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Aerostatic Thrust Bearing with Small Feed Holes – An Overview

*Bivash Chakraborty[1], Prasun Chakraborti[2]
[1]Assistant Professor, Tripura Institute of Technology, Agartala, India
[2] Professor, National Institute of Technology, Agartala, India
**Corresponding author: bivashtit2008@gmail.com*

Abstract- *Aero-static thrust bearings are widely used in high precision conventional applications, e.g., in machine tools, measuring instruments, precise positioning systems, manufacturing and medical equipment. Their appeal is due to the absence of contact between moving and stationary parts, which ensures their low friction, limited heat generation and long life. Moreover, using air bearings usually does not contribute to environmental contamination. Among the various structural design parameters of an air foil bearing, top and bump foils are very much crucial as the generated pressure in the air film gets distributed by the full foil, and the corrugated compliant bump foil props up this top foil by providing damping and structural stiffness to the bearing assembly.This review paper aims to present the state-of-the-art aerostatic bearings research and development with the emphasis on analytical and computational approaches for design and optimisation of bearing performance and further critically review their future research directions and development trends in the coming decade and beyond. The paper is concluded with a discussion on the future trends and challenges in aerostatic bearings research and their applications and potential in precision engineering industries*.

Keywords- Rotor, Bump Foil. Air foil bearing, Top foil, Aerostatic.

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I. INTRODUCTION

Aerostatic bearings, employing a pressurized air film with thickness at the micrometer level to support moving parts and resist external loads, have achieved a considerable performance improvement in motion accuracy, friction, pollution and speed compared with precision rolling bearings. Hence, aerostatic bearings have been widely adopted in various industries, such as the textile industry [1], handing and packaging [2], electronics and semiconductors [3], metrology and ultra-precision machine tools [4], turbomachinery [5], machines for the food industry [6], and medical sector [7], etc. as illustrated in Fig. 1.Air foil bearing is air operated oil-free bearing. The three main parts of air foil bearing are smooth elastic encircling top foil, visco-elastic corrugated compliant (inverse of stiffness) bump foil and sleeve. The encircling top foil is smooth and more flexible than the bump foil. The corrugated bump foil provides backings to thesoft top foil and 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 revolving rotor instead of lubricating oil. Air foil bearing may be subcategorized as elastically supported bump type AFB and leaf type AFB according to their basic foil configurations. Foil bearing is generally aerodynamic (Self-acting), aerostatic (externally pressurized), or a hybrid of aerostatic and aerodynamic. Air foil bearings are also categorized into three generations based on the modification in the structural stiffness in the axial and circumferential directions [6].According to the load direction, foil bearing is further classified as radial and thrust air foil bearing.AFB is the best-suited bearing that can be 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 needan oil lubrication circuit and seal. It is more environmentally friendly and less complicated. The air foil bearing has several advantages over other conventional rotor support journal bearings. The essentialqualities of AFBs are i) enhanced reliability, ii) workingcapacity at very high and low temperatures, iii) elimination of lubrication system and iv) better tolerance to misalignment. The main disadvantages of air foil bearing are i) low load-bearing capacity and ii) the wear and tear of top foil and rotor during starting, stopping, and overloading [14,20].

