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Gas Foil Bearing Technology Enhanced with Smart Materials

Adam Martowicz [1,*] , Jakub Roemer [1,2] , Sławomir Kantor [1] , Paweł Zdziebko [1] , Grzegorz Żywica [3]
and Paweł Bagiński [3]

1 Department of Robotics and Mechatronics, AGH University of Science and Technology, Al. Mickiewicza 30,
   30-059 Kraków, Poland; jroemer@agh.edu.pl (J.R.); slawomir.kantor@agh.edu.pl (S.K.);
   zdziebko@agh.edu.pl (P.Z.)
2 Department of Mechanical, Electronics and Chemical Engineering, Faculty of Technology, Art and Design,
   Oslo Met—Oslo Metropolitan University, Postboks 4, St. Olavs Plass, 0130 Oslo, Norway
3 Department of Turbine Dynamics and Diagnostics, Institute of Fluid Flow Machinery, Polish Academy of
   Sciences, Ul. Fiszera 14, 80-231 Gdańsk, Poland; gzywica@imp.gda.pl (G.Ż.); pbaginski@imp.gda.pl (P.B.)
* Correspondence: adam.martowicz@agh.edu.pl

Abstract: The paper discusses a perspective of the usage of various types of smart materials to enhance the operational properties of Gas Foil Bearings. The authors, referring to the current investigation on thermomechanical characteristics of the above-mentioned bearing type, have focused on the concept of using Shape Memory Alloys, Piezoelectric Transducers, Thermoelectric Modules and Thermocouples to improve both mechanical and thermal behavior of the bearings. Based on the available literature and the authors' experience, the present work provides an overview of the known and perspective applications of smart materials to Gas Foil Bearings. In particular, a discussion on their capabilities, limitations and effectiveness is conducted, taking into account the unique characteristics and requirements of the studied type of bearings.

1. Introduction

Gas Foil Bearings (GFBs) are one of the types of fluid film bearings (also known as slide bearings) which are specifically dedicated to support lightly-loaded shafts and rotors in small-size machines operating at rotational speeds up to several hundred thousand rpm [1–3]. In GFBs, a gaseous medium (preferably air) is employed as a lubricant keeping required clearance between the surfaces of moving parts. Figure 1 visualizes the cross-sectional view of a GFB.

A shaft in a GFB is elevated over the inner surface of the bearing's bushing due to hydrodynamic effect. Specifically, while GFBs' run-up, a wedge-shaped air film is developed between the moving and stationary parts (at the so-called lift-off speed) due to their relative velocity (see Figure 1 for reference, where the hydrodynamic pressure profile is also marked). The resultant elasto-damping properties of a GFB, however, depend on both structural and fluidic parts of the shaft's supporting layer. In a bump type foil bearing its structural part is created with a set of two specialized thin foils made of superalloy, e.g., Inconel. They are known as top and bump foils. The former foil is made as a rolled sheet of metal to provide a proper mechanical interface between the rotating shaft and the remaining parts of the bearing. Moreover, its inner surface is covered by a special anti-friction material to reduce the undesired effects of a dry friction that is observed during run-up and spin-out. The bump foils, in turn, construct a three-dimensional structure to assure required elasticity that is complimentary to the air film.
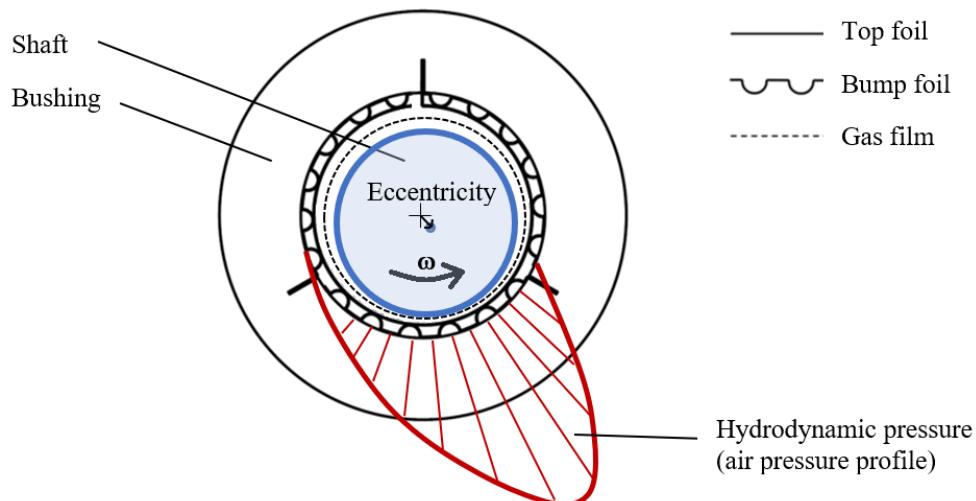
Figure 1. Cross-section of a GFB. Both structural components, i.e., the specialized foils, and a fluidic part (the air) of the supporting layer are shown. There are also the visualized developments of a wedge-shaped gas (air) film and hydrodynamic pressure profiles originated from a relative motion between the rotating part (a shaft's journal) and a top foil. Note, an eccentricity is a geometric measure used to track of the shaft's transverse motion. This quantity defines the translation vector for the center of the shaft during operation of the bearing.

