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Review

Review on Key Development of Magnetic Bearings

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Abstract: A magnetic suspension bearing is a device that suspends the rotating shaft in a balanced position by magnetic force, thereby eliminating the friction between the rotor and the stator. Different from traditional bearing support methods, magnetic bearings show significant advantages in terms of speed, accuracy, and loss. Because there is no contact, magnetic bearings enable high-speed operation, precise control, and zero friction. Magnetic bearings, with their excellent performance, are widely applied in fields such as industrial production, flywheel energy storage, and aerospace. However, with the continuous growth of the demand for high-performance bearings and the deepening of the concept of low-carbon and environmental protection, breakthroughs in the key technologies of magnetic bearings are urgently needed. In this paper, relevant research on magnetic bearings is summarized. Magnetic bearings are classified according to the different ways in which they generate suspension forces. Research on the topological structure design, mathematical modeling, and control strategies of the magnetic bearing system is covered. The aim is to provide readers and researchers with a comprehensive overview of the key technologies of magnetic bearings from a new perspective.

Keywords: magnetic suspension bearings; suspension forces; topology structure design; mathematical modeling; control strategy

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Academic Editor: Ahmed Abu-Siada

Received: 16 December 2024
Revised: 24 January 2025
Accepted: 25 January 2025
Published: 30 January 2025

Citation: Wu, T.; Zhang, W. Review on Key Development of Magnetic Bearings. *Machines* **2025**, *13*, 113. https://doi.org/10.3390/machines13020113

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1. Introduction

With modern industrial technology rapidly advancing towards high precision, high speed, and intelligence, traditional mechanical bearings have gradually revealed their limitations in many crucial application scenarios. This has propelled magnetic suspension bearings to the forefront of research, and in-depth exploration of them is of profound significance. Magnetic suspension bearings (magnetic bearings) rely on the force generated by magnetic fields to support the suspension of the rotor in the rotating state. The force is generated by permanent magnets, magnetic materials, or electrified coils. Compared with traditional mechanical bearings, the difference between the two is that there is no mechanical contact and no friction between the former and other components. The operation energy consumption is low, which is conducive to energy saving and emission reduction. Therefore, the magnetic bearing is a high-performance bearing.

The evolution of magnetic suspension bearing technology epitomizes the wisdom and painstaking efforts of global scientific research teams. In 1842, Earnshow [1] theoretically demonstrated the infeasibility of achieving a stable six-degree-of-freedom suspension of an object under the magnetic field force of permanent magnets, which hindered the development of the magnetic suspension concept. In 1937, Kemper [2] from Germany made a pivotal breakthrough. He put forward a scheme centered on controllable electromagnets,

enabling stable suspension by precisely adjusting the electric current to vary the electromagnetic force. This breakthrough led to the first relevant patent, which further charted the course for subsequent development, spawning two cutting-edge branches: magnetic bearings and magnetic suspension high-speed trains [3].

During the mid-20th century, Beams [4] developed a hybrid magnetic bearing and applied it to a centrifuge, marking a significant leap from theory to practice for magnetic suspension bearings. Beginning in 1969, the French military's scientific research laboratory delved into magnetic bearings [5]. Three years later, they were successfully applied to satellite guide wheels, pioneering aerospace applications. In the 1960s, China initiated research on magnetic bearings, with a relatively backward starting level. In 1982, Tsinghua University carried out a single-degree-of-freedom suspension experiment using a small steel ball to analyze and verify the suspension mechanism, laying a solid foundation for subsequent multi degree of freedom suspension experiments. In 1988, the Harbin Institute of Technology completed the first domestic multi-degree-of-freedom suspension technology test for the spindle of an active magnetic suspension bearing machine tool, meeting expectations in terms of structural design, prototype manufacturing, control system construction, and overall machine joint debugging [6].