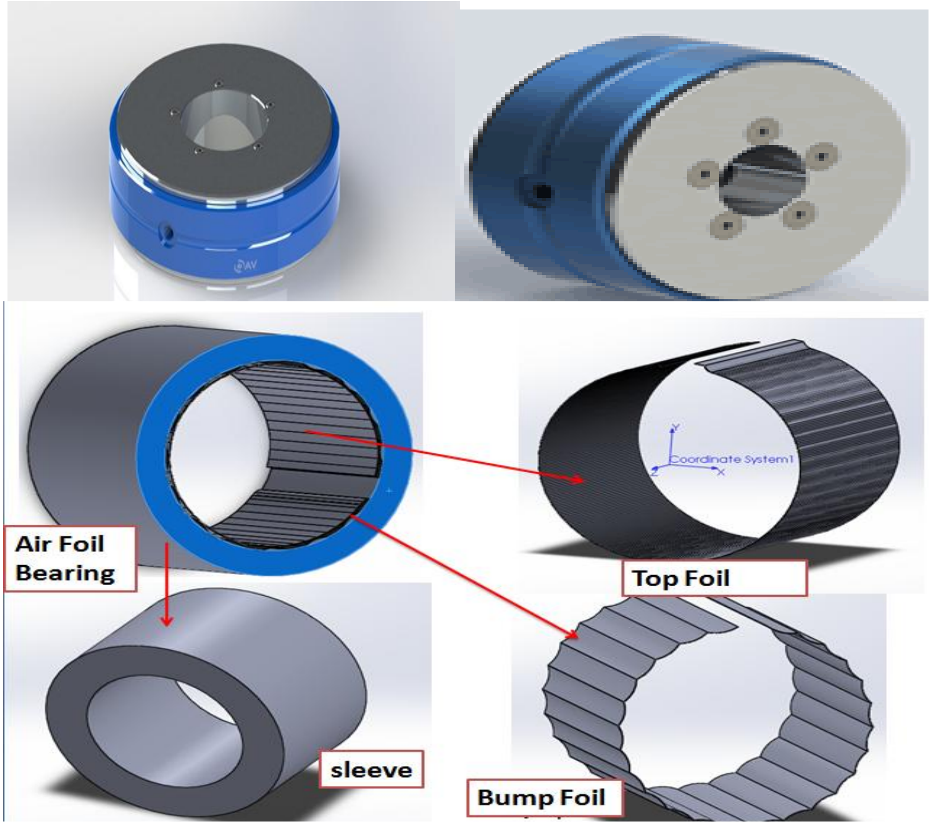

Fig. 1: Components of air foil bearing

The emergence of air lubrication technology dates back to 1828 when Willis [8] experimentally investigated the airflow status between two parallel plane surfaces. At the end of the 19th century, Kingsbury [9] investigated the supporting characteristics of an air journal bearing by experiment, which validated the feasibility of gas bearing. Then, many patents about gas bearing were issued in the early 1900s [10], such as the air thrust bearing designed by Westinghouse [11] in 1904 and the aerostatic journal bearing designed by Abbott [12,35] in 1916. However, in the following decades, only a few articles related to the basic principle of gas lubrication were published [13,33].

After the 1990s, the progressively increasing demands from scientific research and industrial development for the high-precision semiconductor wafer, precision optics components, precision moulds, micro parts, microstructures etc. Which stimulated the advance of ultra-precision machining technology, particularly ultra-precision machine tools. The demands for aerostatic bearings, one of the criticalcomponents for enabling ultra-precision machining, are also significantly increased. The design and development of high-performance air bearing have attracted increasing attention. (Fig. 2 b) lists the ranking of the top ten countries inair-bearing research. It can be seen that the United States, China, and Japan, et al. take the leading position. The top ten countries in gas bearing research also have high demands for ultra-precision equipment, which confirms that gas bearings are indispensable components in the field of ultra-precision equipment.