GFBs exhibit interesting characteristics [4]. First of all, they are technically maintenance-free devices. As previously mentioned, the air may be used to lubricate the bearing. Hence, the operating GFB may consume this medium without limits taking it from the surroundings. The used lubricant is also clean and does not degrade over time. Effectively, its replacement is not an issue as for the liquid based solutions. Moreover, a gaseous medium transported via compressor may also become a lubricant in the installed bearings. It is also worth noting that the energy losses, due to the friction forces, are lower in the case of GFBs compared to their oil and grease counterparts. GFBs also make use of gas for cooling down the bearing's installation.

GFBs resist harsh operational conditions, especially in terms of thermal properties [5]. The bearings may work at high temperatures, i.e., at several hundred degrees Celsius. This advantageous capability results from the fact that all GFBs' components are made of metallic materials. Nevertheless, it should be emphasized that excessive temperature gradients may expose the bearing to the high risk of a damage. However, this issue is discussed in detail in Section 2. Moreover, keeping the operational conditions (primarily the load and rotational speed) within the allowed limits assures continuous generation of the hydrodynamic pressure profile required to maintain correct position of the shaft's journal.

Finally, the construction of a GFB is quite straightforward. Its mechanical components can be easily manufactured using metallic solids and foils. The only inconvenience, which is of practical concern that has been also experienced by the authors of the present work, may be access to retail quantities of the semi-finished superalloy components. Besides, keeping desired material properties may be also a challenge. Hence, only trustworthy suppliers should be considered to assure the purchase of high quality products.

Having made the use of various advantages of GFBs, the following applications of the mentioned bearings are found to be successful [4,6–10]: compressors, turbocharges, blowers, microturbines, motors, air cycle machines, auxiliary power units, aeronautical and medical equipment, installations for food and water treatment.

Making a reference to the above-introduced characteristics of standard GFBs, the authors of the present work discuss opportunities of a further advantageous increase in the bearings capabilities making use of various types of smart materials. In particular, Shape Memory Alloys (SMA)s, Piezoelectric Transducers (PZT)s and Thermoelectric Modules (TEM)s are of concern as well as Thermocouples (TC)s used for measurement purposes. As

shown in the following part of the paper, both the mechanical and thermal properties of the bearings may be improved via applications of these types of smart materials. A detailed scope of the work is as follows. The introductory section, Sections 2 and 3 show general views on both the demanded directions of GFBs improvements and the solutions known to partially overcome some of the bearings' drawbacks, also making a quick reference to the non-smart material—based applications. Next, based on both the available literature and the outcomes of the authors' previous studies, Sections 4–6 report the known applications of smart materials to GFBs, considering SMAs, PZTs and TEMs, respectively. The description of GFB-TEM approaches is complemented with the solutions where TCs are used to measure the temperature of the bearings' components. Adequate brief theoretical introductions regarding each type of the mentioned smart materials are also taken in to account for the sake of applications' clarity. In Section 7, the authors discuss the capabilities, limitations and effectiveness of the referenced GFBs equipped with smart materials. Summary and final conclusions are drawn in Section 8.

2. Demands for Improving Characteristics of Gas Foil Bearings

Although GFBs exhibit many advantageous properties (as referenced in Section 1), it should also be highlighted that there exist some inconveniences that have to be addressed to assure their proper operation [4].

First of all, load carrying capacity in GFBs is much smaller compared to the liquid lubricated bearings. This important limitation may be partially reduced by increasing the GFBs' rotational speed. Anyway, this inherent feature of GFBs originates from low viscosity of a gaseous medium used. Effectively, only lightly-loaded components of rotating machines may be supported with the mentioned type of journal bearings.

Next, even though the GFBs' construction is simple, there is a need for high manufacturing tolerance to keep the correct distance between the shaft's journal and the top foil, i.e., the bearings' clearance. A small change regarding this clearance may lead to a significant reduction in the generated pressure profile and, hence, loss of nominal load carrying capacity, again due to low viscosity of the bearing's lubricant. In reference to the demanding manufacturing quality, there is also high misalignment sensitivity found for GFBs. In fact, the higher precision assured for the bearing's clearance, the more demanding orientation and position alignments required for the cooperating GFBs. Alignment errors influence the bearings' clearances and the capability of normal operation.