In the 1980s, Japan shone brightly in industrial applications. The NTN Toyo Bearing Company and the Electromagnetic Suspension Bearing Company successively launched products such as high-speed milling heads, machine tool electric spindles, and turbomolecular pumps, reaping huge economic benefits [7,8]. Subsequently, they expanded magnetic bearings to the space attitude flywheel field and completed rigorous space verification. During the 1990s, research enthusiasm persisted. The United Kingdom successfully developed a 3.3 MW magnetic suspension turboexpander. Seiko Seiki and Mitsubishi Heavy Industries in Japan also achieved applications of magnetic suspension bearings in machine tool processing and refrigeration compressor fields [9]. In 1996, the Harbin Institute of Technology focused on magnetic bearings for electric spindles, conducting research on their structure and control and completing the overall machine design and tests. The designed magnetic suspension CNC machine tool boasted a high stiffness coefficient and a rotational speed of up to 20,000 r/min.

After the turn of the millennium, research continued to plumb the depths of fundamental technology. In 2006, Zhejiang University launched an inverter-driven, three-pole active magnetic bearing. In 2008, Sun et al. [10] designed a new type of permanent magnet-biased radial magnetic bearing for magnetic suspension flywheels. They proposed a design method based on displacement stiffness and current stiffness by means of the equivalent magnetic circuit method. Hofmann [11] analyzed the magnetic field distribution of magnetic bearings using the equivalent magnetic circuit method to obtain accurate force–flux relationships and optimize the design principle. Schmidt et al. [12] utilized finite element analysis to deeply explore the magnetic circuit coupling and mutual inductance characteristics of three-pole hybrid magnetic bearings. In 2014, Kim et al. [13] designed specialized magnetic bearings for magnetic wireless pumps, significantly optimizing the suspension and operation performance of the pumps. In 2023, Gong et al. [14] studied the influence of PID controller parameters on the unbalance compensation polarity switching control of the active magnetic bearing rotor system and designed the controller.

Currently, the continuous key technological breakthroughs in various countries are expanding the application scope and enhancing the performance indicators of magnetic suspension bearings. In terms of rotational speed, they can achieve ultra-high speeds, reaching tens of thousands of revolutions per minute or even higher, which is highly advantageous in some high-speed rotating equipment. Moreover, they can feature high precision, with extremely small radial and axial runouts of the shaft, usually controllable at

the micron level, ensuring the stability of equipment operation. Regarding load-bearing capacity, depending on different designs and application scenarios, magnetic suspension bearings can carry axial and radial loads within a certain range to meet the requirements of various mechanical devices. At the same time, they have relatively low power consumption because they reduce the energy loss caused by friction in traditional bearings, thus improving energy utilization efficiency. In addition, they possess good dynamic response characteristics, enabling them to quickly adapt to load changes and external disturbances, ensuring the stable and reliable operation of the system. In Table 1, some of the uses and properties of magnetic bearings are detailed.

Table 1. Magnetic bearing specific application and performance index [15].

Applications	Power (kW)	Speed (rpm)
Power Generation	2–150	35,000–220,000
Flywheel Energy Storage System	120	40,000
High-Speed Spindles	1–24	9000–180,000
Turbo Molecular Pumps	Few hundred Watt	100,000
Gas Compressors	10,000	20,000
Air Compressors	100–150	80–15,000
Micro Turbines	50	80,000
Turbo Generators	30	60,000

Because of their unique technical characteristics, the product performance brought by magnetic bearings can lead to innovative leaps for the system and for the performance of traditional general mechanical and electrical equipment. With the backdrop of carbon peaking and carbon neutrality, they can be called an excellent product to achieve energy saving and emission reduction and green and low-carbon goals. Therefore, reviewing the research on magnetic bearings is of great significance. In order to help readers better understand magnetic bearings and researchers to quickly obtain crucial information, this paper systematically reviews the research progress of magnetic bearings and innovatively proposes a classification scheme. Specifically, based on different suspension force types, it conducts a classified discussion on the topological structure design, precise suspension force model, and control strategy of the magnetic bearing system.

