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Design and Development of Different Applications of PATB (Porous Aerostatic Thrust Bearing): A Review

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ABSTRACT

In several applications demanding precise and ultra-precision movements, porous aerostatic thrust bearings had been employed as a crucial precision engineering component and enabling technology. By acting as a lubricant between the moving part and the stationary part in aerostatic bearings, pressurized air almost completely eliminates friction. Since air acts as the lubricant, oil-based lubricants leave no debris behind. The air prolongs the life of the substances by preventing them from slipping and wearing. The aerostatic type uses graphite as a porous film to disrupt the air uniformly over the surface, or a tiny hole is drilled through the centre of the bearing to let the air circulate and produce a thin layer between the components. With an increased reliance on computational and mathematical methodologies for design and bearing performance optimization, this review paper aims to present the state-of-the-art in aerostatic bearings advancement and research. It also conducts a critical analysis of their future research directions and development trends in the next ten years and beyond. Air bearings are utilized in the production of tools like lathes, CMM, and grinders because they are highly precise in their operation and decrease mistakes and production time. Air bearings are available in a variety of forms and sizes. The assessment of future trends and obstacles in aerostatic bearings investigation, as well as their prospective applications in the precision engineering sectors, concludes the study.

Keywords: Aerostatic bearing; Porous layer; Thrust bearing; Precision motions.

Introduction

Due to the simplicity of using porous material to create an aerostatic bearing, aerostatic porous bearings have been effectively used in precision machine tools and precision measurement equipment. Recently, improved ceramics and graphite, which can attain a modest permeability in the range of 10-15 m^2, have frequently replaced metal in porous materials. This is due to the fact that employing porous material with a reduced permeability makes it simple to get a greater bearing stiffness [1-2]. The aerostatic bearings, which have been widely used in a variety of applications, including the manufacturing of semiconductors, medical devices, ultra-precision measuring, turbomachinery, machining equipment, etc., use a pressurised thin air film of micron-level thickness to support the moving objects. Some properties of aerostatic bearings are low friction, precise rotation, and ultra-precision. In order to fulfil the needs for enhanced performance in associated sectors such as semiconductors, defence, microelectronic, textile, aerospace, and measuring instruments, extensive research has been undertaken on the performance of aerostatic thrust bearing [3-5].

Aerostatic bearings serve two primary purposes, namely, the minimization of friction and motion faults. The stiffness, static properties, and load-carrying capacity of aerostatic thrust bearings have all been explored in earlier works. The features of aerostatic porous bearing with something like a surface-limited layer have been published by a number of studies. Aerostatic circular porous thrust bearings were treated with a surface limited layer by Yoshimoto [6]. They looked into the static and dynamic properties of this particular type of graphite bearing both theoretically and empirically. They also presumptively believed that Darcy's law applies to airflow in a surface limited layer. However, because a limited layer was often very thin, the radial flow and porosity in it were considered to be zero in their calculations.

Yabe et al. [7] employed porous metal with a limited layer created using a surface grinder to treat an aerostatic circular porous thrust bearing. For the situation of a reasonably large bearing clearance of some more than 20 mm, where the dynamic characteristics are not significantly