Another issue is the maintenance of thermal stability of GFBs [11,12]. As discussed in Section 1, GFBs may operate continuously at high ambient temperatures. However, excessive temperature gradients are very dangerous for this type of bearing. Below, the authors briefly explain the physical phenomena related to the discussed GFBs' property. During normal operation, i.e., under nominal loads, the developed air film allows for both hydrodynamic pressure generation and heat flow in a bearing. The latter assures the desired level of temperature homogenization within the bearing's body. Nevertheless, the maximum value of the temperature gradient is found in the region of a mechanical load transfer, due to the raised shear forces in the lubricant, existing in the mentioned localization. Expectedly, in the case of overloading and possibly too low rotational speed, the bearing's clearance may become extremely thin which results in the raised temperature gradient. Next, if none of additional, i.e., externally forced, heat flow mechanism is activated, the excessive gradients may rapidly lead to uneven thermal expansion of the bearing's structural components. Thermally induced modification of the specialized foils' geometry, e.g., wrapping their edges, may result in blocking the channels for lubricant flow or even rotor stuck in the GFBs' bushing. The described issue is known as thermal stability loss (or the phenomenon of thermal instability) in GFBs. It is worth noting that thermal instability may also be observed when either the average temperature of the bearing or ambient temperature are low [13–15]. Consequently, dedicated thermal management may be considered an effective solution to decrease undesired gradients of the temperature. In

reference, a comprehensive analytical and numerical study on the influence of temperature on GFBs' performance can be found in [5].

Predicting the static and dynamic characteristics of GFBs is also a major challenge. Due to the fact that these bearings are very complex mechanical systems, where flow and structural phenomena and also fluid–structure interactions occur, the theoretical modeling of GFBs is very difficult. Reliable and experimentally verified computational models of such bearings make it possible to predict their characteristics for a wide range of operating parameters. Dynamic stiffness and damping coefficients are very important in this case. If the values of these coefficients are known, it is possible to design GFBs dedicated to specific applications and predict the characteristics of the entire rotating system with such bearings. The development of universal methods for predicting GFBs' coefficients may contribute to the faster development of this bearing technology.

From a practical point of view, it is important to consider that the durability of a GFB primarily depends on how often run-up and spin-out operations are conducted, rather than on the total time of operation. In fact, any time the bearing exhibits low rotational speeds, i.e., whenever it passes through the air film development or evanescence stage, the accompanying hydrodynamic pressure profile is too low to maintain the bearing's clearance and withstand the load. In effect, a dry friction between GFBs' stationary and moving parts is observed for a certain period of time which, in turn, leads to wear of the protective surfaces in the shaft's journal and top foil.

Lastly, the low viscosity of the lubricant used in GFBs offers very limited damping capabilities of the gaseous supporting layer. Hence, a relatively small amount of mechanical energy may be effectively dissipated, which is important in terms of mechanical vibration reduction.

3. Solutions for Improving Characteristics of Gas Foil Bearings—An Overview

Having considered the above-referenced inconveniences and challenges regarding GFBs' operation, the authors of the present paper discuss below various feasible approaches to enhance the bearing's characteristics. The adequate modifications regarding GFBs' installation may consider:
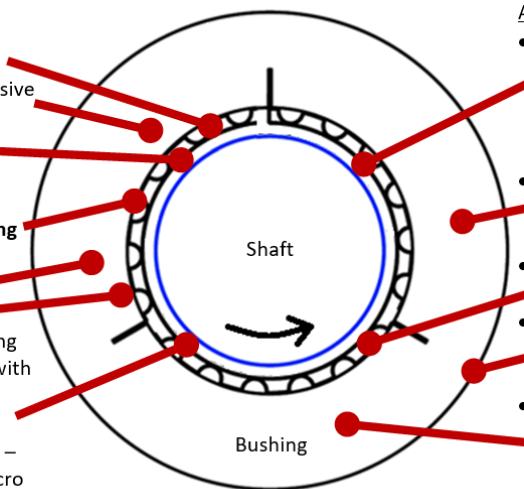
- Improvement of elasto-damping properties (referenced in Figure 2) via passive [16–24] and active methods [25–35].
- Passive [36] and active thermal management [8,37,38] (Figure 3).

One of the most common approaches to enhance the operational properties of GFBs is the modification of elasto-damping properties of the bearing's supporting layer, making use of various technical means and materials. As reported in Figure 2, both passive and active methods may be considered to either introduce structural changes (e.g., via topology or geometry modifications) or add additional components, e.g., made of smart materials.

Similarly, the more uniform temperature distribution in a GFB may be achieved via thermal management to assure thermal stability also for more demanding operational conditions, e.g., in the case of periodical overloading. Again, both passive and active technical solutions may lead to the desired GFBs' capabilities (please see Figure 3 for reference). The former case assumes material and structural modifications for more efficient heat energy acquisition from the region of mechanical load transfer. Complementary to this, the active methods for thermal management make use of either forced air cooling or heat pumps, i.e., TEMs.