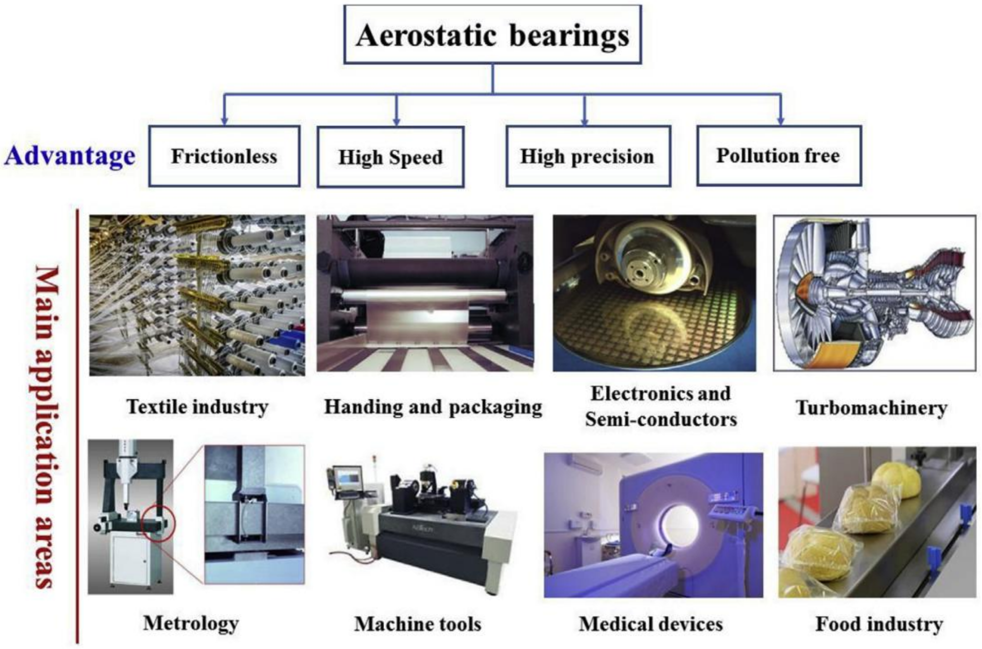

Fig. 2. Main advantages and application areas of aerostatic bearings.

II. STRUCTURAL CHARACTERISTICS OF AEROSTATIC BEARINGS

Aerostatic bearings are also named externally pressurised air bearings, considering that an external air supply system generates air film pressure. The pressurised air is fed into the gap between two bearing surfaces through a specific restrictor and then discharged to the surrounding ambient from the exit edges of bearing clearance. The thin film acts as the lubricant in the clearance between stationary and moving parts. During the working state, the moving and stationary surfaces of air bearing do not contact, not only avoiding many problems of conventional bearings, such as wear and friction but also offering distinct merits for precision positioning [28].

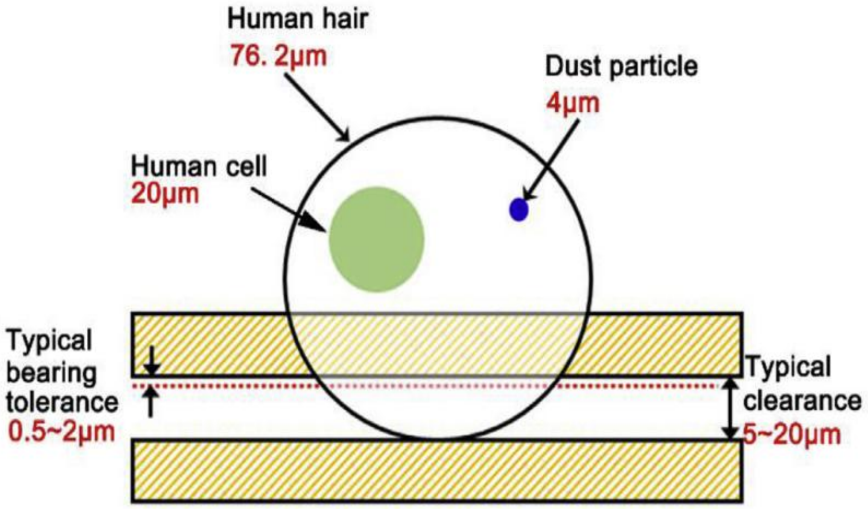

Fig. 3. Typical bearing clearance and tolerance compared with the size of human hair.