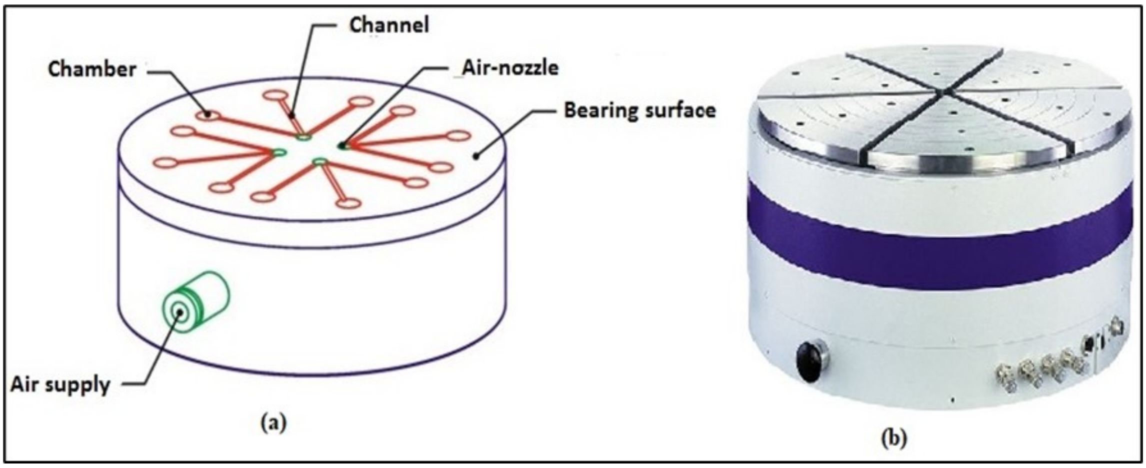

Figure 1: Aerostatic Journal Bearing (a) Schematic View (b) Original View [79]

impacted by the squeezing effect, they reported the theoretically predicted and empirically determined dynamic characteristics of this type of bearing. They discovered that theoretical conclusions drawn from their comparable clearance model were in good accord with the findings of the experiments. An aerostatic annular porous thrust bearing made of surface-restricted graphite was researched by Cui and Ono [8]. The permeability of this porous substance is approximately one-tenth of that of the porous metal that Yabe et al. [7] studied. As a result, they looked at the bearing properties in a limited (10 mm or less) bearing clearance range. Lacquering was used to create the surface-restricted layer of porous graphite material. Using a perturbation approach, Kawashima and Togo et al. [9] theoretically examined the static properties of aerostatic porous ceramic journal bearings. They also applied a confined layer to an aerostatic porous journal bearing; however, they simply displayed the pressure gradient in the porous material.

The techniques of annular groove air supply and entire air supply, which were employed to prevent the deflection of the bearing surface of aerostatic circular porous thrust bearings, were researched by Yoshimoto et al. [10]. Otsu et al. [11] evaluated the dynamic stiffness and damping coefficient of aerostatic porous journal bearings and also demonstrated that raising the permeability and lowering the small surface restriction ratio can result in higher dynamic stiffness and a higher damping coefficient. The micro-vibration of aerostatic thrust bearings with surface limitation provided by T-shaped grooves was explored by Yoshimura et al. [12]. They found that the Reynolds number at the bearing outlet significantly affected the nano-fluctuation of aerostatic bearings. According to research, restrictors made of porous material with permeabilities in the order of 1e-15 mm^2 can reach the ideal bearing clearance of less than 10 mm, which corresponds to the maximum static stiffness. This can increase the stiffness and stability of aerostatic porous bearings. Aerostatic bearings' stiffness and stability are both governed by the internal pressure distribution in the bearing clearance, and the manufacturing flaws have an impact on the thickness of the bearing clearance. Therefore, the effects of manufacturing mistakes cannot be disregarded, particularly in gaps with thinner film. Since 1828, when Willis [13] conducted an experimental investigation into the airflow state between two parallel plane surfaces, air lubrication technology has been a growing field. Kingsbury [14] tested the supporting properties of an air journal bearing near the end of the 19th century, confirming the viability of gas bearing. Then, in the early 1900s, several patents relating to gas bearings were granted [15]. Instances include the air thrust bearing developed by Westinghouse [16] in 1904 and the aerostatic journal bearing developed by Abbott [17] in 1916. However, very few studies pertaining to the fundamentals of gas lubrication were documented in the next decades [18]. Figure 2 displays the Scopus [19] document search results for the keywords "air bearing or gas bearing." Due to demands from the nuclear power and defence sectors, gas lubrication technology initially took off in developed nations like the United States during World War II [20]. Aerostatic bearings have been invented, produced, and extensively used in a variety of sectors since their specific inception, including high-speed dentistry drills [17], space simulators [18], precise machine tools, and measurement equipment [19]. It clarifies the cause of the first discernible upward trend from 1960. Numerous monographs on gas lubrication technology were produced during the 1970s and 1990s, which denotes a mature time for its design theory [13–21]. The top ten nations in terms of air-bearing research are listed in Fig. 2. It is clear that the United States, China, Japan, and other countries hold the top spot. The top 10 nations in gas bearing research are also nations with strong needs for ultra-precision machinery, confirming the importance of gas bearings as essential parts of ultra-precision machinery.