Passive methods:
- Modification of topology, size and geometry of **bump foils** and **sleeves** including progressive stiffness based approaches
- Texturing **top foils**
- Installation of additional structural components:
  - mounted between **bushing** and **bump foil**
  - mounted in **bushing**
  - **bump foil** damper
- Modification of elasto-damping properties of a **top foil,** e.g., with mounted SMA (increase of damping), **PZT** (via energy dissipation in electrical circuit – shunt damping, including Macro Fiber Composites (**MFC**)s)
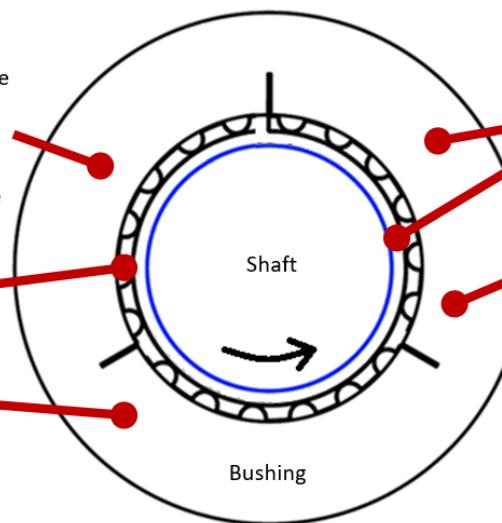
Active methods:
- Continuous control of elasto-damping properties of a **top foil**, e.g., with **PZT** (control over energy dissipation using electrical circuit, including **MFC**)
- Control over GFB's clearance and mechanical preload via **PZT** actuators mounted in **bushing**
- Substitution of **bump foils** via thermally controlled **SMA** wires
- Application of electromagnetic coils/magnetic actuator in the GFB's **housing**
- Application of piezoelectric active radial injection system mounted in the **bushing**

Shaft

Bushing

Figure 2. Scope of structural modifications in GFBs introduced to enhance the elasto-damping properties of the bearings. Various topology, size and geometric changes may be taken into account to improve the performance of GFBs. The modifications may affect both the bushing and specialized foils. Moreover, additional components (also made of smart materials) may be used to achieve an advantageous change in the bearing's properties.

Passive methods:
- Structural modifications:
  - change of geometry of the **bushing** to provide more effective heat transfer to the outer part of the bearing (housing) and the required flow for cooling medium
  - change of **bump foil** geometry to provide required air flow level
- Change of materials (for the **bushing** at most) to provide more effective heat energy transfer

Active methods:
- Air cooling, e.g., making use of dedicated channels in the **bushing** or via additional forced air flow through the **bearing's clearance**
- Use of TEMs installed in the **bushing**

Shaft

Bushing

Figure 3. Thermal management in GFBs applied to enhance the performance of the bearings and prevent the loss of thermal stability. Heat energy source and sink components may be adequately installed to control the heat flow through the GFBs' body and prevent from undesirable excessive temperature gradients.

Even though the scope of the present paper primarily deals with smart material-based applications of GFBs (as referenced in Sections 4–6), in the authors' opinion, it is also worth briefly describing several examples of the approaches that do not make use of the mentioned types of materials, but provide means to effectively enhance the bearings' properties. These selected approaches are presented in the following subsection.

Non-Smart Material Based Solutions—Brief Reference

Below, a brief overview on the examples of non-smart material-based applications for improving properties of GFBs is provided.

- Passive solutions

Amongst passive approaches, it is worth mentioning the concept of progressive stiffness of the supporting layer [24]. The main idea of the approach is to assure self-

adaptive properties of the bearing in terms of adequate modification of the stiffness of the bump foil undergoing mechanical deformation during GFBs' operation. The authors of the cited work conducted numerical simulations in ABAQUS software, employing a nonlinear model of the GFBs' structure. As shown, the bump foil may exhibit a gradual growth of the contact surface between the shaft's journal and the top foil in a controlled way, with the operational deformation of the structural part of the bearings' supporting layer. In reference, the authors of the presented approach have also investigated the influence of the long-lasting cyclic loading on the geometry of the bump foil in a GFB [16]. A modified shape of the bump foil as well as the concept of a rigid bore segment is presented in [22].

The authors of the work [19] introduce additional structural components, namely the flexure pivot tilting pads being mounted between the bearing's bushing and bump foils. The modification considered allows for effective reduction in the cross-coupled stiffness in the structural part of the supporting layer, that, in turn, leads to the improvement of the bearings performance, including the capability of larger load capacity and smaller nominal clearance. The feasibility of the proposed solution was confirmed using both numerical and experimental results.

Another passive solution made use of additional structural components to improve the elasto-damping properties of GFBs is reported in [17]. The referenced work describes the application of metal meshes installed to provide additional supports, i.e., additional bumps, for a top foil. The proposed solution leads to the advantageous increase in damping that improves operational stability of the bearing eventually. The authors also discuss the influence of metal mesh density on the GFBs' performance.

The concept of the introduction of bump foil dampers around the bearing sleeve is presented in [23]. As proven using numerical studies, additional components allow for the increase in the bearing's stability. The authors present and discuss the GFBs' load-displacement characteristics to investigate the influence of the damper thickness as well as sleeve mass and material selection on the bearings' operation.

