World Electric Vehicle Journal

MDPI

Review

Review of Emerging Hybrid Gas–Magnetic Bearings for Aerospace Electrical Machines

Mohammad Reza Karafi [1] and Pedram Asef [2,3,*]

[1] Faculty of Mechanical Engineering, Tarbiat Modares University, Tehran 111-14115, Iran; karafi@modares.ac.ir
[2] e-Motion Laboratory, Mechanical Engineering Department, University College London (UCL), London WC1E 6BT, UK
[3] Advanced Propulsion Laboratory, Mechanical Engineering Department, University College London (UCL), London E20 3BS, UK
* Correspondence: pedram.asef@ucl.ac.uk

Abstract

Hybrid Gas–Magnetic Bearings (HGMBs) are an emerging technology ready to completely change high-speed oil-free rotor support in aerospace electric motors. Because HGMBs combine the stiffness and load capacity of gas bearings with the active control of magnetic bearings, enabling oil-free, contactless rotor support from zero to ultra-high speeds. They offer more load capacity of standalone magnetic bearings while maintaining full levitation across the entire speed range. Dual-mode operation, magnetic at low speeds and gas film at high speeds, minimizes control power and thermal losses, making HGMBs ideal for high-speed aerospace systems such as cryogenic turbopumps, electric propulsion units, and hydrogen compressors. While not universally optimal, HGMBs excel where extreme speed, high load, and stringent efficiency requirements converge. Advances in modeling, control, and manufacturing are expected to accelerate their adoption, marking a shift toward hybrid electromagnetic–aerodynamic rotor support for next-generation aerospace propulsion. This review provides a thorough overview of emerging HGMBs, emphasizing their design principles, performance metrics, application case studies, and comparative advantages over conventional gas or magnetic bearings. We include both a historical perspective and the latest developments, supported by technical data, experimental results, and insights from recent literature. We also present a comparative discussion including future research directions for HGMBs in aerospace electrical machine applications.

Keywords: gas bearing; magnetic bearing; electrical machines; hybrid bearing; aerospace; electrification

check for updates

Academic Editor: Hui Yang

Received: 24 October 2025
Revised: 27 November 2025
Accepted: 1 December 2025
Published: 8 December 2025

Citation: Karafi, M.R.; Asef, P. Review of Emerging Hybrid Gas–Magnetic Bearings for Aerospace Electrical Machines. *World Electr. Veh. J.* **2025**, *16*, 662. https://doi.org/10.3390/wevj16120662

1. Introduction

Aerospace propulsion and power systems demand bearing technologies that can sustain extreme speeds and temperatures without lubrication. Traditional rolling bearings in jet engines face limitations, such as friction, wear, lubrication requirements, and speed constraints [1]. Even advanced ceramic or hybrid rolling bearings, while more durable, still suffer from reduced lifespan and high-speed limitations in aerospace conditions [2]. This has spurred the development of contactless bearing concepts, notably gas (air) bearings and active magnetic bearings, which eliminate mechanical contact and lubrication [3].

The electrification of aircraft propulsion has become one of the most significant technological transformations in the aerospace industry. The pursuit of lower emissions, noise reduction, and improved energy efficiency has motivated extensive research into electric and hybrid-electric aircraft architectures, where electric motors serve as the core propulsion elements [4–6]. Electric aircraft architectures require propulsion systems with high power-to-weight ratios, compact geometry, fault tolerance, and reliable thermal management to meet strict aviation constraints on mass, safety, and performance [4,6]. To achieve these goals, researchers have explored a wide range of motor topologies, including permanent magnet synchronous machines (PMSMs) [7–10], switched reluctance machines (SRMs), axial-flux permanent magnet machines (AFPMs) [11,12], and even superconducting motors [13–15], each offering different trade-offs in torque density, efficiency, and cooling strategy [16–19]. Among these, PMSMs and AFPMs have demonstrated excellent torque density and efficiency, making them strong candidates for distributed propulsion and electric taxiing systems in next-generation aircraft [20,21].

Recent developments in superconducting and high-speed motor technologies are pushing performance boundaries even further. The ASuMED project, for example, demonstrated a fully superconducting 1 MW motor concept achieving specific powers exceeding 20 kW/kg, representing an order-of-magnitude improvement over conventional designs [16,18,22]. These advances, however, introduce substantial engineering challenges, particularly in cryogenic cooling, AC loss minimization, and system integration within the aircraft environment [17,22]. Concurrently, significant progress has been reported in lightweight axial-flux designs tailored for electric taxiing and distributed propulsion, which reduce torque ripple and enable efficient power transmission within compact airframe geometries [19,20]. Despite these achievements, further research is still required in thermal management, insulation materials, and control algorithms to ensure reliability and certification compliance under aviation operating conditions [5,6,21].

Gas bearings or gas foil bearings (GFBs) have become an attractive bearing technology for aerospace high-speed electric machines because they eliminate oil systems (reducing weight and contamination risk), tolerate extreme temperatures, and exhibit low steady-state friction at high rotational speeds [23,24]. Extensive theoretical and experimental work has characterized foil bearing static performance (load capacity, minimum film thickness) and rotor dynamic behavior (stiffness, damping, sub-synchronous motions), showing that careful top-foil and bump-foil design plus coupled thermo-elasto-hydrodynamic modeling are essential to predict performance for aircraft applications (ACMs, turboexpanders, oil-free compressors, and high-speed motors) [25,26]. Practical studies and test rigs that drive rotors with permanent-magnet electric motors demonstrate that polymer-coated and multi-layer foil constructions can improve start/stop behavior and wear resistance for motor-driven test rigs [27,28], while start/stop, thermal-failure risk, and transient instability remain active research topics that directly affect electric-motor integration and control strategies [29,30]. Advances in finite-element top-foil models and thermo-hydro-dynamic coupling have improved prediction accuracy for foil stiffness and damping/damping and minimum film thickness, under realistic operating temperatures and loads. This is particularly important when motors must handle transient loads and touchdown events without oil backup [25,26,31]. Recent parametric and numerical investigations of bump-foil and multilayer thrust designs, and studies on helium hydrostatic gas bearings for ultra-high-speed rotors, show routes to increase load capacity, reduce heating, and extend gas-bearing applicability toward aerospace power systems and cryogenic applications (space/aircraft) where electric motors operate at very high specific powers [24,30,32]. Gas bearings use a thin film of air (or gas) to support the rotor, providing low friction and high-speed capability. They can be self-acting (e.g., air-foil bearings that generate a pressure film via rotation) or externally pressurized (hydrostatic gas bearings) [33]. However, they typically require a minimum rotor speed or external pressure to generate load capacity, making pure gas bearings unreliable during startup or low-speed operation. They also have limited damping, which can lead to sub-synchronous rotor vibrations and stability issues at certain speeds [3].

Active magnetic bearings (AMBs) are especially attractive for aerospace electric-motor applications because they provide contactless, oil-free rotor support, enable active vibration suppression, and offer built-in health monitoring and fault-tolerant design strategies, all of which help meet aviation requirements for low maintenance, contamination-free operation, and high reliability at extreme speeds and temperatures [34,35]. Numerous experimental and analytical studies demonstrate that AMBs can substantially reduce rotor-borne vibration and improve rotor dynamic stability for high-speed permanent-magnet and superconducting motors used in propulsion or auxiliary power units. While their active control allows stiffness/damping shaping to mitigate gyroscopic and unbalance effects that are common at aircraft operating regimes [36,37]. Because aircraft systems must tolerate single-point failures, the AMB literature places heavy emphasis on fault-tolerant topologies (e.g., flux-invariant/biased homopolar designs, heteropolar arrangements, and current-redistribution schemes) and fault-tolerant control algorithms; these enable continued safe operation after coil, amplifier, or controller faults and have been validated on flexible high-speed rotor test rigs relevant to aerospace practice [38–40]. Recent advances in robust and adaptive control (H∞, μ-synthesis variations, model-predictive and fuzzy/variable-gain controllers) and reduced-power, permanent-magnet-biased AMB designs reduce control power consumption and improve rejection of synchronous disturbances, important for aircraft where electrical power and mass budgets are constrained [41,42]. Finally, the AMB community has produced many application-oriented studies (controller synthesis anchored to accurate rotor models, design methods to minimize AMB power loss, and experimental demonstrations on motor-driven rotors) that together show AMBs can enable oil-free, high-speed electric machines for aerospace provided careful attention is paid to controller certification, backup touchdown design, power-electronics thermal management, and system-level mass/power trade-offs during aircraft integration [34,36,37,43]. Magnetic bearings suspend the rotor using electromagnetic forces, actively controlled to maintain position. They excel at zero and low-speed support (including static levitation) and eliminate friction completely [2]. Magnetic suspensions allow precise rotor control and condition monitoring via feedback systems [44]. In aerospace motors, including electric jet engines, rocket turbopumps [45], and AMBs have been explored to replace oil-lubricated bearings, removing the weight and complexity of lubrication systems [46]. Yet, magnetic bearings have limitations in load capacity and efficiency. The magnetic force saturates for large loads; they require heavy electromagnets and continuous power. They generate significant heat from eddy currents and hysteresis, especially at high speeds. They also rely on complex control and backup safety bearings in case of power failure or overload.

Hybrid Gas–Magnetic Bearings (HGMBs) are designed to combine the complementary strengths of gas and magnetic bearings while mitigating their weaknesses [47]. By merging a gas bearing and an active magnetic bearing into one system, an HGMB can provide robust support across the full speed range:

- At startup and low speeds (<1000 rpm), the magnetic bearing component actively levitates the rotor (since a gas film is not yet established);
- At high speeds (>10,000 rpm), the gas film supports most of the load with minimal power loss, while the magnetic bearing can either offload or provide damping and stability control;
- At medium speeds (1000–10,000 rpm), both gas and magnetic bearings contribute to performance to some extent;

- In case one component fails or becomes insufficient (e.g., magnetic system fault or gas film collapse during a shock), the other can temporarily back up the rotor support, greatly improving reliability.

The aerospace sector has driven the development of HGMBs as part of the push for "oil-free" engines and high-speed turbomachinery. For example, small gas turbine power units and turbo compressors have successfully used gas foil bearings but needed improved damping at certain critical speeds [48]. Active magnetic bearings have been implemented in cryogenic rocket turbo pumps to avoid oil in oxygen-rich environments, but sustaining very high speeds solely on magnetic support is challenging [3]. HGMBs promise a solution by tripling the load capacity compared to magnetic bearings alone and maintaining rotor stability across a broad operating envelope. This review paper provides a comprehensive analysis of HGMBs, focusing on their design principles, operational mechanisms, performance characteristics, and representative application demonstrations. It also compares HGMBs with conventional bearing technologies used in aerospace electric propulsion systems. Beyond synthesizing existing literature, this review offers a critical evaluation of HGMBs by highlighting the fundamental limitations of different bearing types, identifying unresolved technical challenges, assessing practical implementation barriers, and outlining future research directions for aerospace applications.

2. Historical Overview of HGMB Development

The concept of combining magnetic and gas bearings dates back two decades, as researchers sought to exploit their complementary features. Early milestones are shown in Figure 1.