Aerostatic bearings have been known to employ porous materials as restrictors in the past. Its improved damping properties, larger load capacity, rigidity, and ease of design and fabrication over traditional restrictors are only a few of its numerous benefits [22]. It is simple to obtain even complex bearing geometries like spherical bearings and aerostatic lead screws [23]. Numerous bearing geometries have been covered in the theories of porous aerostatic

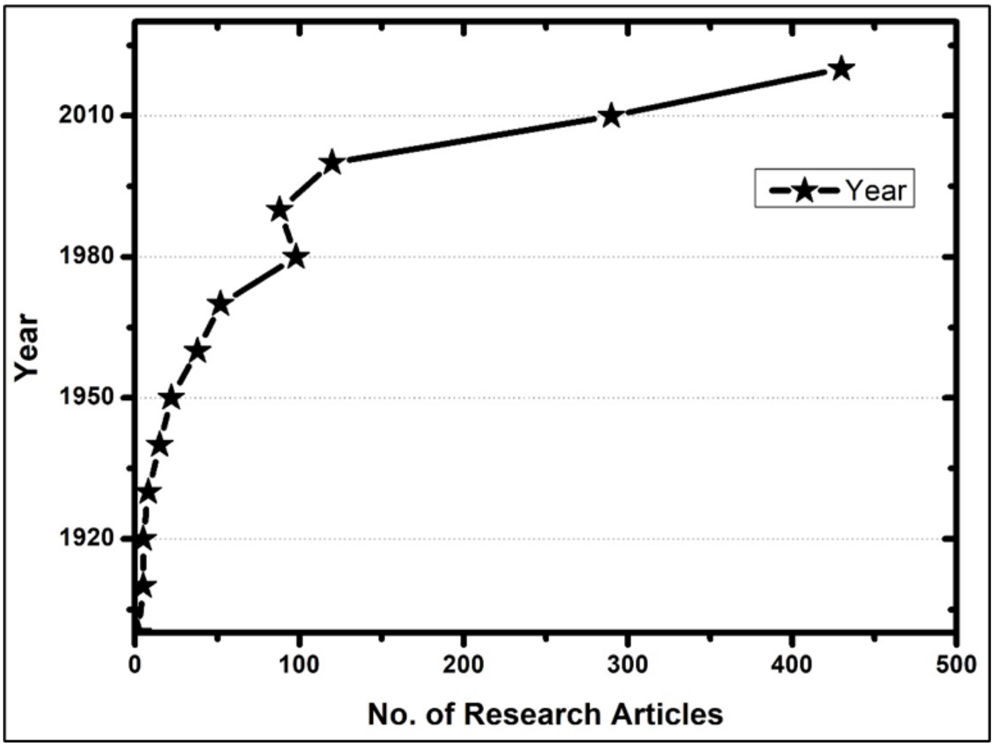

Figure 2: Annual documents quantity of articles related to air bearings by searching with keywords of 'air bearing' in Scopus.

bearings. Two bibliographic evaluations are among the numerous publications; the first was written by Sneck in 1968 [24]. Majumdar subsequently modified this in 1976 [25]. The foundations of porous aerostatic bearings had previously been established in published literature at that point, comprising one-dimensional analytical models and two-dimensional calculations with adjustment for compressible, slip, and inertia flows. Theoretical and experimental research has also been done on dynamic and stability properties. The majority of these papers made the assumption that Darcy's rule applied to flow through porous media.

After 1976, a sizable amount of work was also recorded, particularly more recently as a result of rekindled interest in Japan and Germany. Two primary streams can be formed from them. Several theoretical investigations, including three-dimensional numerical assessments on rectangular thrust bearings that contain additional factors such as permeability anisotropy, tilt, slip flow, offset load etc., have been the focus of a group of researchers in India.