Recent work [18] presents an interesting concept of texturing the top foil for a GFB to improve the bearing's characteristics. As experimentally confirmed, the application of a dimple foil advantageously results in speeding up the air film formation process. Moreover, the authors of the referenced work investigated the effect of the texture on the GFBs' temperature growth and resultant friction coefficient under various lubrication conditions.

As far as passive thermal management is of concern, it is worth mentioning the idea introduced in publication [36]. The presented approach to passive cooling is based on the topology modification of a GFB and is proposed to be conducted by disrupting the flow of a lubricant. The approach makes use of fluidic mixing techniques to break apart the air film. The elaborated thermal management may advantageously increase the load capacity and enhance the GFBs' reliability.

- Active solution

Below, an example of a non-smart material-based GFBs' active approach is referenced. The authors of the work [25] present a numerical study for the case of magnetic actuation performed for a GFB. The mechanical responses of the shaft's have been determined in presence of active control conducted via generation of magnetic forces. These excitations have been introduced into the bearing's equation of motion to assess the GFBs' operation stability. Specifically, the increased bearing's performance has been found after the activation of the PD control process, i.e., desired operational parameters, including increased unbalance carrying capacity, which have been identified for a wider range of the rotational speed due to advantageous elimination of the sub-synchronous harmonic components in the bearing's responses. Although the scope of the work and the presented results are promising and prospective, the authors, unfortunately, do not provide any experimental validation for the elaborated model of a GFB.

4. Applications of Shape Memory Alloys to Gas Foil Bearings

SMAs constitute the group of smart materials exhibiting one- and two-way memory effects and superelasticity (pseudoelasticity) [39,40]. The above-mentioned effects are observed due to thermomechanical phenomena related to the reversible phase transformation (martensitic transformation) in SMAs. The unique thermally and mechanically induced SMA's responses may be easily exploited to construct solid state actuators and dampers. These devices make use of the memory effects and superelasticity, respectively.

Both the memory effects and superelasticity may be employed in GFBs to effectively enhance their operational properties. The authors of the work [27] propose to substitute bump foils in a GFB with SMA wires (circumferentially distributed springs). Hence, active elasto-damping properties control becomes feasible via thermal activation. The thermally induced change of the resultant stiffness of the structural part of the GFBs' supporting layer allows for the desired adjustment of the clearance between the shaft's journal and top foil. Thermal control is performed using electric current supply and dedicated axially mounted pipes, respectively, for heating and cooling the SMA wires. Apart from the experimental study conducted, the authors of the referenced work also report a numerical model of a GFB composed by SMA springs employing the constitutive relation and the Reynolds equation. The simulated elasto-damping characteristics, as well as pressure profiles and load carrying capacity, are identified and discussed in the study. The presented work confirms the feasibility of the proposed solution.

The concept of a passive SMA-based GFB is presented in the research [20]. Specifically, a direct installation of SMA wires on the outer surface of the top foil is proposed, e.g., via gluing or soldering. The authors of the cited work develop the nonlocal model for SMA materials, i.e., an adequate nonlocal formulation for constitutive relation, making use of peridynamics to conveniently deal with various types of nonlinearities for the planned numerical studies. The use of SMA wires is proposed to effectively modify the elasto-damping properties of the top foil, and, hence, reduce the mechanical vibrations of the shaft's journal during operation of the bearing. Thanks to the phenomenon of superelasticity the immanent mechanism of energy dissipation may be employed to enhance the GFBs' characteristics. The work [21] extends the scope of the above-mentioned SMA constitutive description adding the functionality of modeling non-isothermal phase transformations.

5. Applications of Piezoelectric Transducers to Gas Foil Bearings

PZTs are made of smart materials that perform the electromechanical coupling via piezoelectricity [41]. Specifically, the direct and converse piezoelectric effects govern the behavior of PZTs. The former effect describes the electrical response of a piezoelectric transducer subjected to mechanical deformation via the phenomenon of electric charge induction. The later effect refers to the converse energy transformation realized via electrically induced strains.

Due to the electromechanical coupling in PZTs, these devices may be used as either sensors (accelerometers, force and torque sensors, etc.) or solid state actuators. Hence, various applications of piezoelectric transducers have been successfully developed to enhance the properties of GFBs. Below, an overview on the bearings equipped with PZTs is provided.

The work [30] presents an application of the piezoelectric active radial injection system mounted in the GFBs' bushing. The authors report the results of experimental tests in which radial forces generated by the injected lubricants assure the proper operation of the bearing being disturbed. Specifically, independent injection subsystems allow us to adjust the position of the shaft's journal to remain within the acceptable trajectory bounds after external excitation is provided via hammer impact. The amount of injected gas is controlled via PZT valves mounted in the bearing's sleeves. As shown, the developed GFB enables safe operation across the critical rotational speeds and allows for the convenient control of the bearing's dynamic response. This capability considerably reduces the risk of

the GFBs' instability. However, setting the proper values of the controller gains may be a challenging task to finally take advantage of the elaborated capability.