2. Classification of Magnetic Bearings

So far, according to different standards, magnetic suspension can be divided into a variety of categories. According to the different types of bearing suspension force, magnetic bearings can be divided into suction magnetic bearings and repulsive magnetic bearings. The suction magnetic bearing uses the attraction between the permanent magnet and permanent magnet or electromagnetic and permanent magnet to balance the rotor gravity to levitate the rotor. Compared with the suction magnetic bearing, the repulsive magnetic bearing uses the magnetic field generated by the electromagnetic coil to interact with the permanent magnet on the rotor or the interaction of different arrays of permanent magnets. This repulsive force can support the rotor and control its movement to achieve non-contact support and positioning [16,17].

2.1. Suction Magnetic Bearing

2.1.1. Electromagnetic (Active) Magnetic Bearings (AMB)

The electromagnetic (active) magnetic bearing system is a dynamic and inherently unbalanced open-loop system. It establishes a magnetic field closure path on the surface of the rotor through the combination of an iron core and a coil (namely a solenoid), so as to generate an electromagnetic attraction to stabilize the rotor. In order to ensure the stable

operation of the system, an appropriate control loop must be designed. Active magnetic bearings can be classified according to the number of magnetic poles, including 8-pole, 16-pole, and 32-pole magnetic bearings, etc. [18–20]. As shown in Figure 1, the eight-pole active magnetic bearing topological structure is the most typical in industry.

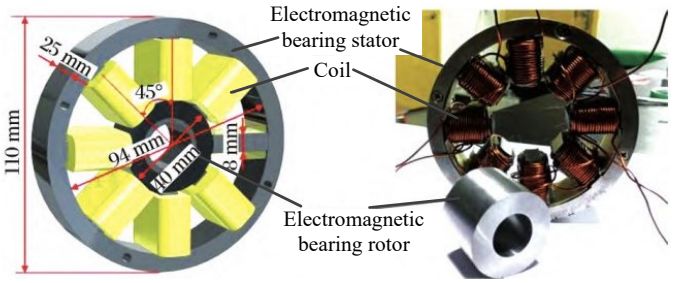


Figure 1. Structure of 8-pole active magnetic bearing [18].

The working principle of the active magnetic suspension bearing is shown in Figure 2. In this process, the rotor offset is continuously monitored by high-precision displacement sensors, and the position information is converted into electrical signals. These electrical signals are then collected by the sampling unit in the controller. After being calculated through different control algorithms (such as PID control, fuzzy control, and sliding mode control), the waveform of the rotor control signal is generated. The control signal controls the current in the electromagnetic coil via the power amplifier. By increasing or decreasing the current in the coil, the electromagnetic force is changed, so that the rotor can be controlled to the equilibrium position. This cyclic process is continuously carried out to ensure that the rotor can be stably suspended in the central position. Moreover, the stiffness and damping of the magnetic bearing can also be altered by adjusting the current of the control coil. The active magnetic bearing is characterized by an inverter drive, small volume, strong nonlinearity, and mature technology.