To produce load-bearing capacity, air bearings need an external high-pressure air supply. Air pressure between 400 and 600 kPa, which is what is generally employed in the sector, is used in the majority of air-bearing applications. The input pressure is rather low, which limits the load-carrying capability. Using a specialised compressor, air bearings may be used in sensitive applications with pressures of up to 1000 kPa. This increases load-bearing capacity and rigidity [28]. In comparison to other bearing ideas, the air bearing offers significant benefits such as extremely low friction, minimal wear, and wide range of working speed [29–30]. The air bearing is a part that is utilised in the construction of ultra-precise machinery. It works incredibly well in absorbing vibrations from the environment [31]. There is very little space between the components and the bearing, which is the fundamental drawback of air bearings. As a result, it needs extremely tight tolerances. It requires compressed air to operate continuously. Air bearings are also not very rigid. However, preloading the bearing can greatly boost rigidity. Preloading air bearings can be done in four ways: weight addition, magnetic attraction, opposing assembly, and vacuum preloading. The vacuum preloading approach is popular since it is small and does not add additional weight [32–33]. To accomplish uniform air distribution to the contact surface and uniform pressure distribution in the air bearing, a porous material is employed [34–35].

The review discussed on this page includes theoretical and experimental research, as well as the major conclusions drawn from them, which are mostly based on the many invented bores. Additionally, several materials used in the fabrication of PATB's components as well as their production processes, have been shown and explored. Additionally, each part offers evaluations in the way of the authors' current examinations, remarks, and potential future paths. In a few instances, it has been discovered that refrigerants, oils or lubricants have already been utilised in compliant bore journal bearings in place of air. As a result, this article has also covered these bearings' performance characteristics. For the convenience of the researchers, a summary of the review and the potential areas for further investigation are provided at the conclusion of this article.

Table 1: Materials used in an aerostatic bearing by different researchers.

Materials Used	Reference No.
Diamond-like-carbon (DLC)	[68]
Chromium	[56, 61,76]
Inconel 618	[54]
Cr-Mb steel	[62–64]
Inconel 718	[56–58]
Molybdenum	[36]
AISI 304	[49]
MoS_2	[43,81]
Inconel Alloy 625	[55]
AISI 4340	[81]
Beryllium Bronze (QBe2.0)	[66],
42CrMo4	[39]
Inconel 718	[28–30,41,45,49, 56,61,79,80]
PS400	[81]
AISI 4140	[42,62,73,82]
Stainless steel	[68]
PS304	[24,43,71,72,83,84]
UNS S17400	[67]
Beryllium Bronze (QBe1.8)	[65]
AISI 301	[59,60]
Amorphous M	[27,30]
AISI 316	[61]
Inconel X-750	[43–74]

Materials used in the fabrication of PATBs

Since the air film's pressure is produced by an external air supply system, aerostatic bearings are also known as externally pressurized air bearings. Through a specialized restrictor, pressurized air is introduced into the space between two bearing surfaces, and from the exit edges of the bearing clearance, it is released into the ambient environment. In the space between fixed and moving pieces, the thin layer serves as a lubricant. Since the moving and stationary surfaces of an air bearing are not in touch while it is operating, it not only avoids numerous issues common to traditional bearings, like wear and friction but also has unique advantages for precise placement.

The characterization of coated layers on the journal substrates and upper foil is offered after a study of the materials used in making the various PATB components. Near the end of this part, the fabrication processes for the bearing components were covered. According to a literature review, the journal/rotor as well as the sleeves, are often made from the same materials. Moreover, to reduce tribological issues and boost heat dissipation during starts and stops, hard-coated layers have been placed on the top-compliant foil or journal and bearing surface. To give resistance to fatigue and extra dampening to the system, compliant journal-bearing surfaces should have good elastic behaviour and increased heat conductivity. To create the traditional stiff PATBs and the rotors, the researchers employed high carbon chromium (AISI 52100) alloy steel [36]. The rotors and PATBs have also been constructed using stainless steel-(AISI TY416) and toughened steel [37–39]. Additionally, sleeves for the PATBs have also been made using stainless steel-(SAE/ AISI 316 L) [40]. Graphite has been put on the PATBs to enhance their tribological behaviour. Additionally, it was discovered that bronze was used in the manufacturing of both the standard and herringbone grooved stiff PATBs' sleeves [38, 41, 42].