In reference to the above-presented research, the authors of the work [35] develop a gray-box model for an active GFB. In the presented solution, PZT valves are used to control the lubricant injection, and, hence, excite the GFB system. The experimentally validated GFB model allows us to represent the dynamics of the bearing system for a given range of rotational speeds. One of the main goals of the study is to provide a reliable tool for the identification of the parameters of the controllers dedicated for active lubrication [30]. Eventually, the demanded significant growth of damping coefficients has been achieved based on the identified GFB model.

An application of piezoelectric composites, i.e., Macro Fiber Composites (MFC), to control the operational properties of a GFB is presented in [34]. Making the reference to the concept of adaptive bearing, the authors focus on the modeling aspects. A single specialized active segment (shell) of a GFB equipped with MFC is analyzed, making use of the laminate theory, Hamilton principle and, finally, the Ritz method to yield an approximate solution. The authors consider flexure joints between the GFBs' shells. Additionally, the results of the conducted shape optimization are presented for the parameterized model of a specialized shell. The optimization aims at achieving shell deformation close to the given bore shape during MFC activation.

A comprehensive description of the operation of the MFC-activated components (curved flexible shells), including both experimental and numerical outcomes, may be found in [4,31]. The elaborated model explicitly introduces electromechanical coupling present in MFC, applying the electric field accordingly to the direction of piezoelectric fibers. The conducted experiments have allowed for model validation. High agreement obtained between the results of theoretical and experimental investigations confirms the usability of the elaborated model.

The concept of circumferentially distributed and radially oriented PZTs stacks in a GFBs' bushing is presented in [32]. The proposed active control of the bearing operation allows for adjusting the GFBs' clearance via PZT activation. The PZTs are mounted directly under the bearing's foils. Hence, both local and global change on the air film thickness (i.e., shape modification for the bearings sleeve) is feasible. The authors present the results of numerical studies conducted for various operational scenarios changing the nominal clearance, preload and voltage which supplies PZTs. The proposed solution enhances the dynamic response of the bearing in terms of vibrations that may appear for natural frequencies. The conducted numerical simulations provide shaft's journal eccentricities and trajectories, stiffness and damping coefficients as well as transient responses for various rotational speeds. As confirmed, the activation of PZTs advantageously makes it possible to safely pass across the critical rotational speeds.

The studies [26,28,29] report the application of circumferentially oriented PZTs built-in into the body of the GFBs' bushing. As presented in the cited works, it is feasible to adjust mechanical preloads in the bearing making use of PZTs and mechanical amplifiers (lever amplifiers) constructed with flexures. The desired radial displacement of the GFBs' foils is achieved after voltage activation of the PZTs. The lever amplifiers allow for gaining the effect of the electrically induced strain of the PZTs. As proven based on the results of experimental and simulation analyses, the proposed solution exhibit the following features: controllable clearance, stiffness and the shaft's journal eccentricity, which results in higher operational stability. The earliest paper [26] presents the model of the above-discussed active bearing. The model takes into account both the structural passive parts, i.e., the specialized foils, and the active components—PZTs. Linked springs and rigid links have been used to approximate the properties of the GFBs' foils. Drag torque, resultant stiffness and damping coefficients and eccentricity are found with the elaborated model subjected to various supply voltages.

The work [28] is a continuation of the above referenced numerical study. The authors investigate the properties of a nonlinear model of an actively controlled GFB. The nonlinear

dynamic responses of the bearing are analyzed making use of the shaft's journal trajectories with relevant Poincaré maps and fast Fourier transform. Additionally, the minimum thickness of the air film and the amount of dissipated energy for a single cycle of the shaft's orbit are identified. The elaborated model has been successfully verified using experimental results. Further results of experimental investigations are presented in the complementary paper [29]. The work describes the behavior of the tested GFBs' installation in the presence of real-time controllable mechanical preloads. Moreover, the influence of the shaft unbalance on the bearing's response is also discussed. The authors have also identified the critical rotational speeds for various voltages.

The study [33] reports a hybrid bearing that integrates a common ball bearing and an internally mounted GFB. In the proposed solution, the GFBs' clearance is actively adjustable via electromagnetic coils installed in the bearing's housing. The inner ring of the ball bearing is held using PZTs. The authors show the capability of mechanical vibration reduction in the shaft's journal during the bearing's operation. A dedicated control system may effectively change the resultant elasto-damping characteristics of the GFB component that enhances the hybrid bearing's performance.

6. Applications of Thermoelectric Modules and Thermocouples to Gas Foil Bearings

TEMs (also referred to as Peltier modules) are devices made of n- and p-type semiconductors that allow one to impose heat energy flow [42]. The amount of transported energy is controlled with the electric current supplying the device. The energy flow is governed by the Peltier effect. TEMs are solid components, hence, they do not require any refrigerants and do not exhibit mechanical wear due to lack of moving parts. One of the major disadvantages of using TEMs is limited energy efficiency. Specifically, exceeding the consumption of a given specific current leads to a reduction in both heat energy transport efficiency and the ability to maintain the demanded temperature difference between the module's hot and cold sides (junctions).