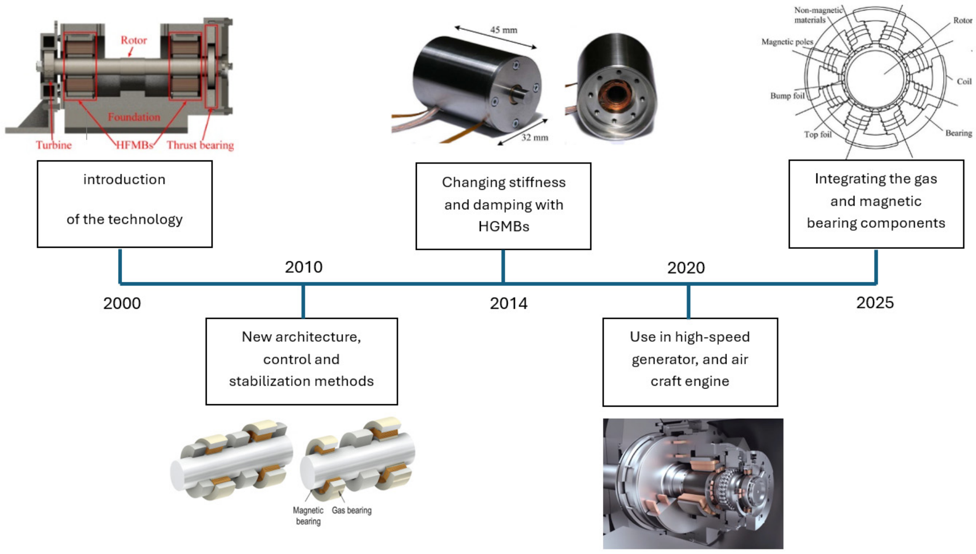


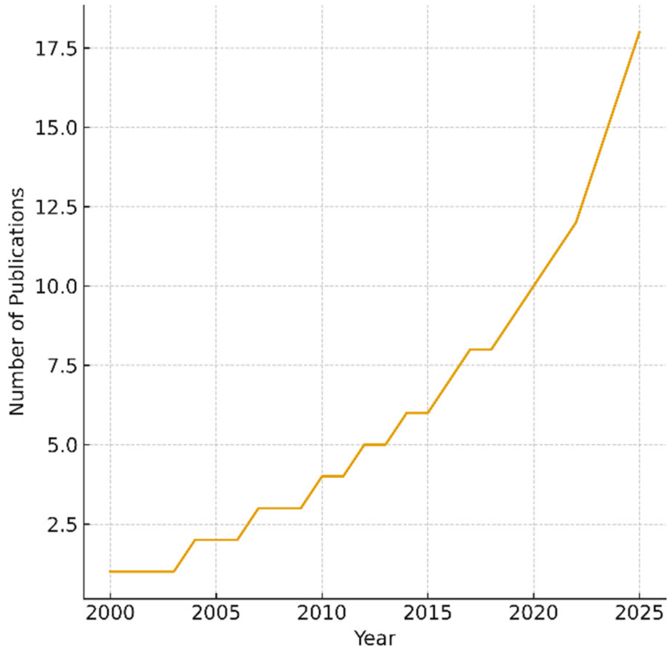
Figure 1. Timed graph to show the milestones in the HGMB technology.

- In the 2000s: Advances in foil air bearings and AMBs laid the groundwork for hybridization. By 2000, Heshmat et al. [1] reported that merging foil (gas) bearings with magnetic bearings was possible and extremely attractive, envisioning a bearing that takes advantage of the strengths of each while minimizing each other's weaknesses. Early theoretical studies proposed active control of foil bearings and the idea of magnetic augmentations to improve stability. Swanson et al. [2] built and tested a hybrid foil-magnetic bearing for a small turbine engine rotor (31–53 kN thrust class). In tests, the velocity reached up to 30,000 rpm, and the hybrid bearing shared the rotor load between a compliant airfoil journal bearing and an active magnetic bearing. At

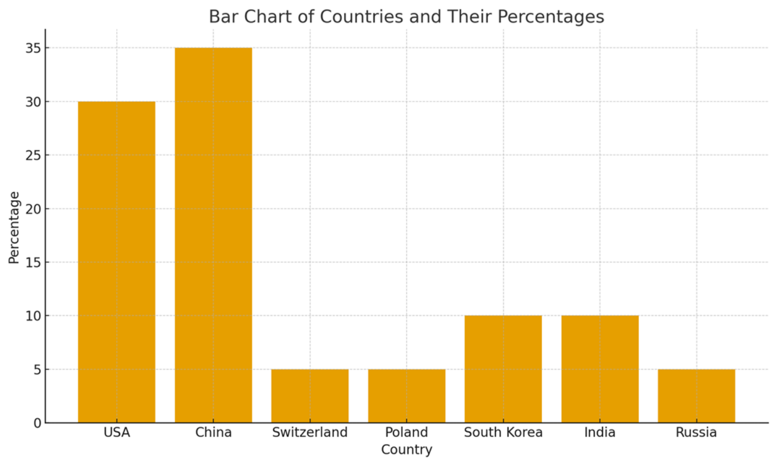
22,000 rpm, the hybrid bearing carried over 5300 N of load. Notably, this tripled the load capacity compared to the AMB alone, demonstrating the huge load advantage of adding a gas bearing. A custom control algorithm adjusted the magnetic force to actively tune load sharing. The rotor ran stably with small vibrations, and when the magnetic coils were deliberately shut off, the foil bearing alone safely supported the rotor at full speed until a controlled coast-down was executed. This experiment proved the feasibility of HGMBs for high-speed turbomachinery and their fail-safe potential. Following the initial success, hybrid bearing research continued, especially in contexts requiring oil-free operation and oil-free turbomachinery applications. In 2002, a refined version of the hybrid bearing was published [3], confirming the earlier Turbo Expo results and garnering wider attention (cited by dozens of subsequent works). In 2003 [49], a large 150 mm diameter hybrid foil-magnetic bearing was experimentally investigated for heavy-duty turbomachines, further demonstrating scalability. Meanwhile, active magnetic bearings alone had begun seeing use in specialized aerospace applications like control moment gyroscopes and rocket engine turbopumps. Pushing the need for fault-tolerant designs and highlighting the appeal of hybrid backup support.

- In the 2010s: Control Integration and New Architectures. Research in the 2010s addressed the rotor dynamic stability issues of gas bearings by leveraging magnetic actuators as dampers. For instance, Looser et al. in 2014 [48] developed an active magnetic damper to stabilize a high-speed rotor on gas bearings, effectively a form of hybrid support where the magnetic system provides damping. They found that by tuning the magnetic bearing's control stiffness, they could suppress the rotor vibration modes that pure gas bearings struggled with. By the late 2010s, several patents on air-foil magnetic hybrid bearings and numerous prototypes had emerged, indicating growing maturity. However, these systems often used a "nested" configuration, the magnetic bearing and foil bearing were separate components arranged in the same housing or one inside the other, which increased complexity and size.
- In the 2020s: Recent Developments. The past few years have seen a surge of interest in HGMBs, driven by the needs of cryogenic electrical machines, high-speed generators, and hydrogen economy applications. Liu et al. in 2021 [46] published an extensive review summarizing the state-of-the-art in HGMB theory, simulations, and experiments up to 2020. They highlighted inherent challenges in design, analysis, and control that needed to be solved for reliable operation. Building on this, researchers have proposed single-structured HGMBs, where a single device acts as both a gas and magnetic bearing, eliminating duplicate components. Falkowski et al. in 2022 [45] present a detailed study on the design of magnetic bearings specifically for electric jet engine rotors. By 2024, Liu et al. [50] introduced a single-structure HGMB tailored for high-speed cryogenic turboexpanders, such as hydrogen liquefaction turbines. This design integrates the magnetic poles as the journal for the gas bearing, drastically simplifying the assembly and raising the system's critical speeds. The proposed HGMB design used one bearing at each end of the rotor, each bearing being both magnetic and gas journal. Simulation and analysis verified that the design could support the rotor throughout its operating map and offered simpler construction and higher critical speeds than an equivalent foil bearing design. Ha et al. in 2024 [51] investigated the application of an Integrated Hybrid Air-Foil Magnetic Thrust Bearing (i-HFMTB) in a 250 HP air compressor system. Their work demonstrated that conventional air-foil journal bearings often suffer from rigid-mode instabilities, such as sub- and super-synchronous vibrations, which can limit system performance and reliability. By combining the passive load-supporting capacity of air-foil bearings

with the active vibration control of magnetic bearings, the i-HFMTB successfully suppressed these instabilities. Concurrently, advanced modeling in 2025 quantified the performance trade-offs (like clearance effects) to guide HGMB optimization. These latest works mark a transition of HGMBs from experimental novelty towards practical design methodologies for aerospace applications. Figure 2 shows some information about the number of papers and countries that conducted the studies on HGMBs in aerospace motors.



(**a**)



(**b**)

Figure 2. (**a**) Number of papers per year from 2000 to 2025 and (**b**) countries that studied/developed HGMBs in aerospace motors.

Table 1 summarizes selected aerospace programs and research prototypes employing or evaluating HGMB technology, such as NASA's turboelectric distributed propulsion systems and ESA's cryogenic turbopumps. Each entry lists typical operating conditions (rotational speed, load, and temperature range).

Table 1. Representative aerospace applications and performance requirements relevant to HGMBs [1,4,50].

Aerospace System	Typical Speed Range	Operating Temperature	Radial Load Capacity Required	Environment/ Working Fluid	Technical Motivation for HGMB
Cryogenic H_2 Turbo-Expander (Hydrogen liquefaction, ESA/industry) [50]	40,000–70,000 rpm	20–90 K	200–800 N	Hydrogen, cryogenic	Minimize magnetic coil heating; oil-free; maintain stiffness at cryogenic viscosity
Rocket Turbopump (LOX/LH_2 environment) [1]	20,000–35,000 rpm	300–600 °C transient	3–6 kN	Liquid oxygen or hydrogen	No oil allowed; tolerate high shock load; fail-safe capability during magnetic shutdown
Electric Aircraft High-Speed Propulsion Motor [4] NASA's Turboelectric Distributed Propulsion, Airbus ZEROe	20,000–40,000 rpm	100–200 °C	500–1500 N	Air; high-altitude low-density	Reduce losses, suppress vibration; lightweight oil-free support for distributed propulsion

3. Design Principles of Gas, Magnetic, and Hybrid Bearings

Before diving into HGMB specifics, it is important to understand the operating principles of the two constituent technologies, gas bearings and magnetic bearings, and how they can be combined.

3.1. Principles and Performance of Gas Bearings

Gas bearings support rotors on a cushion of pressurized gas (usually air). The two main types of gas bearing are discussed in the following subsections.

3.1.1. Hydrodynamic Gas Bearings

Hydrodynamic (self-acting) gas bearings, such as air-foil bearings, use the rotor's motion to generate a pressurized gas film that supports the load. Foil journal bearings add compliant, elastic layers that tolerate misalignment and provide some damping. These bearings are well-suited for aerospace applications due to their ability to support high loads at elevated speeds with minimal friction, even in high-temperature environments without the need for lubrication. However, at low speeds or during standstill, they offer no load support, and their inherently low stiffness and damping can lead to rotor instabilities. Mitigation strategies include lift-off assist mechanisms, such as magnetic bearings, and the incorporation of additional structural damping. Figure 3 shows the hydrodynamic gas bearings component.

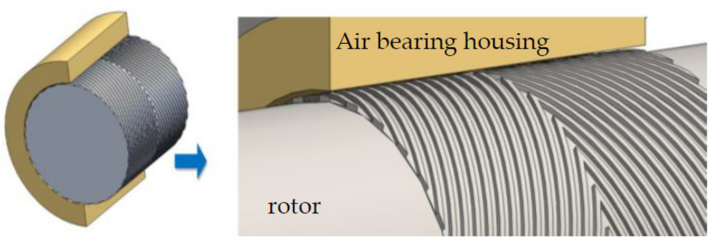


Figure 3. Hydrodynamic gas bearings.

