speed of operation.
- c). Theoretically, the load capacity of foil gas bearing is not limited, so it's anticipated to improve the load capacity further, for example, improving the depositing technology of the coating may increase the load capacity.
- d). Reliable predictive performance methods and design guidelines are still hard nuts to crack.
- e). The innovation of the mechanical structure is still insufficient, it is anticipated that the new structure not only can improve dynamic characteristics but also be analyzed conveniently.
- f). hybrid bearing technology is expected to research in depth.

Acknowledgements

This work was financially supported by the Scientific Research Program of Shaanxi Provincial Education Department (Program No.17JK1022).

References

- [1] DellaCorte, C., Valco, M. J. Load capacity estimation of foil air journal bearings for oil-free turbomachinery applications. *Tribology Transactions* 2000; 43(4):795-801.
- [2] Walton II, J. F., Heshmat, H. Application of foil bearings to turbomachinery including vertical operation. *Journal of Engineering for Gas Turbines and Power* 2002; 124(4):1032-41.
- [3] Hou, Y., Wang, B. C., Xiong, L. Y., Wu, G., Ling, M. F., Chen, C. Z. Application of aerodynamic plate-foil journal bearing for cryogenic turboexpander. *Proceedings of the Conference on Cryogenics and Refrigeration*. Hangzhou, China, April, 1998.
- [4] Heshmat, H., Shapiro, W., Gray, S. Development of foil journal bearings for high load capacity and high speed whirl stability. *Transactions of the ASME Journal of Lubrication Technology* 1982; 104(2):149-56.
- [5] Heshmat, H., Walomit, J., Pinkus, O. Analysis of gas-lubricated compliant journal bearings. *ASME Journal of Lubrication Technology* 1983; 105:647-55.
- [6] NASA Glenn Research Center. Creating a turbomachinery revolution. Available at: <https://www.nasa.gov/centers/glenn/about/fs14grc.html> (Accessed on: February 10, 2017).
- [7] Y. B. Lee, T. H. Kim, C. H. Kim, N. S. Lee, D. H. Choi. Dynamic characteristics of a flexible rotor system supported by a viscoelastic foil bearing (VEFB). *Tribology International* 2004; 37(9):679-87.
- [8] Giri L. Agrawal. Foil air/gas bearing technology--an overview. *ASME International Gas Turbine and Aeroengine Congress and Exhibition*. New York, United states, 1997.
- [9] Keith A. Hurley. Experimental determination of the rotor dynamic coefficients of gas lubrication foil journal bearing. PhD Dissertation, The Pennsylvania State University,

Pennsylvania, United States, December 1998.

- [10] Jones, Allen M. Adjustable tension foil bearing. US4815864(1989).
- [11] Trippett Richard J. Variable preload foil bearing. US4445792(1984).
- [12] C. A. Heshmat, H. Heshmat. An Analysis of Gas-Lubricated, Multi-leaf foil journal bearings with backing springs. ASME Journal of Tribology 1995; 117(3):437-43.
- [13] Miller Jr., William H. Multi-pad compliant hydrodynamic journal bearing. US4229054(1980).
- [14] Heshmat Hooshang, Shapiro Wilbur. Compliant journal bearing with angular stiffness gradient. US4262975(1981).
- [15] Heshmat Hooshang, Shapiro Wilbur, Gray Stanley. High load, whirl free, foil journal bearing. US4465384(1984).
- [16] Silver Alexander, Wenban James R. Foil bearing. US4178046(1979).
- [17] Saville, Marshall P. Lee-van GU. Stepped foil journal foil bearing. WO011469(1992).
- [18] H. Heshmat. High load capacity compliant foil hydrodynamic journal bearing. US5988885 (1999).
- [19] Heshmat Hooshang. High load capacity compliant foil hydrodynamic journal bearing. US6158893(2000).
- [20] Kang Sun Goo, Saville Marshall. Hydrodynamic journal foil bearing system. US6964522(2005).
- [21] Mohawk Innovative Technology Inc. Introduction of 4th generation compliant foil bearings. Available at: <http://miti.cc/products/compliant-foil-bearings/> (Accessed on: February 10, 2017)
- [22] Geng Haipeng. Dynamics of an aerodynamic compliant foil bearing-rotor system. PhD Dissertation, Xi'an Jiaotong University, Xi'an, China, 2007(In Chinese).
- [23] Dellacorte C, Valco M. J. Load capacity estimation of foil air journal bearings for oil-free turbomachinery applications. STLE Tribology Transactions 2000; 43(4):795-801.
- [24] Walowit, J. A., Arno, J. N. Modern developments in lubrication mechanics. Applied Science Publishers Ltd: London, UK, 1975.
- [25] Omori Naomichi. Radial foil bearing. US20140169708(2014). -----46---→25
- [26] Omori Naomichi. Radial foil bearing. US20140241653(2014).
- [27] Omori Naomichi. Radial foil bearing. US9011008(2015).
- [28] Omori Naomichi. Radial foil bearing. US8944686(2015).
- [29] Omori Naomichi. Radial foil bearing. US20160010682(2016).
- [30] Omori Naomichi. Radial foil bearing. US20160348714(2016).
- [31] Yoshino Masato, Fujiwara Hiroki. Foil bearing. US20160265437(2016).
- [32] Kang Sun Goo, Saville Marshall, Hurley Keith A. Hydrodynamic journal bearing. US7553086(2009).
- [33] Adams Robbie J., Giesler William L., Takeuchi Don, Passman Eric. Wear resistant foil bearing assembly. US20090274401(2009).
- [34] Adams Robbie J., Giesler William L., Takeuchi Don, Passman Eric. Wear resistant foil bearing assembly. US7832933(2010).
- [35] Rocchi Jerome, Grau Gregory. Aerodynamic foil bearing. US20160369838(2016).
- [36] Scharrer, Joseph K. Magnetically active foil bearing. US5519274(1996)
- [37] Heshmat Hooshang, Walton II, James F. Hybrid foil-magnetic bearing with improved load sharing. US6965181(2005).