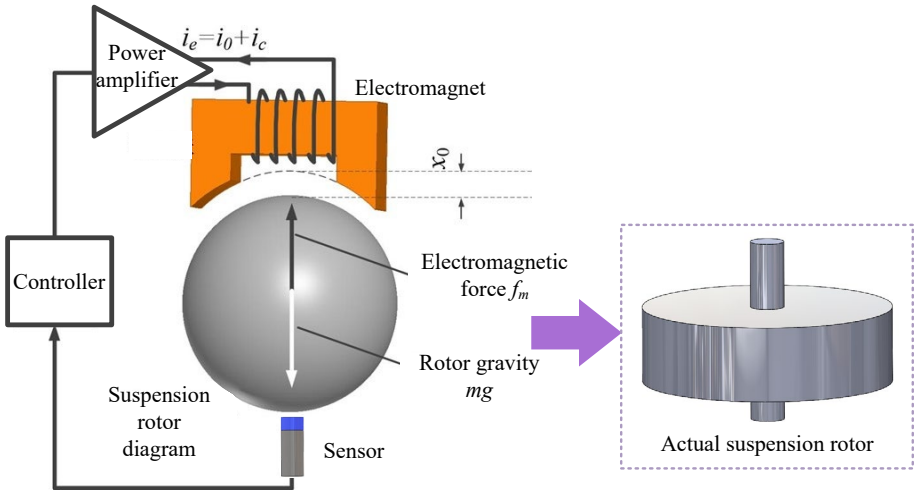


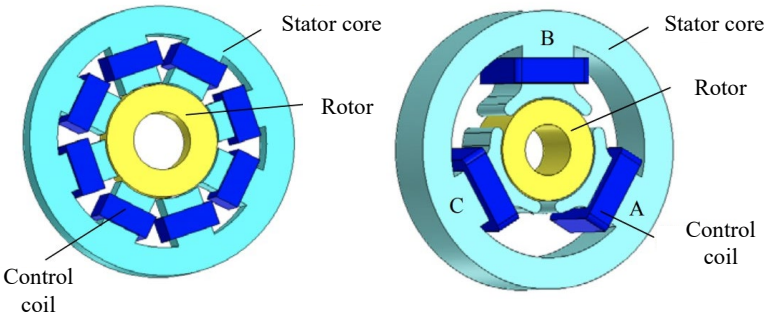
Figure 2. Magnetic suspension bearing working principle diagram.

According to the way of driving the magnetic bearing control coil, the active magnetic bearing can also be divided into DC and AC active magnetic bearings.

(1) DC active magnetic bearing

For a long time, researchers at home and abroad have been mainly committed to the study of DC magnetic bearings. Therefore, DC magnetic bearings have become the most classic and commonly used magnetic suspension bearings. DC magnetic bearings

usually use bipolar or unipolar power amplifiers to deliver the required control current to the control coil. Common DC magnetic suspension bearings have three- or eight-pole structures [21], as shown in Figure 3a. The DC power amplifier employed in DC magnetic bearings is at a disadvantage in terms of quantity and energy consumption compared with that in AC magnetic bearings. However, due to the symmetrical distribution of its bearing structure, the controller for it is more easily designed than that for the symmetrical structure of AC magnetic bearings in terms of control.



(**a**) 8-pole DC magnetic bearing (**b**) 3-pole AC magnetic bearing

Figure 3. Active magnetic bearing classification topology [21].

(2) AC active magnetic bearing

For a magnetic suspension bearing with a three-pole structure, if the three control coils can be driven by inverters commonly used in three-phase motors, significant progress will be made in terms of cost reduction, power loss reduction, and system structure simplification. The AC active magnetic bearing with a three-pole structure, as shown in Figure 3b, supplies power to the control coil through an AC three-phase power inverter [22]. Therefore, AC magnetic suspension bearings have received great attention in recent years and have developed rapidly. Unlike DC power amplifiers, which can only provide suspension forces in one direction, three-phase inverters enable magnetic bearings to generate suspension forces in multiple directions. This makes the volume of AC magnetic bearings usually much smaller than that of DC magnetic bearings. In terms of a control strategy, AC magnetic bearings can adopt the vector control method which is widely used in AC motor control. In addition, the radial suspension principle of AC magnetic suspension bearings is similar to that of the bearing-less motor. The AC magnetic suspension bearing can be regarded as a special magnetic suspension bearing with the pole number of torque winding 0 and the pole number of suspension winding 1. Therefore, the suspension control technology of the bearing-less motor has important reference significance for the development of the AC magnetic suspension bearing.

In addition to the traditional topology of symmetrical design, many scholars have creatively designed many non-traditional-shaped active magnetic bearings. As shown in Figure 4, the active magnetic bearing consists of two stator assemblies and a rotor assembly, which is suspended in the air by two claw-shaped conical stators [23]. Each pole pair of the magnetic bearing can provide axial and free radical forces to the rotor at the same time. Each stator tooth is wound with a coil. Eight stator teeth with excitation coils form the magnetic poles of the bearings. Adjacent magnetic poles have opposite polarity, and their coils are connected in series to form a magnetic pole pair. Thus, each stator consists of four pairs of magnetic poles, which form four flux loops. Therefore, the rotor can be stably suspended in the air by the magnetic force generated by the two stators on the left and right sides.