To reduce wear and improve heat dissipation rate during rotor start and stop, several coating materials were applied to the PATB bore/rotor surfaces. The compliant-bore surfaces were made using a variety of materials with strong elastic and damping capabilities. The dynamic and tribological performances of PATBs have been compared, but little study has been done to compare them when the materials for the compliant surface, sleeve, coating, and rotor are changed. The functioning of rotors sustained by PATBs during frequent stop/start and extended running circumstances with various factors was also the subject of few research, which has been reported.

Operating Conditions for PATB:

The gas film clearance is often less than 10 m, which is quite small. Accurate measurements of the pressure distribution in the bearing clearance might be challenging to achieve. There are two primary ways to assess pressure distribution. To detect the pressure distribution in the gas film, the pressure sensor is first connected to the orifice. On one of the pad's surfaces, the orifice is drilled [56]. In the literature, this tiny aperture is referred to as the flow intake (dp = 0.2 mm) [58]. This method's pressure distribution and the outcomes of the numerical simulation are in good accord. Although, there are still certain drawbacks to the approach used to connect the pressure sensor to the orifice plate. Secondly, there are noticeable and not insignificant changes to the airflow in the small gap, as well as significant measurement errors. Moreover, the number and location of experimental data that may be collected using this approach are also constrained [112].

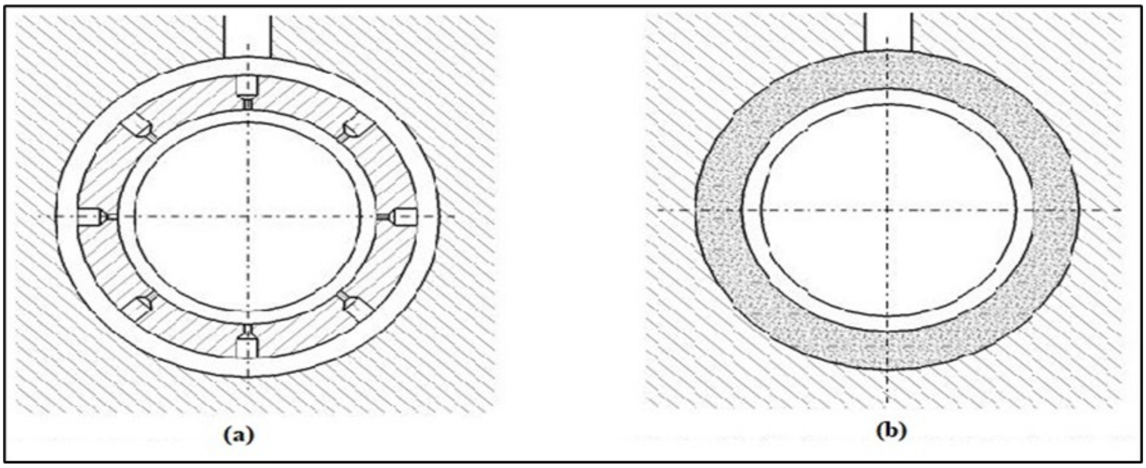

Figure 3: Aerostatic Thrust Bearing (a) with a simple orifice (b) with a porous layer [111]

Theoretical Research on PATB:

The previous research on theoretical modelling methods and related performance evaluations of aerostatic bearings under continuously loaded situations is reviewed in this part, along with a few notable works that represent state-of-the-art investigation in this field. This section discusses the evolution of research on various PATBs (as shown in Fig. 3).