A hydrodynamic air bearing works by using the relative motion of its surfaces to generate high-pressure air, which creates a "fluid wedge" that lifts the rotating surface and separates it from the stationary one. The high speed of the surfaces pulls air into a converging channel, compressing it and generating enough pressure to support a load, eliminating physical contact except during startup and shutdown. Herringbone grooves machined into aerodynamic bearings are well known to produce improvements in bearing stiffness and stability at high operating speeds.

3.1.2. Hydrostatic Gas Bearings

Externally pressurized (hydrostatic) gas bearings maintain a pressurized gas film using an external supply, allowing load support even at zero speed and providing high stiffness [46]. They require continuous gas and complex plumbing, which limits their use in aerospace applications, but they set a performance benchmark [52]. Gas bearings generally enable high-speed, low-wear operation with negligible friction, as seen in micro-turbines and auxiliary power units. Key performance metrics include load capacity and stiffness/damping [49], which affect rotor vibrations. Pure gas-supported rotors can still experience instabilities, often mitigated using hybrid magnetic dampers. Figure 4 exhibits the components of a typical hydrostatic gas bearing.

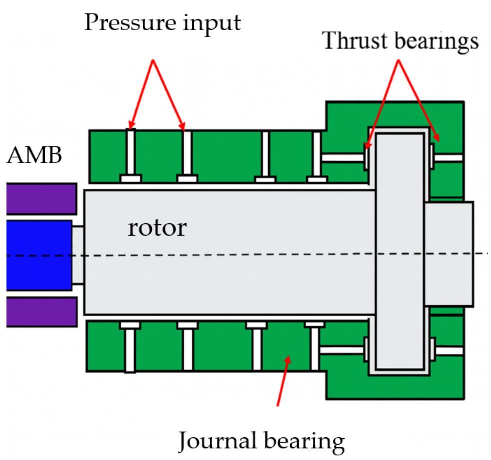


Figure 4. Hydrostatic gas bearings. Note that the pressure input, thrust bearings, and journal bearings correspond respectively to the pressurized-gas supply, the axial-motion prevention mechanism, and the radial hydrostatic gas bearing.

A hydrostatic air bearing works by externally supplying pressurized air into a gap between two surfaces, creating an air cushion that keeps them separated and allows for frictionless movement. When a load is applied, the gap on the loaded side closes, increasing air pressure and resistance to airflow, while the opposite side opens, reducing resistance and pressure. This pressure difference generates a restoring force that supports the load without any contact between the surfaces. In Figure 4, there is a magnetic bearing on the left and a hydrostatic bearing on the right. The air bearing restrains radial and axial forces. It consists of radial and thrust bearings.

3.2. *Principles and Performance of Magnetic Bearings*

Magnetic bearings use electromagnetic actuators to support the rotor without contact. Figure 5 shows a schematic view of a magnetic levitation system.

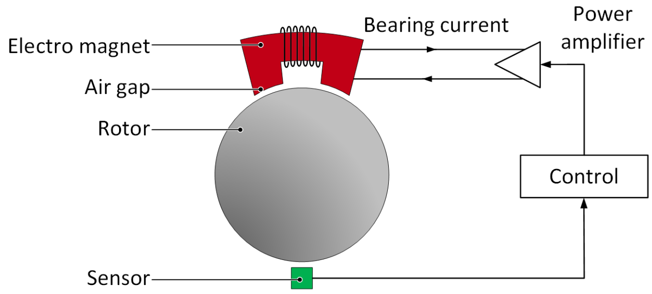


Figure 5. Schematic view of a magnetic levitation system.

In an active magnetic bearing system, sensors detect the radial position of the rotor. This feedback is sent to the control system, which then sends an exciting signal to the amplifier and then to the stator winding. By exciting the coil, the rotor position is adjusted to a predefined position set by the controller.

The most common are active magnetic bearings (AMBs), which actively control rotor position via feedback loops. A variety of controllers, such as PID [49], adaptive nonlinear control [44], optimal control [53], sliding mode control [54], robust control [55], fuzzy control [56], neural network control [57], and gain scheduling, speed-dependent control [58] have been used to control AMBs. A typical AMB has rotor-mounted ferromagnetic targets and stator coils. By regulating the coil currents, the system produces forces that center the rotor. Key features of an AMB are:

I Zero-Friction, Active Control: Because there is no physical contact, friction is eliminated, and there is no need for lubrication. This yields potentially unlimited life (no wear) and no contamination, critical for high-purity or vacuum environments (e.g., oxygen turbopumps, space applications). An AMB system continually monitors rotor position (usually with eddy-current sensors) and adjusts currents to maintain stability [45]. This active control can also deliberately adjust stiffness and damping by feedback gains, allowing tunable rotor support. For instance, an AMB can be made “softer” or “stiffer” in real-time operations, and can inject damping to quench vibrations [3]. Such capability is impossible in passive bearings and is very attractive for managing critical speeds and transient loads.

II Load Capacity and Bias Currents: Magnetic bearing load capacity depends on magnetic flux, limited by material saturation and heating [4]. Bias currents linearize force but cause continuous power loss, while zero-bias designs reduce losses at the cost of nonlinearity and lower stiffness [3]. Compared to gas bearings, AMBs are less stiff, allowing the rotor to “float,” which can be advantageous by lowering critical speeds and promoting self-centering, thus widening the stable operating range.

III Auxiliary Systems: An AMB setup demands a control system, power electronics, and backup bearings. The control hardware monitors sensor signals and drives the actuator coils. If the magnetic power or control fails, the rotor must safely coast on backup (usually rolling element) bearings [2], which are only engaged in emergencies. This need for redundant support and continuous power is a disadvantage of magnetic bearings in aerospace applications, where a sudden power loss could cause loss of support. However, in a well-designed system, magnetic bearings have been shown to handle rapid dynamic loads and shock inputs better than mechanical bearings, because the active control can react to disturbances [46]. They have been researched for decades and are now used in niche but critical applications, such as satellite reaction wheels, turboexpanders, and experimental electric aircraft engines [46].

4. Hybrid Bearing Configurations and Design Approaches

HGMBs integrate the complementary advantages of gas and magnetic bearings while compensating for their individual limitations. By uniting a gas bearing with an active magnetic bearing in a single system, HGMBs are capable of delivering stable and reliable rotor support throughout the entire operating speed range. The AMB compensates for the lack of damping, and the air bearing compensates for the lack of stiffness in a hybrid system. Several architectures have been explored to implement HGMBs:

I Nested or Concentric Bearings: An early approach is to physically collocate a gas bearing and a magnetic bearing around the same rotor journal. The nested layout saves space (shorter rotor length than two separate bearings) and was used in several prototypes. However, it requires a fairly complex construction (embedding foil pads within a magnetic circuit) and precise alignment [52,59].

II Series (Axial) Arrangement: Another approach simply places a magnetic bearing next to a gas bearing along the shaft. This is easier to implement (each bearing retains its own structure), and the control strategy can modulate how load is shared (e.g., through a coupling or compliance). The downside is a longer rotor and potential dynamic coupling issues [1,60]. Figure 6 reveals these two types. The air bearing housing is made of a porous, non-ferromagnetic material such as aluminum or ceramic. In contrast, the magnetic bearing stator is made of ferromagnetic iron and has a laminated structure to prevent the generation of eddy currents within it.

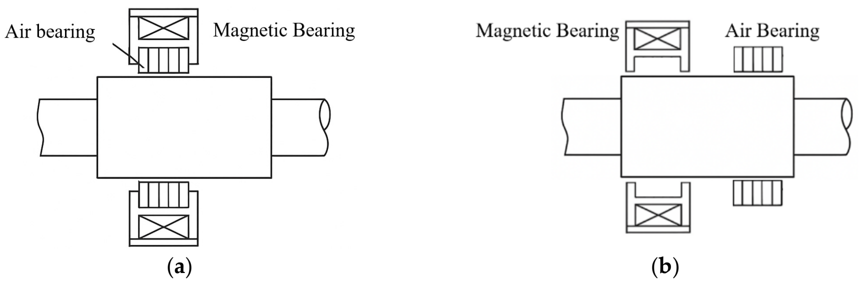


Figure 6. (**a**) nested configuration and (**b**) series configuration of HGMBs.

For the side-by-side type, the lower-order critical speeds (which cause resonance in the rotor) can be altered by bearing positions or lengths, yet the rotor length is extended, and bearing concentricity is demanded. As for the nested configuration, the gas bearing is inserted in the gap between the inner diameter of the magnetic bearing and the rotor. The space inside the AMB that traditionally contains the coils is used as the gas bearing's housing by molding with an epoxy that has no magnetic properties. Heshmat [58,61] patented the nested configuration and proposed a load-sharing strategy associated with rotating speeds. The power input of the magnetic bearing is adjusted in response to the rotor position and rotating speed. The magnetic force is reduced as the rotational speed climbs, while it increases as the rotational speed decreases.

III Integrated Single-Structure HGMB: The latest designs strive to truly integrate both functions into one bearing element [48]. In a single-structured HGMB, the goal is that the same physical gap and surfaces serve as both the magnetic bearing air gap and the gas film clearance. This eliminates separate foil structures or external gas feeds where the gas film is a simple clearance between the rotor and the stator sleeve. The main difficulty here is clearance compatibility: Magnetic bearings typically need a larger gap on the order of 0.5–1 mm for large AMBs to avoid saturating and to allow enough control range. Whereas gas bearings work best with very small clearances on the order of 50 μm to generate high pressure [46]. This design has been specifically proposed for cryogenic turboexpanders used in hydrogen liquefaction, which require frequent start-stop cycles and ultra-high speeds of 70,000 rpm. In such electrical machines, traditional oil bearings cannot be used due to contamination/viscosity issues [48], and pure magnetic bearings would generate too much heat and consume too much power at high speed in a vacuum-like environment. A single-structured HGMB can provide the needed performance while minimizing frictional losses and complexity [50]. Figure 7 shows an integrated Single-Structure HGMB.

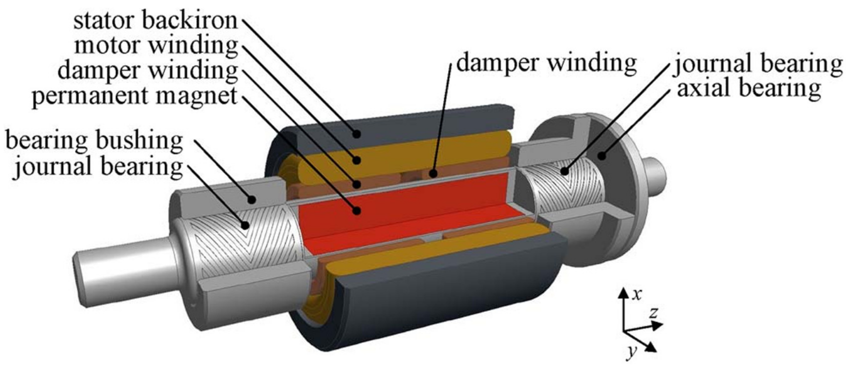


Figure 7. Integrated Single-Structure HGMB [48].

IV Zero-Bias Magnetic Hybrid: A variant in design philosophy is using zero-bias AMB in the hybrid to further reduce power loss and heating. Typically, AMBs use bias currents [3]; however, a "zero-bias HGMB" means the magnetic bearing part has no DC and only actively provides corrective forces as needed. Without bias, the magnetic stiffness is lower [46]. Therefore, the gas bearing must carry more of the static load. Liu et al. in 2025 [62] examined a single-structured HGMB under zero-bias operation. They simulated that while a zero-bias AMB alone had reduced load capacity and dynamic stiffness, combining it with a rigid gas bearing allowed the hybrid to function well even with zero bias. The benefit was a significant reduction in power consumption and heat generation compared to a traditional biased HGMB or pure AMB. The zero-bias HGMB performed ideally for light loads at ultra-high speeds or in cryogenic environments where any heat is problematic. This suggests that future HGMBs do not need bias current, making the system more efficient for aerospace applications, where every Watt of waste heat counts heavily.