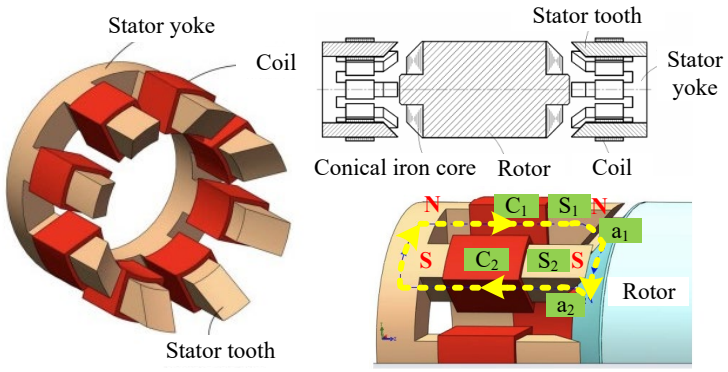


Figure 4. Claw type stator active magnetic suspension bearing [23].

2.1.2. Hybrid Magnetic Bearings (HMB)

Hybrid magnetic bearings, also known as permanent magnet biased magnetic bearings, have a mechanical structure including a stator, a biased permanent magnet, a control coil, and a rotor, as shown in Figure 5. The working principle is that the magnetic field of the permanent magnet returns to the permanent magnet through the stator, air gap, and rotor, and forms a closed magnetic circuit, which is used to generate a biased magnetic field, so that the rotor can remain in the center of the stator when the control coil is not energized. If the rotor position is offset by external interference (including fluctuations from the environment, the gyroscopic effect generated by the high-speed operation of the rotor, and sudden changes in the surrounding temperature gradient, etc.), the offset is balanced by adjusting the current of the control coil in the same way as the active magnetic bearing, so that the rotor is stably suspended in the center of the stator. Hybrid magnetic bearings can also adjust the stiffness and damping of magnetic bearings by changing the current in the coil. Hybrid magnetic bearings are superior to other common types of magnetic bearings in terms of low loss balance, high performance, and low coil ampere-turns and volume, and they are easy to manufacture and control.

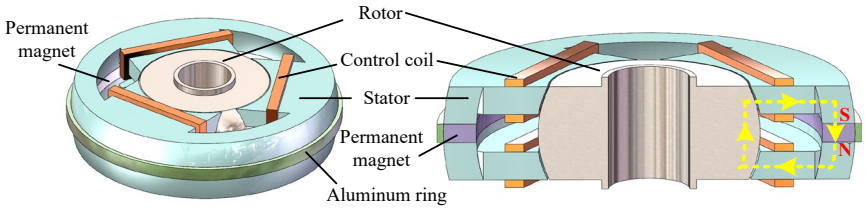


Figure 5. Structure diagram of hybrid magnetic bearings [24].

Hybrid magnetic bearings can be classified into a single degree of freedom (1-DOF), two degrees of freedom (2-DOF), three degrees of freedom (3-DOF), four degrees of freedom (4-DOF), and five degrees of freedom (5-DOF) according to the controllable degrees of freedom. In Ref. [25], a 3-DOF magnetic bearing with embedded high integration is designed. As shown in Figure 6, the axial part of the magnetic bearing adopts a double permanent magnet ring structure, and the axial suspension eliminates the gravity influence of the flywheel through the suction suspension force provided by the axial direction. The blue path is the axially biased magnetic path, and the red path is the axially controlled magnetic path. The eddy current sensor installed in the axial position detects the axial deviation of the flywheel rotor, the axial control coil passes the corresponding current, and the magnetic flux superposition in the air gap generates the magnetic force that pulls the flywheel back to the balance position.