Malanoski [37] solved the numerical simulations to determine the radial stiffness and the system critical mass using FDM and Runge-Kutta (4th Order) techniques. With modifications in rotating speed, the stability zones were demonstrated. Using FEM and the perturbation approach for discretization, Bonneau and Absi [83] and Faria [84] observed the alterations of stiffness coefficients of bearing with variations in eccentricity ratio, compressibility number, groove depth, and groove angle. By using the time marching approach, Kim et al. [85] showed a significant increase in stability by employing axial grooves at the beginning of each stage in a multi-stepped PATB. Critical mass, critical frequency, and stability zones for the helical grooved PATB (conical) or rotor system have been shown by Pan and Kim [86] using variations in compressibility number. In the instance of the herringbone grooved PATB, Chu et al. [87] utilised the perturbation approach and FEM for discretization, and the results demonstrate enhanced dynamic coefficients when compared to plain bore PATB under lightly loaded conditions. By taking into account lobbed bore geometry and the time marching approach, Rashidi et al. [88] have observed periodic responses and multi-periodic responses of the journal centre. By maximising geometric/operating characteristics, Schiffmann and Favrat [89] decrease windage losses and increase stability margin. In order to increase the rotor critical speed, the ideal groove dimensions have been proposed by Miyanaga and Tomioka [90]. According to Guenat and Schiffmann [161], herringbone grooved journal bearings, as compared with plain journal bearings, are more susceptible to moist air. The load-carrying capacity, which has improved with an expansion in the contact area between leaf foils, was determined using FDM by Du et al. [91] and Li et al. [92]. When the couple-stress parameter was increased, Laouadi et al. [93] observed that the peak pressure, altitude angle, frictional losses, and side leakage were all reduced. In order to solve the modified Reynolds equation, Bonello [94] used FEM and FDM. He then noticed that the clamped free or leading trailing edge of the top foil combination produced a uniform film thickness in the diverging zone, which produced atmospheric pressure. The implications of friction and partings along bump foil-top foil and sleeve-bump foil have been studied by Gu et al. [95]. The model's output has been contrasted with the experimental data and previously published models, and any differences have been explained. Baum et al. [96] found that the suggested model is very computationally productive in respect of accuracy and time by using FEM and Galerkin's approach to determine pressure distribution, load-displacement curves, solution accuracy, and simulation time. The 3D deformation simulations of top or bump foil, bearing sleeve, contact between the bump and top foil, FEM approach, and misalignment for discretization have been studied by Yongpeng et al. [97] and Zhao and Xiao [98]. They discovered that at the diverging area of the film, the top foil is momentarily disconnected from the assisting bump foil. By using the perturbation method and the FEA method, Howard et al. [49] assessed the bearing dynamic coefficient and noted that as the grove depth increased and the damping coefficient across the trend of the external load increased, whereas the coefficient decreased as it is perpendicular to the external load.

Experimental Research on PATB:

External damping is a useful technique for reducing the large amplitude vibrations, according to a literature review on the experimental investigation of the rotor's dynamic characteristics, which is supported by conventional rigid bore PATBs [7-31]. The gas/air film's direct damping coefficients are improved by external damping. The air/gas film's cross-coupled stiffness allowed dissipation forces to work in opposition to the unstable tangential forces generated. The generated tangential force aids in reducing rotor vibrations. In this part, a summary of the experimental study work carried out by several tribologists is presented.