Design Trade-Offs and Integration Challenges

The integration of gas and magnetic bearing within a single bearing architecture introduces fundamental design trade-offs that strongly influence load capacity, stiffness, damping, and thermal stability. The challenge lies in reconciling the conflicting requirements of the magnetic and gas subsystems while maintaining compactness and reliability for aerospace use.

Magnetic bearings typically require relatively large air gaps, typically 0.5–1 mm, to prevent magnetic saturation and to provide adequate room for rotor dynamic control. In contrast, gas bearings develop pressure through viscous shearing in a thin gas film and, therefore, operate most effectively with clearances on the order of 10–80 µm. These two orders of magnitude difference impose a serious integration challenge. A clearance optimized for the magnetic subsystem leads to insufficient gas film pressure at high speed, whereas one optimized for the gas subsystem risks magnetic instability or rotor–stator contact during transients.

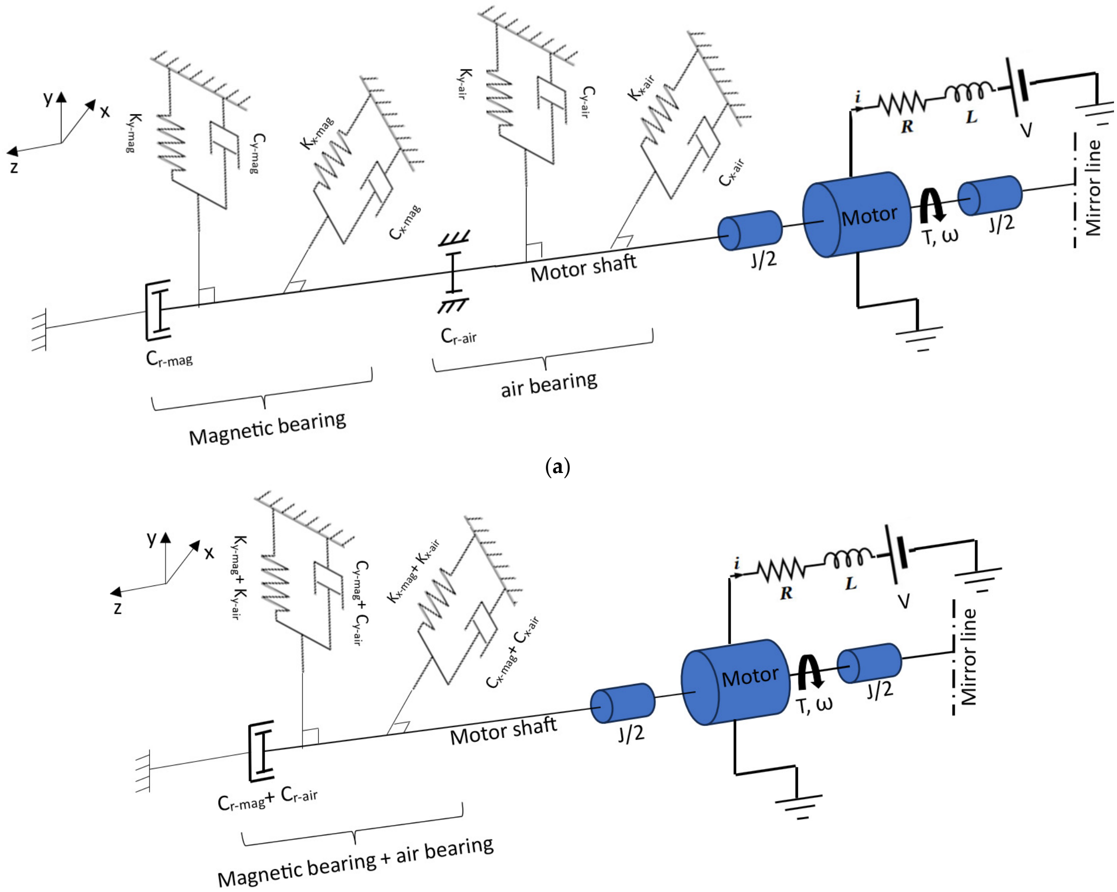
To balance these conflicting demands, multi-zone or stepped clearance geometries have been proposed in series arrangement configurations, in which a central magnetic zone maintains a larger gap while peripheral gas film lands employ smaller gaps. In the case of a nested configuration, there is a single clearance shared by both systems. However, because a large portion of the load is supported by the hydrostatic air bearing, the excitation current required by the magnetic bearing is significantly reduced, which in turn lowers the risk of magnetic saturation. In addition, the housing of the air bearing is usually made of non-ferromagnetic material, creating a separation between the stator and rotor that further helps prevent saturation. Active control strategies can also be used to dynamically adjust the magnetic lift so that the rotor gradually centers itself as the hydrodynamic pressure builds up. Such clearance optimization directly affects the overall stiffness–damping trade-off: increasing clearance enhances damping but reduces load capacity, while smaller gaps increase stiffness but raise the risk of instability.

Thermal behavior represents another key integration issue. Magnetic actuators generate Joule and eddy-current losses proportional to current and frequency, while gas bearings experience viscous shear heating within the thin film. These effects can interact nonlinearly. A temperature rise reduces gas viscosity, lowering film pressure and stiffness, while simultaneously increasing the resistivity and potential demagnetization in magnetic materials. Effective thermal management, therefore, requires a coupled analysis of heat generation and transfer between the magnetic coils, rotor surface, and gas film. Design strategies include segmented coil winding with active cooling channels, high-thermal-conductivity laminations, and optimized gas film venting to enhance convective heat removal. In cryogenic applications, temperature gradients can also alter the magnetic permeability and gas properties, requiring careful compensation in both material choice and control algorithms.

Material compatibility governs both performance and longevity of HGMBs in aerospace systems. Structural components often employ Inconel, titanium alloys, or Si_3N_4 ceramics to maintain stiffness at high temperatures while minimizing eddy-current losses. The magnetic core typically uses laminated Fe–Si or amorphous alloys to reduce hysteresis losses, whereas the gas film surfaces require superfinished coatings such as diamond-like carbon (DLC) or molybdenum disulfide to resist wear and oxidation. For cryogenic or high-vacuum environments, materials must retain magnetic properties and dimensional stability under large thermal gradients. Hybrid material stacks combining soft-magnetic composites with non-magnetic heat-resistant layers have shown promise for balancing magnetic efficiency with thermal endurance.

Overall, the successful realization of HGMBs depends on the co-optimization of electromagnetic, fluid-dynamic, and thermal parameters. Achieving stable operation across both magnetic and gas-dominated regimes requires a balanced clearance design, efficient heat management, and careful material engineering. These interrelated factors define the true design space of next-generation aerospace HGMBs.

Figure 8 presents an electromechanical model of a series and nested configurations of HGMBs. In this graph, the parameters R, L, V, i, J, T, ω, $C_{r\text{-air}}$, $C_{r\text{-mag}}$, $K_{y\text{-mag}}$, $K_{x\text{-mag}}$, $C_{x\text{-mag}}$, $C_{y\text{-mag}}$, $K_{y\text{-air}}$, $K_{x\text{-air}}$, $C_{y\text{-air}}$, $C_{x\text{-air}}$ stand for resistance of the motor winding, inductance of the motor winding, voltage, current, moment of inertia of the motor shaft, torque, rotational speed, rotational damping of the air bearing, rotational damping of magnetic bearing, magnetic bearing stiffness in y direction, magnetic bearing stiffness in x direction, magnetic bearing damping in x direction, magnetic bearing damping in y direction, air bearing stiffness in y direction, air bearing stiffness in x direction, air bearing damping in the y direction, air bearing damping in the x direction, respectively.



(**a**)

(**b**)

Figure 8. Schematic approximation of (**a**) series, (**b**) nested configuration of HGMBs.

In this model, the shaft of the electric motor is assumed to be rigid. Both the magnetic bearing and the air bearing exhibit rotational damping or losses. The rotational damping in the air bearing arises from the shear deformation of the air film between the shaft and the bearing housing, whereas the rotational damping in the magnetic bearing results from eddy current formation within the motor shaft.

In addition to rotational damping, both bearings possess stiffness and damping in the x and y directions, as illustrated in Figure 8. The stiffness and damping of the magnetic bearing in these directions can be adjusted by controlling the excitation currents in the coils and through its feedback controller. Similarly, the stiffness and damping of the air bearing can be tuned by varying the air supply pressure and adjusting the viscosity of the working fluid.

To facilitate the electromechanical modeling and design of HGMBs, it is advantageous to represent the system using an equivalent electrical circuit. The equivalent circuit diagram of the electromechanical model of an HGMB is shown in Figure 9. In these equivalent circuits, the parameters F_x, F_y, M, $\dot{x}$, $\dot{y}$, L', R' are force in x direction, force in y direction, mass of the motor shaft, the velocity in x direction, the velocity in y direction, converted value of the inductor from the secondary of the transformer to the primary, and converted value of resistance, respectively.

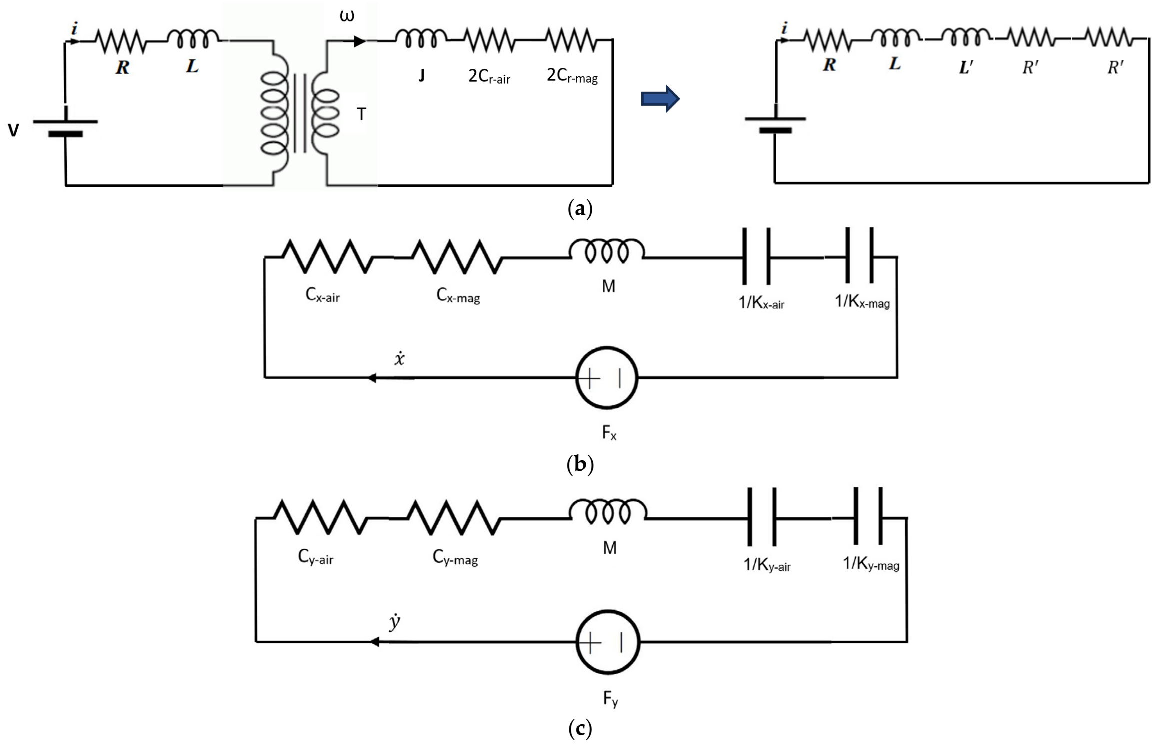


Figure 9. The equivalent circuit diagram of the electromechanical model of an HGMB, (**a**) in rotational direction, (**b**) in x direction, (**c**) in y direction.