A TC is constructed as an electrical connection of two conductors (the hot junction) [43]. The remaining two free ends of the conductors compose the so-called cold junction which should be maintained at the referential temperature (ambient temperature). If the temperatures of the two junctions differ, the electromotive force E is adequately generated thanks to the thermoelectric effect, i.e., the Seebeck effect. The measured electric potential drop E can be considered as a quantity proportional to the temperature difference.

As referenced in Sections 1 and 2, thermal management (heat flow management) is critical for the operation of a GFB. Hence, both TEMs and TCs may be advantageously used to provide effective means to control the flow and dissipation of heat energy within the body of the bearing. The former components allow one to guide the heat flow by acting as the active energy sources and sink, whereas the latter devices can measure the temperatures at the demanded localizations in a GFB. The work [37] reports the results of experimental investigation on the GFB installation equipped with TEMs and TCs. The authors propose an active cooling method, making use of TEMs installed in the GFBs' bushing. TCs have been applied to measure the temperature on the outer surface of the top foil. The conducted measurements confirm the capability of reducing the bearing's average temperature as well as its gradient without affecting the dynamic properties of the shaft's journal.

The recent work [8] extends the scope of the above-presented study. Specifically, numerical simulations are employed to assess various scenarios for GFBs' thermal management. The obtained results have been experimentally confirmed. Based on the theoretical and experimental findings, the authors have proposed strategies for effective reduction in undesired temperature gradients that should lead to a considerable decrease in the risk of thermal stability loss for an operating GFB.

An innovative method dedicated to temperature measurements in a GFBs' top foil is presented in [38]. The authors propose to extend the standard functionality of this foil, i.e., assurance of a smooth surface for developing the air film, also to become a sensing

component via integration of TCs. For the experimentally tested approach, platinum wires are soldered to the outer surface of the top foil and establish a matrix of TCs with a common electrode which is a part of the foil.

7. Discussion

Presented in Sections 4–6, a variety of the applications of smart materials to enhance the properties of GFBs is unquestionable. In reference, the known SMA, PZT, TEM and TC—based approaches are discussed below making use of their major characteristics collected in Table 1.

All the above-referenced applications seem to exhibit complementary features important in view of the GFBs' performance. Specifically, SMA-based solutions are efficient in terms of energy dissipation to reduce the undesired mechanical vibrations of the shaft's journal. Moreover the construction of a GFB-SMA is relatively simple. Unfortunately, the high inertia of the involved physical phenomena (a low change rate of elasto-damping properties induced by thermal activation) considerably limits the scope of active approaches. However, SMA based installations offer demanded control functionality in cases when long-term and low-rate changes of the GFB's properties are required and satisfying. Adequate mechanical actuations may be generated via shape memory effects in response to the low frequency changes on the operational conditions (loads). Nevertheless, SMAs exhibit the desired characteristics to develop passive solutions. In these solutions the phenomenon of superelasticity is employed, which does not require any thermal activation. As already mentioned, advantageous mechanical energy dissipation is possible thanks to the mechanically initiated phase transformations. The wider hysteresis of the SMA component's stress–strain characteristics is the larger amount of energy that may be effectively collected from the bearing to improve the stability of its operation via a reduction in mechanical vibrations.

Due to the specific properties of piezoelectric materials, PZT/MFC based installations provide very precise and fast control over the mechanical displacement. Hence, an active PZT/MFC system may react rapidly to precisely adjust the bearing's preload and clearance. As a result, the above-referenced functionality may provide the conditions required to maintain the air film, and, hence, assure GFBs' stability under harsh operational parameters. It is worth noting that circumferentially distributed PZTs allow one to utilize a multiple-lobe clearance. Hence, the bearing's air film may be formed relatively freely. Unfortunately, only a limited amount of energy may be dissipated via piezoelectric components. Moreover, the construction of a GFB-PZT is complicated, especially in cases when the PZT stacks are built-in into the bearings bushing. High voltage may be also required to supply the PZTs and MFCs and obtain desired strains.

Extraordinary thermal properties are found for the TEM and TC—based approaches to GFBs. As proven during experimental investigations, effective thermal management in a GFB may be performed making use of both TC sensors and TEM-based heat energy sink/source control. The risky temperature gradients may by reduced to prevent from thermal stability loss. However, the referenced solutions exhibit a couple of major disadvantages, namely, design and structure complexity and nontrivial selection of control algorithms that would lead to the desired heat energy flows within the entire body of the bearing.

In the authors' opinion, extraordinary properties of GFBs could be achieved for the combined solutions GFB-SMA-TEM and GFB-PZT/MFC-TEM. The capability of simultaneous control on the mechanical and thermal characteristics of the bearing seems desired due to potential further reduction in the risk of operational stability loss. In fact, the bearing may adequately and rapidly react to the changing environmental and loading conditions to prevent both reduction in the air film thickness and loss of thermal stability.