To determine power loss, Radil and Dellacorte [99] assessed frictional torque. Then they showed a 3D map in case of power loss with respect to various rotating speeds and external loads. According to Li et al. [100]'s observations, the vertical eccentricity increases as the bearing load increases while decreasing as the rotating speed increases. Employing the piezoelectric actuator frequency and voltage, Ha et al. [101] examined the floating height and discovered that when the piezoelectric actuator voltage was raised, the squeezing film pressure at zero rotating speed increased the floating height of the journal. The viability of the function of the compression spring-supported PATB has been shown by Song and Kim [102]. After the rotor is in the air, Andres et al. [103] monitored the bearing torque with the temperature increase. As the rotating speed and applied load have grown, so have the frictional torque and bearing temperature. In the lengthy steady-state procedure, Feng et al. [104] noticed that the bearing temperature (measured using a thermocouple) had achieved a saturation level. Mahner et al. [105] discovered that an increase in the external load led to an increase in the component assembly temperatures. Eddy current displacement sensors were used by Li et al. [106] to test load-carrying capacity and bearing clearance, and the results were compared to data from theoretical model simulations. According to Andres et al. [103], the breakaway torque has grown with the rotor's speeds during start-up and lift-off and also with the rise in the external load. In order to benchmark the results from theoretical analysis, Lee et al. [79] and [103] conducted load-deflection tests, rotor constant-speed tests, and coast-down tests. They also assessed transient temperature values. They also noticed that the stiffness values increased as well when the density of the metal mesh rose. When compared to older, bump-type PATBs, the new bore PATB (with metal mesh compliant) exhibits better damping properties. Among other tests, Andres and Chirathadam [103] carried out a load-deflection test, a coast-up and coast-down test, and a dynamic shaker test. The foil metal mesh bearing has exhibited less frictional power and airborne torque, more energy dissipation, and an earlier lift-off speed than the traditional bump-type PATB. PATB with several leaves that is compliant was studied by Tian et al. [31] and found to have essentially consistent BDCs over the perturbation frequency range. Electronic actuators have been employed by Feng et al. [68] to adjust the bore geometry. The driving actuator voltage has grown along with the airborne drag torque. Guan et al. [108] noted that the piezoelectric actuators' supply voltage might be adjusted to reduce sub-synchronous vibrations. According to Hu et al. [109], the bump-type shim foil-supported new bore-compliant PATB has produced a smaller rotor orbit (with less vibration in both directions) than a traditional bump-type PATB. In comparison to traditional bump-type PATBs, the rotor supported on the innovative bore bearing exhibits significantly reduced sub-synchronous vibrations, according to Liu et al. [91]. By adding dampening, the metal mesh blocks' enhanced mesh density has resulted in less sub-synchronous vibration amplitudes. However, thorough three-dimensional numerical formulations for the operation of bump-type refrigerant-lubricated journal bearings have been introduced, and the tribo-dynamics of these kinds of bearings have been studied by the authors [110]. These formulations incorporate thermal, eddy viscosity, turbulence effects, and vapour/liquid transition.

Conclusions and Future Scope:

It is well acknowledged that research is being conducted worldwide to investigate and enhance the load-carrying capacity, rotor dynamics, and tribological performances accompanied by compliant and rigid bore PATBs. Additionally, it has been shown that operations at low eccentricity ratios make the rotors sustained by rigid bore PATBs susceptible to dynamic instabilities. Based on the review of the literature on porous thrust aerostatic journal bearings provided in this article, the key points observed from the literature review are listed below:

- When determining the tribo-dynamic performance of PATBs, factors such as bearing bore geometry, operating circumstances, and clearance are crucial.
- Many unique compliant bore geometries that provide compliance throughout the operations have been proposed in previous research.
- Furthermore, the clearance change caused by the thermal expansion of bearing parts has been taken into consideration in the design of PATBs.
- However, limited numbers of literatures can be found on the tribological and experimental investigations of novel aerostatic journal bearings.
- When employing PATBs, self-excited sub-synchronous rotor vibrations and nonlinear dynamic performance are perceived.
- The tribological experimental investigations of novel PATBs are understudied.
- The ability to carry higher load for long time is improved by the increase in air viscosity that occurs when the ambient temperature rises.
- The capacity to carry the loads is negatively impacted by rarefaction, which is further encouraged by a rise in the ambient temperature.

There is a need for more investigation into how to use surface texture technologies to minimise friction and wear. It is necessary to conduct experimental research on the newly described compliant bore geometries to comprehend the tribological behaviours under various operating conditions. Compliant bore bearings/ conical aerodynamic rigid, which can handle both radial and axial thrust simultaneously, have not been the subject of any study. To determine its feasibility, thorough research is needed.

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