It is possible to calculate the current consumption of the motor using Equation (1).

$$\left(R + 2R'\right)i + \left(L + L'\right)\frac{di}{dt} = V \tag{1}$$

To determine the displacements of the motor shaft in the x and y directions, the equivalent circuits shown in Figure 8b,c can be solved. The current in each of these circuits corresponds to the shaft velocity in the x or y directions, and its integral represents the displacement. The governing equations for these two circuits are given in Equations (2) and (3). The solutions of these differential equations provide the displacement, velocity, and acceleration responses of the system.

$$M\ddot{x} + \left(C_{x-air} + C_{x-mag}\right)\dot{x} + \left(K_{x-air} + K_{x-mag}\right)x = F_x \tag{2}$$

$$M\ddot{y} + \left(C_{y-air} + C_{y-mag}\right)\dot{y} + \left(K_{y-air} + K_{y-mag}\right)y = F_y \tag{3}$$

The dynamic behavior of HGMBs results from a strong electromechanical coupling between the magnetic circuit and the compressible gas film. A complete theoretical description requires simultaneous consideration of electromagnetic, fluid-dynamic, and mechanical domains. The gas film is resolved using computational fluid dynamics (CFD) solvers under thin-film assumptions, while magnetic flux density and Lorentz forces are computed in finite element (FEM) electromagnetic domains. Iterative data exchange between the two solvers enables convergence of pressure and field distributions. Modern implementations utilize reduced-order coupling schemes or co-simulation frameworks such as ANSYS–Fluent–Maxwell 2025 R2 or COMSOL Multiphysics 6.3. These methods capture cross-domain effects with high fidelity but require considerable computational resources. These methods can be used to evaluate the parameters $C_{r\text{-}air}$, $C_{r\text{-}mag}$, $K_{y\text{-}mag}$, $K_{x\text{-}mag}$, $C_{x\text{-}mag}$, $C_{y\text{-}mag}$, $K_{y\text{-}air}$, $K_{x\text{-}air}$, $C_{y\text{-}air}$, $C_{x\text{-}air}$ in the electromechanical model of the HGMB.

For preliminary design, linearized stiffness and damping coefficients can be derived assuming small perturbations around the equilibrium position. The combined force, F_{total} on the rotor, may be expressed as the sum of the magnetic bearing force, $F_{mag,}$ and air bearing force, F_{air}.

$$F_{total} = F_{mag} + F_{air} = k_{mag}x + c_{mag}\dot{x} + k_{air}x + c_{air}\dot{x} \quad (4)$$

where k_{mag}, c_{mag} and k_{air}, c_{air} are magnetic and gas film stiffness and damping coefficients, respectively. These simplified equations of 2 and 3 provide qualitative insight but are valid only for small displacements (<10% of clearance) and moderate speeds (<0.5 of the transition speed). The simplified analytical formulation serves as a foundation for control design and parameter optimization.

5. Performance Characteristics and Comparative Analysis

In evaluating HGMBs for aerospace use, several performance metrics are of interest, such as load capacity, stiffness and damping, friction losses (efficiency), temperature and thermal management, complexity, reliability, and overall suitability for high-speed operation. This section compares HGMBs against pure gas bearings and pure magnetic bearings along these lines, highlighting experimental data where available.

5.1. Load Capacity and Speed Range

Load capacity is where HGMBs typically excel. By sharing loads, a hybrid bearing can support heavier rotors or greater forces than either technology alone of similar size [46]. In the 2000 Swanson test [3], the hybrid bearing system supported a load of 5.3 kN, compared to just 1.8 kN sustained by the AMB alone, demonstrating that the foil bearing contributed an additional 3.5 kN of load-carrying capacity. Magnetic bearings by themselves often cannot handle large masses in high-g ($g = 9.8\ \text{m/s}^2$) environments due to magnetic saturation limits. Gas bearings scale with surface area and speed. They can carry very high loads at high speed, e.g., some designs [49] can theoretically hold tens of kN if sized properly and given enough stiffness. HGMBs allow the rotor to reach those high speeds (i.e., 20 k to 100 k rpm) safely so that the gas film can take on the heavy lifting. This is particularly desirable in reusable rocket engine turbopumps and electric aircraft motors, where you might have high radial loads during operation but still need to spin up from zero without contact.

Gas bearings alone usually require exceeding a minimum speed (>1000 rpm) to generate hydrodynamic lift [51]. Magnetic bearings alone have no minimum speed but have an upper speed limit dictated by rotor dynamics and power. Active magnetic bearings have been used up to ~60 k–70 k rpm in laboratory settings for small rotors [46], but above that, eddy current losses and control bandwidth become problematic. In contrast to other bearing types, gas bearings improve with increasing speed, as higher rotational speeds enhance gas film lift, though frictional losses eventually rise as well. In HGMBs, active magnetic levitation enables stable operation from standstill (0 rpm) [3]. While at higher speeds, the gas film becomes the dominant support mechanism. Ensuring efficient and stable performance across a wide speed range. For example, Gandzha et al. in 2022 [33] designed a combined gas–magnetic bearing for a 100 kW microturbine targeting 70,000 rpm continuous operation. Their design utilizes magnetic bearings only for startup and low-speed stabilization, then transitions to gas-dynamic mode at high rpm (up to 70 krpm). This would not be feasible with pure magnetic bearings at that speed/power level due to excessive losses and likely instability, nor with pure gas bearings because of the startup. Thus, HGMBs extend the practical speed range of magnetic bearings and ensure support through the entire speed ramp.

5.2. Stiffness, Damping, and Stability

Some crucial performance aspects are the effective stiffness and damping of the non-contact bearings, which govern the rotor's vibrational behavior.

Magnetic bearings offer actively controlled stiffness [58]. However, in terms of inherent (open-loop) stiffness, they are relatively soft. The rotor is held by a magnetic "spring" whose stiffness is typically on the order of 10^5–10^6 N/m, which is lower than that of a comparably sized fluid film bearing [1]. They make up for this by active stabilization [3], closing the loop adds effective damping and stiffness. If not properly controlled, AMBs can be unstable (the rotor will drift off center, since magnets alone create a negative stiffness). In practice, a well-tuned AMB can exhibit very high effective stiffness at its operational frequency and provide substantial damping by quickly adjusting the current to counteract motion [59].

Gas bearings (especially foil bearings) have high static stiffness due to the thin gas film, where small displacements produce large pressure changes [3]. For instance, externally pressurized gas bearings can have stiffness in the range of 10^7–10^8 N/m for large sizes [1]. However, they often have low damping. Gas has little viscosity (especially air); therefore, it does not dissipate much energy. Some damping comes from the material of foil bearings or feedback (if using active injection) [46]. The low damping can allow vibration to persist or even grow, i.e., unstable whirl.

HGMBs ideally combine a reasonable stiffness, from the gas film at high speed, with additional damping from active magnetic control [60]. Experiments confirm this synergy, e.g., Basumatary et al. in 2019 [52] showed via simulations that adding an electromagnetic actuator to a gas foil bearing system could suppress sub-synchronous instabilities and increase the overall stability margin.

One critical aspect of stability in HGMB design is the rotor-bearing clearance. Excessive clearance, often favored to enhance magnetic performance, significantly compromises the stiffness and damping of the gas film, leading to instability under lower load conditions [46]. Conversely, overly tight clearance improves gas film support but restricts the space available for magnetic control, increasing the risk of rotor contact and magnetic saturation. They found that, at 46,000 rpm, a gas bearing with 30 µm clearance had 16.8 times the load capacity of one with 150 µm clearance. However, a smaller clearance also restricts the rotor's freedom of movement. Even minor displacements can result in rotor-to-bearing contact. They noted that insufficient clearance risks rotor-stator contact and thermal runaway due to friction heating. However, excessive clearance leads to poor stiffness and, thus, lower stability. Their results showed that increased radial clearance led to increased rotor vibration and instability; remarkably, the gas-bearing component became very sensitive to disturbances at a large gap.

In high-speed aerospace electric motors (e.g., an electric jet engine shaft or a turbopump), the rotor often passes through critical speeds during ramp-up. Here, the damping is critical to get through smoothly.

5.3. Friction Losses and Efficiency

One major advantage of both gas and magnetic bearings over traditional ones is the elimination of rubbing friction [1]. In aerospace engines, reducing bearing friction means less heat to remove and higher overall efficiency [46]. The mechanical loss due to friction in bearings is 5 to 20% of the overall losses. But it rapidly increases with operating speed.

Gas bearing losses come from shearing the gas film (viscous drag) and pumping losses (in hydrodynamic types) [51]. The shearing losses of the air bearing are less than 1% of the overall losses of a motor. These losses scale with surface speed, gas viscosity, and the inverse of clearance (a tighter gap increases shear). At very high speeds, air friction can become significant, though still far less than the sliding friction of a lubricated contact.

Also, during start–stop cycles, if a gas bearing momentarily contacts, friction and wear can occur. Remarkably, advanced foil coatings are designed to handle brief rubs [46].

Magnetic bearing losses come mainly from electrical sources, i.e., eddy currents induced in the rotor, hysteresis losses in magnetic materials, and resistive or joule heating in coils. These typically increase with rotor speed and any high-frequency control currents. If a bias current is used, there is a constant power draw that turns into heat. Magnetic bearings are often water-cooled or air-cooled in high-power applications to reduce these losses [46].

Hybrid bearings can minimize overall losses by dividing labor [3]. At low speeds (<1000 rpm), gas drag is negligible, and the only losses are from the magnetic bearing, which are generally low at low speeds. At high speeds (>10,000 rpm), the magnetic bearing can be unloaded or at least not work as hard. Consequently, its current (and losses) can be reduced, while the gas bearing naturally takes over with some drag. The net effect is often a lower combined loss than either would have on its own over the full cycle. For example, a clearance-focused study [62] reported that increasing radial clearance reduced the total losses in the combined bearing system. Particularly by cutting gas shear losses, a larger clearance (150 μm vs. 30 μm) cut the gas bearing's air friction loss by up to 80%. Of course, that came with a much lower load capacity; therefore, a compromise is needed. Then it indicates that if load demands are not extreme, designing the hybrid with a slightly looser gas film gap dramatically improves efficiency. They also found that at large clearances, the AMB had to work harder under eccentric rotor conditions, leading to more loss in the magnetic part. Essentially, an off-center rotor in a large-gap scenario forces the AMB to constantly pull it back. However, in a tight gap, the gas film itself re-centers it with some drag. Hence, designers must consider the interplay, in which an optimal design should minimize the sum of magnetic and gas losses.

The zero-bias strategy is one specific way to reduce magnetic losses. By eliminating bias current, ohmic and eddy losses due to bias flux disappear. Liu et al. [62] demonstrated that the power consumption of a zero-bias HGMB was significantly lower than that of a comparable biased system or pure AMB. The gas bearing carried part of the load; thus, the reduced magnetic capability did not compromise performance for the intended operating conditions. Nonetheless, the drop in coil losses and absence of bias heating made it ideal for cryogenic and long-duration applications.