The gap must be small enough to ensure the pressure to obtain optimal aerostatic bearings' performance. Generally, a clearance of 5–20 μm is adopted. From Fig. 3, it can be noted that the gap is about 4–15 times smaller compared with the dimension of human hair. Considering the dust particle size is close to gap clearance, the air should be well filtered to ensure the bearing works appropriately. Moreover, sealing and cleaning of paths are critical to prevent contamination. In addition, the form error of the mating surfaces is generally required to be better than one-tenth of clearance height, which presents a challenge to the manufacturing capability. To reach this stringent form tolerance requirement for bearing surfaces with varying shapes, including planar surfaces, cylindrical surfaces, and spherical surfaces, precision machinery and methods are needed. Overall, the manufacturing and testing of air bearing have higher environmental requirements. Usually, clean and temperature-controlled environments and vibration-isolated platforms are required.

III. BASIC OPERATING PRINCIPLE OF AEROSTATIC BEARINGS

Take a thrust bearing with a pocket-type orifice restrictor to illustrate the basic operating principle of aerostatic approaches, as shown in Fig. 4. High-pressure air flows through the feed restrictor into the clearance. It then radiates to the edge of the air film, where it flows into the ambient environment. H0 is the initial clearance. As the air passes through the feed orifices and enters the clearance between two bearing surfaces, the pressure at the inlet of restrictor p_s falls to PD. Then the pressure gradually decreases to pa from the orifice exit to the bearing clearance outlet. The load capacity FW of the bearing at the initial state is equal to the weight of moving parts W. After a load F acting upon the path, the clearance decreases from h_0 to h_1.Minorsupport will reduce the drop of pressure through the restrictor. Therefore, the pressure p_d increases top$'_d$, giving a higher load capacity FW′ to balance external load F. Here, FW′ = W + F. A smaller clearance will lead to higher load capacity and vice versa.