Table 1. Properties of smart material-based GFB approaches.

Method Used to Enhance the GFBs' Performance	Advantages / Potentials	Drawbacks / Inconveniences
1. GFB equipped with SMAwires substituting bump foils [27]	Straightforward active method to control the bearing's stiffness via thermal activation—managing heating (making use of electric current) and cooling (with dedicated pipes with fluids) processes; capability of the bearing's damping control	Relatively high inertia of the control process due to the nature of the thermally induced mechanical responses of SMAs, e.g., compared to the PZT-based solutions; Requirement of an effective cooling method
2. Concept of a GFB equipped with SMA wires installed on a top foil [20,21]	Straightforward passive method dedicated to reduce mechanical vibrations via energy dissipation available for the phenomenon of superelasticity; experimentally validated SMA wire models for both isothermal and non-isothermal phase transformations dedicated for future use in GFB models	Not yet experimentally validated complete SMA-based GFB model
3. Application of PZT valves to control radial air injection (active lubrication) [30,35]	Active method with experimentally proven efficiency; fast operation that allows for quick response of the GFB when subjected to the external radial excitation (sudden shocks); high potential of further investigation; reduced demands regarding manufacturing tolerances; advantageous growth of damping coefficients	High system complexity; setting the parameters of the PZT valve controller may be a challenge—the performance of the control system must be experimentally verified that may be time consuming
4. Application of PZT composites—MFC to modify elasto-damping properties of the structural parts of the GFBs' supporting layer [4,31,34]	Active method with experimentally proven efficiency; fast operation; very high precision of positioning the GFBs' structural parts	High voltage may be required to supply MFC
5. Concept of application of radially oriented PZT stacks to control the GFBs' clearance/preload [32]	Active method; capability of precise adjustment of the GFBs' foils; fast operation; very high precision of positioning the GFBs' structural parts	High voltage may be required to supply PZTs; requires experimental validation; high system complexity and costly solution
6. Application of circumferentially oriented PZT and flexure-based mechanical amplifiers to control the GFBs' clearance/preload [26,28,29]	Active method; capability of activation of large and fast deformations of the foils to adjust the clearance; experimentally tested; multiple-lobe clearance; controllable GFBs' stiffness and the shaft's journal eccentricity	High voltage may be required to supply PZTs; high system complexity and costly solution
7. Hybrid bearing (ball bearing and GFB) equipped with PZTs and electromagnetic coils [33]	Unique features not met in other applications—advantageously combines functionalities of both types of bearings; capability of effective change of elasto-damping properties of the bearing; interesting perspective of further research	Complex design and structure; complex and costly control system required for coils and PZTs; large space required for entire installation; complex power system used to supply two types of electromechanical actuators
8. Applications of TEMs and TCs to GFBs for thermal management [8,37,38]	Unique features not met in other applications; capability of effective control of the temperature filed in a top foil; interesting perspective of further research; Experimentally verified	Complex design and structure; complex and costly control system; large space required for entire installation; complex power system used to supply TEMs

Finally, it should be noted that the presented solutions should be adapted to industrial conditions. Even though the desired capabilities are experimentally confirmed for most of the referenced applications and concepts, additional tests are still required to develop the presented installations to the more demanding operational cases and obtain robust technical solutions.

8. Summary and Final Conclusions

Installation of smart materials in GFBs provides various unique capabilities. The authors of the present paper report successful applications of SMAs, PZTs/MFCs, TEMs and TCs employed to enhance the performance of the bearings in terms of both mechanical and thermal properties. However, the adaptation of the proposed solutions to the industrial conditions may be crucial for their further progress and desired marked interest. It should be also highlighted that GFBs are still designed taking into account case-depended requirements. This specificity of GFBs additionally makes it difficult to formulate general design guides even for their standard constructions.

Applications of various types of smart materials advantageously aid to reduce common problems in GFBs. As reported in the literature, SMAs and PZTs/MFCs may effectively change the resultant elasto-damping properties of the supporting layer in a bearing. Hence, the operation of a GFB remains stable even for demanding excitations and environmental conditions. PZTs/MFCs seem more suitable for active solutions taking into account the relatively higher inertia of the control process observed for SMA—based approaches. Moreover, the use of TEMs and TCs allow for efficient GFBs' thermal management. The heat flow within the GFB may be guided via TEMs, based on the temperature measurements conducted with TCs.

There are still reported drawbacks and inconveniences raised for the smart material-based GFBs solutions that should be addressed to increase their future applicability. The most important are design and structure complexity as well as demanding requirements regarding power supplies.

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Abbreviations

The following abbreviations are used in this manuscript:

GFB	Gas Foil Bearing
SMA	Shape Memory Alloy
PZT	Piezoelectric Transducer
TEM	Thermoelectric Module
TC	Thermocouple
MFC	Macro Fiber Composite

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