In aerospace electric motors, any elimination of an oil lubrication system, as HGMBs allow, also indirectly improves efficiency by reducing weight and parasitic power usage (e.g., oil pumps) [46]. For instance, magnetic bearings in an electric jet engine design were noted to remove the need for an oil system [63], thereby reducing the aircraft engine's weight and complexity. Similarly, using air as a lubricant means no auxiliary cooling for oil, which can be a significant overhead in engine design.

5.4. Complexity, Reliability, and Design Maturity

HGMBs combine gas/air films and magnetic control, increasing design complexity but offering redundancy and enhanced safety [2]. Single-structured designs simplify hardware, reduce weight, and lower failure points. The hybrid mechanism provides a fail-safe behavior, e.g., if the magnetic system fails, the gas bearing can catch the rotor [64]. Similarly, if the gas film fails, the magnetic system can stabilize it. While active magnetic and gas bearings are mature, hybrid bearings remain specialized, with limited prototypes and custom applications. Coupled simulations integrating magnetic actuation and gas film behavior are being developed to model their non-trivial interactions accurately. Still, engineers need expertise in both fluid film dynamics and electromagnetic control for HGMB's development.

5.5. Control Strategies for Hybrid Gas–Magnetic Bearings

Hybrid Gas–Magnetic Bearings (HGMBs) support a rotor through two distinct regimes: magnetic actuation at low speeds and gas film levitation at high speeds. The primary control challenge is ensuring a stable and precisely positioned rotor during the transition between these modes. Common strategies range from simple, robust PID controllers, which are limited by system nonlinearities, to more advanced methods like adaptive control, which handles parameter variations, and intelligent fuzzy or neural controllers that manage uncertain dynamics without explicit models.

Effective transition management during rotor acceleration involves shifting load support from the magnetic actuators to the gas film. This is achieved through techniques such as gain scheduling, mode-switching logic, and fault-tolerant blending that can reactivate magnetic forces during disturbances. Overall, HGMB control demands tight coordination between subsystems, with emerging research focusing on adaptive and model predictive control (MPC) algorithms. These advanced methods, particularly sensor-fusion-based MPC, are key to achieving the autonomous, optimized performance required for next-generation aerospace electric drives.

Table 2 provides a comparison of pure gas bearings, pure magnetic bearings, and Hybrid Gas–Magnetic Bearings in the context of aerospace motors.

HGMBs can provide significantly higher load capacity than conventional AMBs, but this improvement is not universal and depends strongly on geometry, clearance, and operating conditions. The commonly cited threefold increase originates from Swanson et al. [2], who measured 5.3 kN for a hybrid bearing versus 1.8 kN for an equivalent AMB at 22,000 rpm. Later studies, however, have reported a broader range of enhancement factors (1.5×–3.5×), reflecting the varying balance between magnetic stiffness and gas film stiffness. Because gas film stiffness increases with surface velocity and decreases with clearance, significant performance gains occur only when the gas film dominates, and the magnetic bias remains sufficient for stable centering.

Current research is still limited by a lack of systematic experimental data across the full range of pressure, clearance, and temperature conditions relevant to high-speed applications. Most available studies do not simultaneously validate theoretical predictions with experimental measurements, and many modeling approaches overlook nonlinear interactions between magnetic fields and fluid dynamics. To advance the technology toward reliable deployment in aerospace systems, further work is needed to develop comprehensive scaling laws that relate geometry, rotational speed, and material properties to overall load capacity and performance.

Table 3 summarizes how the lifetime of HGMBs evolves with rotor speed and the dominant physical mechanisms at each operating regime. At low speeds (0–5 krpm), the magnetic bearing subsystem carries nearly all the load, and because no mechanical contact occurs, the lifetime is effectively unlimited and constrained only by the thermal behavior of the magnetic coils. In the intermediate range (5–20 krpm), both magnetic and gas film forces contribute to rotor support, and endurance remains stable with only minor thermal cycling effects. As speed exceeds 20 krpm, the gas film begins to dominate load support; experimental studies on foil-based hybrids consistently report operational lifetimes exceeding 10,000 h under these conditions. At very high speeds (>40 krpm), lifetime becomes sensitive to foil fatigue, thermal stress, and boundary lubrication effects, particularly in compliant-foil architectures. Cryogenic HGMBs benefit from the absence of lubricant degradation, achieving foil endurance levels above 10^7–10^8 cycles, while hydrostatic HGMBs, owing to their externally pressurized film and absence of physical contact, can, in principle, achieve unlimited operational lifetime. Together, these results highlight the strong speed-dependent durability of HGMBs and the importance of selecting the appropriate hybrid configuration for the intended operating regime.

Table 2. Comparison of gas bearings, magnetic bearings, and Hybrid Gas–Magnetic Bearings for aerospace applications.

Aspect	Gas Bearings (GFBs/HGBs)	Magnetic Bearings (AMBs)	Hybrid Gas–Magnetic Bearings (HGMBs)
Load Capacity	Hydrodynamic: 0.5–2 kN (depends on speed) [1,49] Hydrostatic: up to 5–10 kN [52]	Typical: 0.5–2 kN [1] Large AMBs: 2–6 kN (limited by saturation) [4,46]	3–5× AMB capacity [3] 5.3 kN demonstrated in turbine tests [3]
Stiffness (radial)	10^6–10^8 N/m (small clearances 10–80 μm) [33]	10^5–10^6 N/m (open-loop) 10^6–10^7 N/m (closed-loop) [58]	10^6–10^8 N/m (combined effect) [52]
Damping	Very low: 10–200 N·s/m [51]	Closed-loop equivalent damping tunable: 200–2000 N·s/m [58]	High damping at low speeds (AMB) + moderate damping at high speeds (gas film) [60]
Speed Limit	Foil bearings: 20,000–200,000 rpm [26] Hydrostatic: 10,000–80,000 rpm [33]	Most AMBs: 10,000–60,000 rpm [46]	Demonstrated: 30,000–70,000 rpm [33]
Power Loss	Air shear loss <1–3% of motor losses [46]	Joule + eddy losses: 20–200 W per bearing [46]	Lowest combined: 20–50 W in hybrid mode, AMB losses low at high speed, gas losses low at low speed [3]
Operating Temperature	−200 °C to >650 °C [24]	−200 °C to 200 °C (coil resistivity increases with temp) [46]	Cryogenic to high-temp ranges depending on design [50]
Clearance Range	10–80 μm [33]	300–1000 μm [4]	50–300 μm (compromise for hybrid integration) [46,52]
Startup Behavior	Requires speed or external pressure [51]	Excellent: supports rotor at 0 rpm [3]	AMB handles zero speed; gas takes over at high speeds [33]
Failure Behavior	Film collapses → rub [51]	Power loss → rotor drops to backup bearing [45]	Redundancy: each system backs up the other [3,47]
Volume, Mass	Small [23]	Large (due to coils + iron) [46]	20–35% volume reduction 10–25% mass reduction [50]

Table 3. Lifetime evolution of HGMBs at different rotor speeds.

Rotor Speed Range	Dominant Mechanism	Lifetime Trend
0–5 krpm	Magnetic heating (AMB-dominated)	Essentially unlimited (AMB-limited)
5–20 krpm	Mixed magnetic–gas loading	Lifetime stable; minor thermal cycling
>20 krpm	Gas film dominated	>10,000 h demonstrated (foil-based hybrids)
>40 krpm	High-speed structural stress	Depends on foil fatigue and boundary lubrication

Table 4 presents the variation in hybrid bearing power losses with rotational speed, highlighting the shift from magnetic to gas film dominance as speed increases. At low speeds, the active magnetic bearing (AMB) supplies the full levitation force, resulting in relatively high electrical losses (40–120 W). As speed rises to 10,000–40,000 rpm, the gas film increasingly supports the rotor, allowing the magnetic subsystem to unload, which reduces AMB losses to as little as 5–20 W. Gas film shear losses remain modest throughout the operating range, even at very high speeds. Consequently, total hybrid losses decrease by 50–80% between standstill and high-speed operation [65]. This natural redistribution of support load significantly improves overall efficiency and reduces magnetic coil heating—an essential advantage for high-speed aerospace electric machines where thermal limits are stringent [66]. Efficiency improves significantly in cryogenic systems due to the low viscosity of the gas shear. Hybrid operation reduces AMB coil heating by 35–70%, essential for aerospace electric motors [67].

Table 4. Hybrid bearing power loss versus rotor speeds.

Speed	AMB Power Loss	Gas Bearing Loss	Total Hybrid Loss
0 rpm	40–120 W	0 W	40–120 W
10,000 rpm	20–80 W	1–3 W	25–85 W
40,000 rpm	5–20 W	3–7 W	10–25 W
60,000 rpm	5–10 W	5–12 W	10–22 W

6. Future Research Directions and Conclusion

HGMBs offer the complementary advantages of gas bearings and active magnetic bearings, yet several fundamental challenges currently limit their widespread use in high-speed aerospace applications. The most critical issues arise from the nonlinear and speed-dependent load-sharing between the gas film and magnetic actuator, particularly during transient regimes where neither subsystem behaves predictably. Existing modeling frameworks oversimplify thermal–fluid–electromagnetic interactions by assuming linear magnetic forces, isothermal gas films, and small rotor motions. In contrast, real turbomachinery operates with large excursions, strong thermal gradients, and rapidly fluctuating loads. These limitations become even more severe under cryogenic conditions, where changes in gas viscosity, thermal contraction of components, and altered coil resistance affect stability and controllability.

In addition to modeling challenges, HGMBs face practical constraints related to sensor integration, reliability, and manufacturability. The need for high-bandwidth magnetic control, multi-parameter sensing, and compact packaging introduces risks of electromagnetic interference and limits system robustness. Hybrid systems also exhibit unique failure modes such as gas film collapse, magnetic saturation under shock, and pressure-supply interruption in hydrostatic stages, while comprehensive reliability models are still absent. Tight tolerances and the complexity of aligning magnetic and gas-bearing components further restrict scalability. Future research should focus on unified multi-physics modeling, adaptive load-sharing control, cryogenic-optimized designs, low-loss magnetic materials, standardized experimental benchmarking, and miniaturized architectures for next-generation aerospace propulsion and electric aircraft systems.

While significant progress has been made, HGMB technology is still evolving, and several areas merit further research before hybrids can be widely adopted in aerospace motors:

i Optimization of Design Parameters: As evidenced by recent studies [50,68] on clearance and geometry, finding the optimal balance in design (clearance, bearing size, bias current, etc.) is complex. Future work will involve multi-physics optimization—concurrently tuning magnetic circuit designs, fluid film geometries, and control laws. The goal is to maximize load and stability while minimizing losses and ensuring reliability. Tools that can co-simulate rotor dynamics with both fluid film and magnetic control will be invaluable. In particular, defining standards or guidelines for HGMB design (analogous to well-known charts and formulas for traditional bearings) will help engineers not intimately familiar with the technology to adopt it confidently.

ii Advanced Control and Sensing: The active magnetic component provides an opportunity to implement sophisticated control algorithms for the rotor-bearing system [48]. Research can explore adaptive control that adjusts based on rotor speed (e.g., gradually handing off to the gas bearing) and fault-tolerant control [3] that can detect a failing sub-component and compensate via the other. Additionally, magnetics allows for built-in sensing (the AMB actuators themselves can sense rotor position through inductance changes). Active damping algorithms [48] will continue to be refined to extend the stable range of gas films.

iii Integration with Motors: A future direction is integrating HGMB with the propulsion electric motor itself. For instance, an axial gap motor could conceivably incorporate a gas film in the gap and use the motor windings for cantering at low speeds. Liu et al. [50] study basically went in this direction by choosing an axial generator to complement the bearing design. Such integration can yield ultra-compact and efficient designs, but would require joint optimization of electromagnetic torque and suspension forces.

iv Robustness in Real Conditions: Aerospace environments include vibrations, shocks (e.g., an aircraft landing or a rocket stage separation), and wide temperature swings. HGMB prototypes should be tested under such conditions. Particularly, the behavior under sudden external loads or loss-of-power scenarios [49] needs further study to ensure the hybrid system transitions smoothly to backup mode. The role of touchdown or backup bearings in an HGMB-equipped system should also be refined. Perhaps they can be smaller or simpler given the hybrid's inherent redundancy, but they may still be needed for certification. Work on emergency modes (e.g., magnetic bearing catching the rotor after a sudden speed drop that collapses the gas film) will build confidence in the technology.

v Application-Specific Adaptation: Different applications might require tailoring the hybrid approach. For example, a rocket turbopump might use a permanent magnet biased AMB combined with hydrostatic helium bearings—a somewhat different variant than an aircraft cabin air compressor that might use foil bearings with an actively controlled magnetic damper. Research into hybrid configurations for specific aerospace systems (like turbo-fan engine shafts, cryocooler turbines, etc.) will likely continue. Each has unique requirements (life, noise, power, environment) that may push the design one way or another.