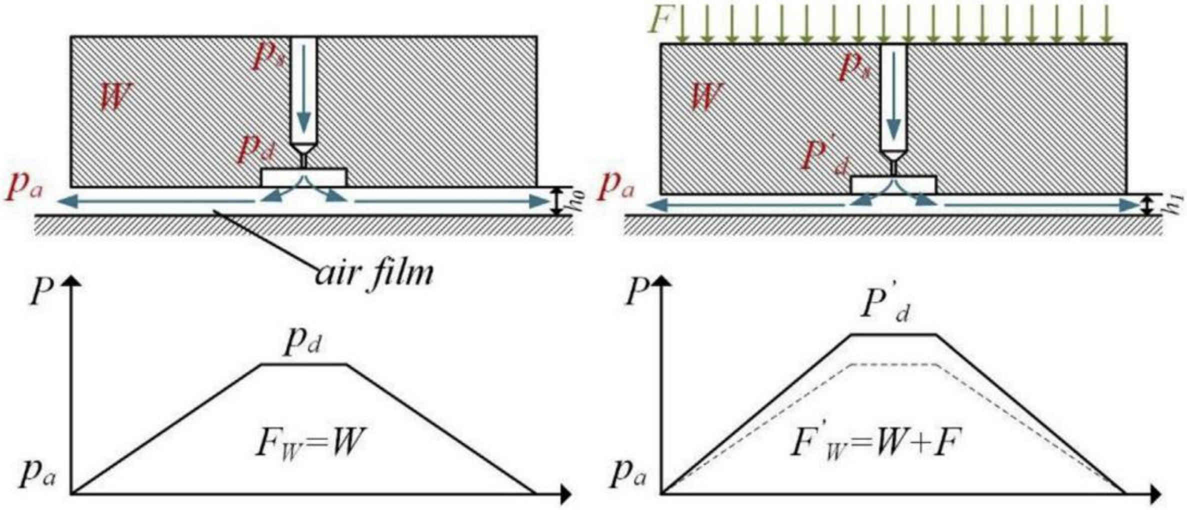

Fig. 4. Operating principle of aerostatic bearings

IV. ANNULAR ORIFICE AND SIMPLE ORIFICES

The most widely adopted restrictors are orifice restrictors because they are easy to manufacture, and plenty of design information is available to guide the design of this type of bearings. Orifice restrictors can be divided into two types [22,32], namely annular orifice (or inherently orifice type restrictor) and simple orifice (or pocketed orifice type restrictor); both are turbulent flow devices. The airflow passage area of the annular orifice restrictor is πdh. d is the orifice diameter, and h is air film thickness. A simple orifice restrictor could be acquired by manufacturing a small cylindrical recess with a depth larger than d/4 around the orifice. Using such a restrictor, the airflow passage area increases from πdh to πd2/4. It has been found that the performance of simple orifice-type bearing is about thirty per cent higher than that of bearing with an annular orifice restrictor [16,34]. However, due to the recess of a simple orifice restrictor, there is a large storage volume for air within the bearing, which negatively affects the stability of the path. Hence, the ways with simple orifice restrictors are more prone to instability, whereas the approach with the annular orifice is free from instability [17].

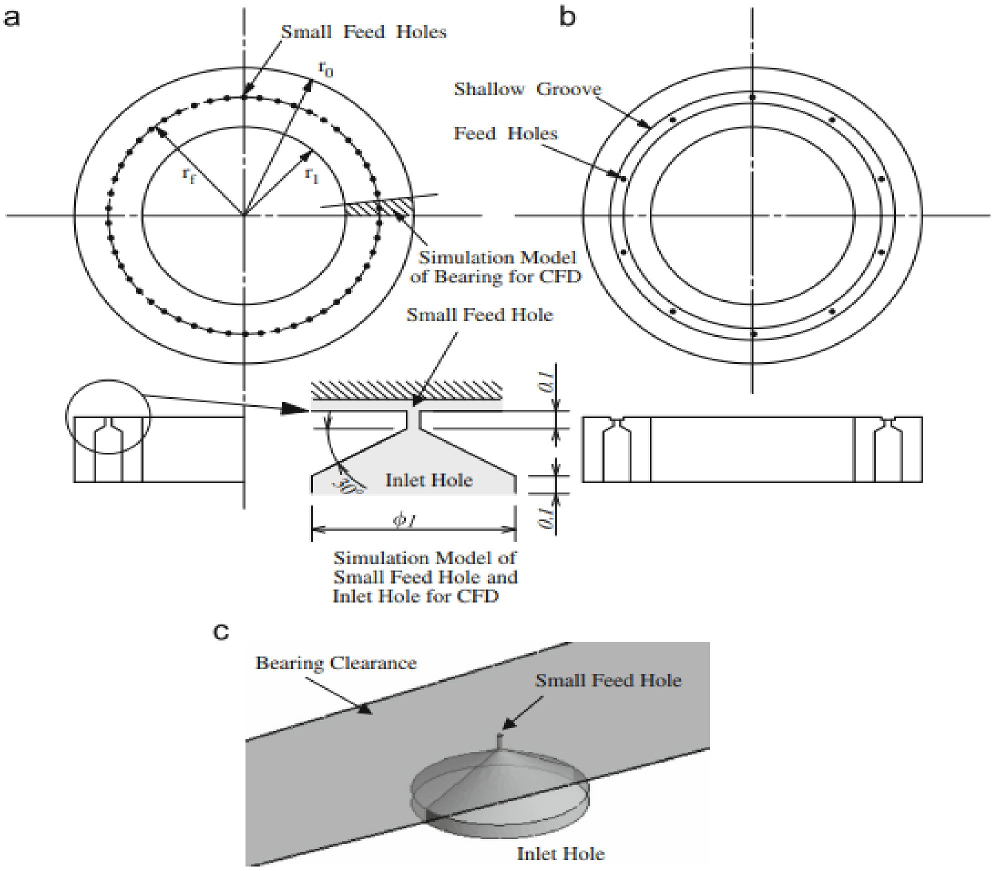

Fig. 5. Aerostatic thrust bearings treated in this paper [unit: mm]. (a) Bearing with small feed holes, (b) Bearing with compound restrictors and (c) Three-dimensional view of the simulation model.