7. Conclusions

Hybrid Gas–Magnetic Bearings (HGMBs) have emerged as one of the most promising technologies for next-generation aerospace electric machines, bridging the operational gap between gas and magnetic bearings. They offer a unique capability to provide continuous, contact-free rotor support from zero speed to ultra-high rotational speeds, ensuring oil-free operation, reduced frictional losses, and exceptional reliability. This review highlights that HGMBs effectively integrate the high load-carrying capacity and stiffness of gas bearings with the precise active control and damping of magnetic bearings, resulting in superior overall stability and efficiency.

The most significant outcome of the reviewed studies is that HGMBs can increase the load capacity compared to standalone magnetic bearings while maintaining full levitation across the entire speed range. Their dual-mode operation allows magnetic levitation during startup and low-speed conditions, while the gas film becomes dominant at high speeds, drastically reducing control power consumption and thermal losses. These advantages make HGMBs ideal for high-speed, oil-free aerospace systems, including cryogenic turbopumps, electric propulsion units, auxiliary power systems, and hydrogen compressors, where extreme rotational speeds, cleanliness, and reliability are critical. Additionally, zero-bias HGMBs have shown particular promise for cryogenic or long-duration applications, where power efficiency and thermal management are vital.

Nevertheless, HGMBs are not universally optimal. For moderate-speed and heavy-load applications where simplicity, robustness, and mature certification are essential—such as large propulsion gearboxes, fans, or mechanical transmissions—traditional rolling or hydrostatic bearings may still be preferable due to their established reliability and straightforward integration. Likewise, for very high-speed but low-load rotors, such as small turbines or micro-compressors, pure gas foil bearings can remain the simplest and most lightweight solution. Conversely, for low-speed precision systems or those requiring active vibration suppression, such as satellite reaction wheels or positioning systems, pure AMBs continue to offer unmatched controllability and monitoring capabilities without the need for gas supply systems.

Overall, the literature demonstrates that HGMBs occupy a strategic niche—they are most advantageous where both load demand and speed range are high, where oil-free and maintenance-free operation is mandatory, and where system efficiency and thermal stability are tightly constrained, as in electric aircraft propulsion or reusable rocket turbomachinery. As modeling tools, control strategies, and manufacturing methods advance, HGMBs are expected to evolve from laboratory prototypes to fully certified components in aerospace propulsion systems. Their successful integration could mark a paradigm shift toward hybrid electromagnetic–aerodynamic rotor support, enabling the next generation of lightweight, efficient, and environmentally sustainable aerospace engines.

8. Methodology of Literature Search and Selection

A structured literature review was performed using Web of Science, Scopus, and Google Scholar to establish the publication statistics in Figure 2 and to ensure a systematic basis for this study. Publications were included only if they focused on HGMB, AMB, and gas bearing design, modeling, or experimental validation and were relevant to aerospace, turbomachinery, cryogenic systems, or high-speed electric machines, limited to peer-reviewed work from 2000 to 2025. Papers with only superficial mentions of hybrid bearings, duplicates, or patents lacking technical data were excluded. The search initially identified 137 records, which were reduced to 108 after removing duplicates and finally to 68 publications after applying all selection criteria; these 68 works constitute the dataset used for the statistical analysis and form the core literature examined in this review.

Author Contributions: Conceptualization, M.R.K. and P.A.; methodology, M.R.K. and P.A.; software, M.R.K.; validation, M.R.K. and P.A.; formal analysis, M.R.K. and P.A.; investigation, M.R.K. and P.A.; resources, M.R.K. and P.A.; data curation, M.R.K.; writing—original draft preparation, M.R.K.; writing—review and editing, P.A.; visualization, M.R.K.; supervision, M.R.K. and P.A.; project administration, P.A.; funding acquisition, P.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Heshmat, H.; Chen, H.M.; Walton, J.F., II. On the Performance of Hybrid Foil-Magnetic Bearings. *J. Eng. Gas Turbines Power* **2000**, *122*, 73–81. [CrossRef]
2. Swanson, E.E.; Heshmat, H. Oil-Free Foil Bearings as a Reliable, High Performance Backup Bearing for Active Magnetic Bearings. In Proceedings of the ASME Turbo Expo 2002, Amsterdam, The Netherlands, 3–6 June 2002. [CrossRef]
3. Swanson, E.E.; Heshmat, H.; Walton, J. Performance of a Foil–Magnetic Hybrid Bearing. *J. Eng. Gas Turbines Power* **2002**, *124*, 375–382. [CrossRef]
4. Wang, Y.; Zhang, C.; Zhang, C.; Li, L. Review of High-Power-Density and Fault-Tolerant Design of Propulsion Motors for Electric Aircraft. *Energies* **2023**, *16*, 7015. [CrossRef]
5. Adu-Gyamfi, B.A.; Good, C. Electric Aviation: A Review of Concepts and Enabling Technologies. *Transp. Eng.* **2022**, *9*, 100134. [CrossRef]
6. Brelje, B.J.; Martins, J.R.R.A. Electric, Hybrid, and Turboelectric Fixed-Wing Aircraft: A Review of Concepts, Models, and Design Approaches. *Prog. Aerosp. Sci.* **2019**, *104*, 1–19. [CrossRef]
7. Asef, P.; Perpiñà, R.B.; Lapthorn, A.C. Optimal Pole Number for Magnetic Noise Reduction in Variable-Speed Permanent Magnet Synchronous Machines with Fractional-Slot Concentrated Windings. *IEEE Trans. Transp. Electrif.* **2019**, *5*, 126–134. [CrossRef]
8. Asef, P.; Perpiñà, R.B.; Moazami, S.; Lapthorn, A.C. Rotor Shape Multi-Level Design Optimization for Double-Stator Permanent Magnet Synchronous Motors. *IEEE Trans. Energy Convers.* **2019**, *34*, 1223–1231. [CrossRef]
9. Asef, P.; Bargallo, R.; Lapthorn, A.; Tavernini, D.; Shao, L.; Sorniotti, A. Assessment of the Energy Consumption and Drivability Performance of an IPMSM-Driven Electric Vehicle Using Different Buried Magnet Arrangements. *Energies* **2021**, *14*, 1418. [CrossRef]
10. Asef, P.; Lapthorn, A. Overview of Sensitivity Analysis Methods Capabilities for Traction AC Machines in Electrified Vehicles. *IEEE Access* **2021**, *9*, 23454–23471. [CrossRef]
11. Vatani, M.; Stewart, D.R.; Asef, P.; Ionel, D.M. Optimal Design of Coreless Axial Flux PM Machines Using a Hybrid Machine Learning and Differential Evolution Method. In Proceedings of the 2025 IEEE International Electric Machines & Drives Conference (IEMDC), Houston, TX, USA, 18–21 May 2025; pp. 1262–1267. [CrossRef]
12. Stewart, D.R.; Vatani, M.; Alden, R.E.; Lewis, D.D.; Asef, P.; Ionel, D.M. Combined Machine Learning and Differential Evolution for Optimal Design of Electric Aircraft Propulsion Motors. In Proceedings of the 2024 13th International Conference on Renewable Energy Research and Applications (ICRERA), Nagasaki, Japan, 9–13 November 2024; pp. 1823–1828. [CrossRef]
13. Saeidabadi, S.; Parsa, L.; Corzine, K.A.; Kovacs, C.; Haugan, T. Double-Rotor Flux Switching Machine with HTS Field Coils and Superconducting Shields for Aircraft Propulsion. *IEEE Access* **2024**, *12*, 132508–132520. [CrossRef]
14. Spaven, F.; Liu, Y.; Bucknall, R.; Coombs, T.; Baghdadi, M. Thermal Design of Superconducting Cryogenic Rotor: Solutions to Conduction Cooling Challenges. *Case Stud. Therm. Eng.* **2021**, *28*, 101423. [CrossRef]
15. Baghdadi, M.; Ruiz, H.S.; Fagnard, J.F.; Zhang, M.; Wang, W.; Coombs, T.A. Investigation of Demagnetization in HTS Stacked Tapes Implemented in Electric Machines as a Result of Crossed Magnetic Field. *IEEE Trans. Appl. Supercond.* **2015**, *25*, 6602404. [CrossRef]
16. Grilli, F. Superconducting Motors for Aircraft Propulsion: The Advanced Superconducting Motor Experimental Demonstrator Project. *J. Phys. Conf. Ser.* **2020**, *1590*, 012051. [CrossRef]
17. Caughley, A.; Lumsden, G.; Weijers, H.; Jeong, S.; Badcock, R.A. Cooling of Superconducting Motors on Aircraft. *Aerospace* **2024**, *11*, 317. [CrossRef]
18. Haran, K.S.; Kalsi, S.; Arndt, T.; Karmaker, H.; Badcock, R.; Buckley, B.; Haugan, T.; Izumi, M.; Loder, D.; Bray, J.W.; et al. High-Power-Density Superconducting Rotating Machines—Development Status and Technology Roadmap. *Supercond. Sci. Technol.* **2017**, *30*, 12. [CrossRef]
19. Hao, Z.; Ma, Y.; Wang, P.; Luo, G.; Chen, Y. A Review of Axial-Flux Permanent-Magnet Motors: Topological Structures, Design, Optimization and Control Techniques. *Machines* **2022**, *10*, 1178. [CrossRef]
20. Kelch, F.; Yang, Y.; Bilgin, B.; Emadi, A. Investigation and Design of an Axial Flux Permanent Magnet Machine for a Commercial Midsize Aircraft Electric Taxiing System. *IET Electr. Syst. Transp.* **2018**, *8*, 52–60. [CrossRef]
21. Fang, S. Design Study of an Aerospace Motor for More Electric Aircraft. *IET Electr. Power Appl.* **2020**, *14*, 2881–2890. [CrossRef]
22. Weng, F.; Zhang, M.; Lan, T.; Wang, Y.; Yuan, W. Fully Superconducting Machine for Electric Aircraft Propulsion: Study of AC Loss for HTS Stator. *Supercond. Sci. Technol.* **2020**, *33*, 10. [CrossRef]
23. Branagan, M.; Griffin, D.; Goyne, C.; Untaroiu, A. Compliant Gas Foil Bearings and Analysis Tools. *J. Eng. Gas Turbines Power* **2016**, *138*, 054001. [CrossRef]
24. Jin, C.; Li, C.; Du, J. A Review on the Dynamic Performance Studies of Gas Foil Bearings. *Lubricants* **2024**, *12*, 262. [CrossRef]
25. San Andrés, L.; Kim, T.H. Analysis of Gas Foil Bearings Integrating FE Top Foil Models. *Tribol. Int.* **2009**, *42*, 111–120. [CrossRef]
26. San Andrés, L.; Kim, T.H. Thermohydrodynamic Analysis of Bump-Type Gas Foil Bearings: A Model Anchored to Test Data. *J. Eng. Gas Turbines Power* **2010**, *132*, 042504. [CrossRef]

27. Park, J.; Kim, D.; Sim, K. Development and Performance Measurements of Gas Foil Polymer Bearings with a Dual-Rotor Test Rig Driven by Permanent Magnet Electric Motor. *Appl. Sci.* **2022**, *12*, 1505. [CrossRef]
28. Żywica, G.; Bagiński, P.; Roemer, J.; Zdziebko, P.; Martowicz, A.; Kaczmarczyk, T.Z. Experimental Characterization of a Foil Journal Bearing Structure with an Anti-Friction Polymer Coating. *Coatings* **2022**, *12*, 1252. [CrossRef]
29. Shi, T.; Xiong, W.; Peng, X.; Feng, J.; Guo, Y. Experimental Investigation on the Start-Stop Performance of Gas Foil Bearings-Rotor System in the Centrifugal Air Compressor for Hydrogen Fuel Cell Vehicles. *Int. J. Hydrogen Energy* **2023**, *48*, 27183–27196. [CrossRef]
30. Hu, B.; Hou, A.; Deng, R.; Wang, R.; Wu, Z.; Ni, Q.; Li, Z. Numerical Investigation of Bump Foil Configurations Effect on Gas Foil Thrust Bearing Performance Based on a Thermo-Elastic-Hydrodynamic Model. *Lubricants* **2023**, *11*, 417. [CrossRef]
31. Kim, T.H.; San Andrés, L. Heavily Loaded Gas Foil Bearings: A Model Anchored to Test Data. *J. Eng. Gas Turbines Power* **2008**, *130*, 012504. [CrossRef]
32. Ke, C.; Qiu, S.; Li, K.; Xiong, L.; Peng, N.; Zhang, X.; Dong, B.; Liu, L. Numerical Computation and Experimental Research for Dynamic Properties of Ultra-High-Speed Rotor System Supported by Helium Hydrostatic Gas Bearings. *Lubricants* **2024**, *12*, 302. [CrossRef]
33. Gandzha, S.; Nikolay, N.; Chuyduk, I.; Salovat, S. Design of a Combined Magnetic and Gas Dynamic Bearing for High-Speed Micro-Gas Turbine Power Plants with an Axial Gap Brushless Generator. *Processes* **2022**, *10*, 1067. [CrossRef]
34. Maslen, E.H.; Sortore, C.K.; Gillies, G.T.; Williams, R.D.; Fedigan, S.J.; Aimone, R.J. Fault-Tolerant Magnetic Bearings. *J. Eng. Gas Turbines Power* **1999**, *121*, 504–508. [CrossRef]
35. Li, M.-H.; Palazzolo, A.B.; Kenny, A.; Provenza, A.J.; Beach, R.F.; Kascak, A.F. Fault-Tolerant Homopolar Magnetic Bearings. *IEEE Trans. Magn.* **2004**, *40*, 3308–3318. [CrossRef]
36. Sahinkaya, A.; Sawicki, J. Robust Control of Active Magnetic Bearing Systems with an Add-On Controller to Cancel Gyroscopic Effects: Is It Worth It? *J. Vib. Control.* **2021**, *27*, 359–375. [CrossRef]
37. Tamisier, V.; Font, S.; Lacou, M.; Carrere, F.; Dumur, D. Attenuation of Vibrations Due to Unbalance of an Active-Magnetic-Bearing Milling Electro-Spindle. *CIRP Annals* **2001**, *50*, 255–258. [CrossRef]
38. Maslen, E.H.; Allaire, P.E.; Noh, M.D.; Sortore, C.K. Magnetic Bearing Design for Reduced Power Consumption. *J. Tribol.* **1996**, *118*, 839–846. [CrossRef]
39. Na, U.J. Fault-Tolerant Control of Magnetic Bearings with Force Invariance. *J. Mech. Sci. Technol.* **2005**, *19*, 731–742. [CrossRef]
40. Agarwal, P.K.; Chand, S. Fault-Tolerant Control of Three-Pole Active Magnetic Bearing. *Expert Syst. Appl.* **2009**, *36*, 12592–12604. [CrossRef]
41. Xu, Y.; Wang, X.; Liu, M.; Li, N.; Yu, T. Fuzzy Variable Gains Robust Control of Active Magnetic Bearings Rigid Rotor System. *IET Intell. Transp. Syst.* **2024**, *18*, 90–106. [CrossRef]
42. Javed, A.; Mizuno, T.; Takasaki, M.; Ishino, Y.; Hara, M.; Yamaguchi, D. Lateral Vibration Suppression by Varying Stiffness Control in a Vertically Active Magnetic Suspension System. *Actuators* **2018**, *7*, 21. [CrossRef]
43. Na, U.J. Fault Tolerance of Homopolar Magnetic Bearings. *J. Sound Vib.* **2004**, *272*, 495–511. [CrossRef]
44. Tian, Z.; Wei, Z.; Sun, Y. Nonlinear Adaptive Control for Hybrid Foil-Magnetic Bearing. In Proceedings of the 2017 IEEE International Conference on Mechatronics and Automation (ICMA), Takamatsu, Japan, 6–9 August 2017; pp. 81–86. [CrossRef]
45. Falkowski, A.; Mazurek, P.; Szocl, T.; Henzel, M. Radial Magnetic Bearings for Rotor–Shaft Support in Electric Jet Engine. *Energies* **2022**, *15*, 3339. [CrossRef]
46. Liu, Q.; Ahn, H. Hybrid Gas-Magnetic Bearings: An Overview. *J. Appl. Electromagn.* **2021**, *53*, 123–145. [CrossRef]
47. Barati, H.; Karafi, M. A Hybrid Contactless Air-Magnetic Bearing System for Operating at 15,000 rpm. *Iran. J. Mech. Eng. Trans. ISME* **2024**, *25*, 40–62. [CrossRef]
48. Looser, A.; Kolar, J.W. An Active Magnetic Damper Concept for Stabilization of Gas Bearings in High-Speed Permanent-Magnet Machines. *IEEE Trans. Ind. Appl.* **2014**, *50*, 2363–2372. [CrossRef]
49. Heshmat, H.; Xu, D.S. Experimental Investigation of 150 mm Diameter Large Hybrid Foil/Magnetic Bearing. In Proceedings of the 2003 International Gas Turbine Congress, Tokyo, Japan, 2–7 November 2003.
50. Liu, Q.; Ge, R.; Wang, L.; Ren, T.; Feng, M. Single-Structured Zero-Bias Hybrid Gas-Magnetic Bearing and Its Rotor Dynamic Performance. *International J. Appl. Electromagn. Mech.* **2024**, *74*, 79–99. [CrossRef]
51. Ha, Y.; Kim, J.; Jeong, K.; Lee, Y. Rigid Mode Vibration Control for 250 HP Air Compressor System with Integrated Hybrid Air-Foil Magnetic Thrust Bearing (i-HFMTB). *ASME J. Eng. Gas Turbines Power* **2024**, *146*, 041002. [CrossRef]
52. Basumatary, K.K.; Kumar, G.; Kalita, K.; Kakoty, S.K. Stability Analysis of Rigid Rotors Supported by Gas Foil Bearings Coupled with Electromagnetic Actuators. *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.* **2019**, *234*, 427–443. [CrossRef]
53. Yang, C.; Knospe, C. Optimal Control of a Magnetic Bearing without Bias Flux. In Proceedings of the 1997 American Control Conference, Albuquerque, NM, USA, 6 June 1997; pp. 1534–1538. [CrossRef]

54. Rong, H.; Zhou, K. Nonlinear Zero-Bias Current Control for Active Magnetic Bearing in Power Magnetically Levitated Spindle Based on Adaptive Backstepping Sliding Mode Approach. *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.* **2016**, *231*, 3753–3765. [CrossRef]
55. Chen, S.; Weng, C. Robust Control of a Voltage-Controlled Three-Pole Active Magnetic Bearing System. *IEEE/ASME Trans. Mechatron.* **2010**, *15*, 381–388. [CrossRef]
56. Hung, J.Y. Magnetic Bearing Control Using Fuzzy Logic. *IEEE Trans. Ind. Appl.* **1995**, *31*, 1492–1497. [CrossRef]
57. Chen, S.Y.; Song, M.H. Energy-Saving Dynamic Bias Current Control of Active Magnetic Bearing Positioning System Using Adaptive Differential Evolution. *IEEE Trans. Syst. Man Cybern. Syst.* **2019**, *49*, 942–953. [CrossRef]
58. Heshmat, H.; Walton, J.F., II. Hybrid Foil-Magnetic Bearing with Improved Load Sharing. U.S. Patent No. US6965181B1, 15 November 2005.
59. Yang, B.; Geng, H.; Sun, Y.; Yu, L. Dynamic Characteristics of Hybrid Foil-Magnetic Bearings (HFMBs) Concerning Eccentricity Effect. *Int. J. Appl. Electromagn.* **2016**, *52*, 271–279. [CrossRef]
60. Jang, H.; Kim, J.; Han, D.; Jang, D.; Ahn, H. Improvement of High-Speed Stability of an Aerostatic Bearing-Rotor System Using an Active Magnetic Bearing. *Int. J. Precis. Eng. Manuf.* **2014**, *15*, 2565–2572. [CrossRef]
61. Heshmat, H. Hybrid Foil-Magnetic Bearing. U.S. Patent US6353273B1, 15 September 1998.
62. Liu, Q.; Wu, M.; Ge, R.; He, W.; Cheng, Z. Effect of Radial Clearance on Static and Dynamic Performances of Single-Structured Hybrid Gas-Magnetic Bearing Rotor System. *ASME J. Tribol.* **2025**, *147*, 104601. [CrossRef]
63. Zhang, H.; Yin, Q.; Guan, H.; Cao, Y.; Feng, K. Theoretical Investigation of Hybrid Foil-Magnetic Bearings on Operation Mode and Load Sharing Strategy. *Proc. Inst. Mech. Eng. Part J J. Eng. Tribol.* **2022**, *236*, 2491–2506. [CrossRef]
64. San Andrés, L.; Rodríguez, B. Experiments with a Rotor-Hybrid Gas Bearing System Undergoing Maneuver Loads from Its Base Support. *ASME J. Eng. Gas Turbines Power* **2020**, *142*, 111004. [CrossRef]
65. Liu, X.; Shi, Z.; Wang, M.Q. Study of the failure criterion for non-lubricated hybrid bearings under high-speed and heavy-load conditions. *Tribol. Int.* **2026**, *214*, 111174. [CrossRef]
66. Wu, T.; Zhang, W. Review on Key Development of Magnetic Bearings. *Machines* **2025**, *13*, 113. [CrossRef]
67. Du, Y.; Zhang, G.; Hua, W. Review on Research and Development of Magnetic Bearings. *Energies* **2025**, *18*, 3222. [CrossRef]
68. Liu, Q.; Wang, L.; Feng, M. Clearance Compatibility and Design Principle of the Single-Structured Hybrid Gas-Magnetic Bearing. *Ind. Lubr. Tribol.* **2023**, *75*, 1219–1228. [CrossRef]