V. SLOT RESTRICTOR

The air inlet can be a narrow continuous, or discrete slot with a width of several micrometres [23,37]. The slot restrictor is similar to the orifice restrictor by replacing a small hole witha rectangular space. Slot restrictors can generate a laminar flow inside the air film, providing good stability compared with orifice restrictors [24,36]. However,many available pieces of literature could provide guidelines for the design of aerostatic bearings with slot restrictors [25,26]. It remains somewhatchallenging to manufacture a narrow slot with several micrometres. Thus, applying aerostatic approaches with slot restrictors has been minimal[21].

VI. GROOVE RESTRICTOR

The air inlet can also be specially arrayed grooves around the orifice machined in one of the bearing surfaces [27,38]. When combining orifices with arrayed tracks, the pressure that decays from orifices to the edge of the gas film can be inhibited. Therefore, a more uniform pressure distribution within the air film can be acquired. Consequently, the air bearing has higher stiffness and load capacity. But its manufacturing cost is usually higher than simple orifice feeding air bearings.

VII. POROUS RESTRICTOR

Aerostatic porous bearings employ porous materials as a restrictor to feed the pressurised air into bearing clearance [28,29]. Since a large amount of tiny and tortuous passage within porous materials could serve as restrictors, namely porous orifices, a uniform pressure profile can be achieved inside bearing clearance. Thus, the aerostatic porous bearing has substantially high stiffness, load capacity, damping, and pneumatic stability, compared with other aerostatic bearings. [30,31, 36]. Moreover, owing to a large amount of porous orifice, the porous media surface could provide better bearing protection. When air supply failure occurs, the bearing could be allowed to adjust spontaneously without damaging the support surface. However, due to its special material properties, during the machining process, the porous material is easy to be clogged.Moreover, it may release very tiny particles under working conditions, which is not desirable in clean machining environments such as equipment for manufacturing the semiconductor wafer [15,18]. In general, all types of restrictors have their advantages and disadvantages. Different restrictor methods could be combined as compound restrictors to enhance aerostatic bearings' performances comprehensively [19].

VIII. CONCLUSIONS

This paper aims to provide a systematic and comprehensive analysis of the latest research progress on aerostatic bearings. The literature on aerostatic approaches is reviewed from the perspectives of static characteristics, pneumatic hammer, stability, dynamic characteristic, and air-induced vibration. Some important conclusions can be drawn:

(1) Researchon orifice feeding aerostatic bearings has been carried out, which contributes to establishing design principles. But, the poor stability of such kindsof orifice bearings limits their application in ultra-high-speed applications. The underlying design principle for aerostatic approaches with slot restrictors, grooved restrictors, porous restrictors, and compound restrictors has not been elucidated, which needs further investigation.

(2) The air hammer vibration formation mechanism is still not fully determined. Some critical issues include the negative effect of the microscopic turbulent airflow, the influence of bearing mass, and structural stiffness and damping, the result of fluid-structure interaction considering the squeeze film effect, and how the rotor is converted from stable to an unstable motion under specific operation condition, need further investigation in future research.

(3) A consensus has been reached on the cause of nanometre order vibration that the turbulent flow inside air film is the vibration source. More work should be conducted to clarify the negative impact of air-induced vibration on the pneumatic hammer vibration and high-speed stability of the aerostatic spindle, the positioning accuracy of the machine tool's feed drive system and the machined surface quality surface.

(4) The rapid development of multi-physics coupling simulation algorithms and commercial software provides an efficient tool to study the complex phenomenon of aerostatic bearings, such as pneumatic hammer and high-speed stability. However, research on coupling modellingmethods of aerostatic approaches is insufficient, which needs more investigation in future work.

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