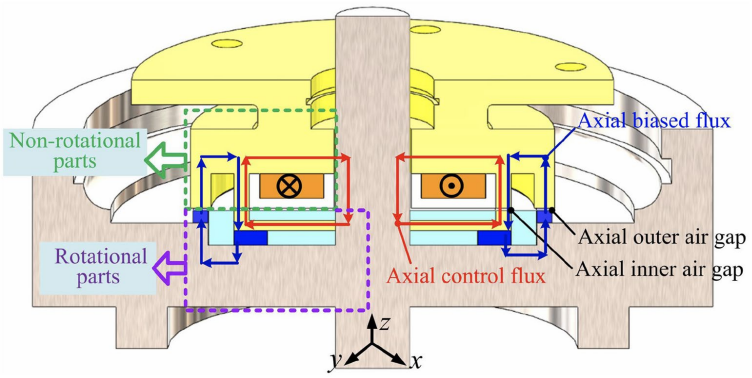


Figure 6. A 3-DOF magnetic bearing structure [25].

Xu et al. [26] proposed 4-DOF hybrid magnetic bearings. They consist of two active parts and a passive part, and each active part has four stator magnetic poles, along the x and y directions around the circumference, divided into two layers. The passive part has two complete magnetic rings located in the middle of the 4-DOF HMB. The active and passive parts have permanent magnets, and their magnetization directions are shown in Figure 7. The solid line represents the bias flux path generated by the permanent magnet, and the dashed line represents the control flux path generated by the control coil. The two active parts can control the four-degree-of-freedom motion, translation motion, and two inclined motions of the rotor, and the passive part can realize the axial elastic motion of the rotor.

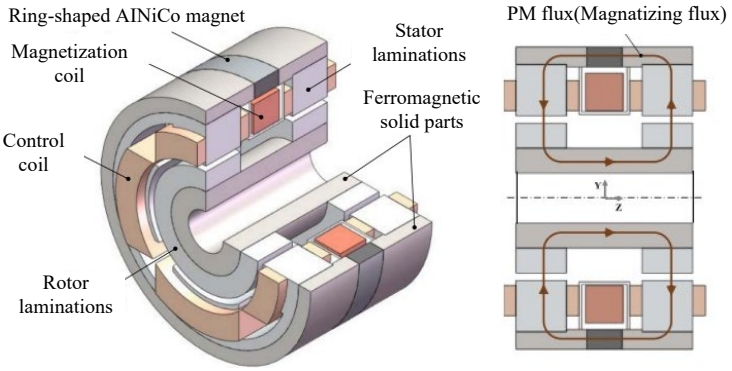


Figure 7. A 4-DOF magnetic bearing structure [26].

At present, the 5-DOF magnetic bearings usually designed are scattered, consisting of two plus two plus one or two plus three, but there are also five-degrees-of-freedom integrated magnetic bearings with very high integration. In Ref. [27], an AC two-degrees-of-freedom hybrid magnetic bearing and an AC–DC three-degrees-of-freedom hybrid magnetic bearing are combined to form a five-degrees-of-freedom AC magnetic suspension bearing. In Ref. [28], a compact five-degrees-of-freedom hybrid magnetic bearing is proposed, but the control flux passes through the radial and axial air gap at the same time, which makes the design of the control system complicated. In Ref. [29], a cone-type five-degrees-of-freedom hybrid magnetic bearing is proposed, but each of its magnetic flux paths has magnetic and magnetic coupling, which made it difficult to improve the suspension accuracy. In Ref. [30], a five-degrees-of-freedom hybrid magnetic bearing structure is proposed. The rotor is saucer-shaped, and the magnetic bearing has the advantage of high anti-interference ability and avoids self-coupling of the magnetic circuit. As shown in Figure 8, the magnetic bearings are arranged such that the radial/torsional magnetic bearings are tiled and stacked. The axial magnetic bearing, which is C-shaped, is located outside the flywheel, forming an axial hybrid magnetic bearing with an upper–lower dual-

permanent-magnet structure. This combination further improves the system's integration. The radial/torsional hybrid magnetic bearing is composed of radial three-poles, torsional three-poles, and multiplexed permanent magnets. A magnetic-circuit structure of shared yet non-interfering magnetic circuits is adopted in this magnetic bearing, jointly achieving the control of two degrees of freedom in the radial direction and two degrees of freedom in the torsional direction.

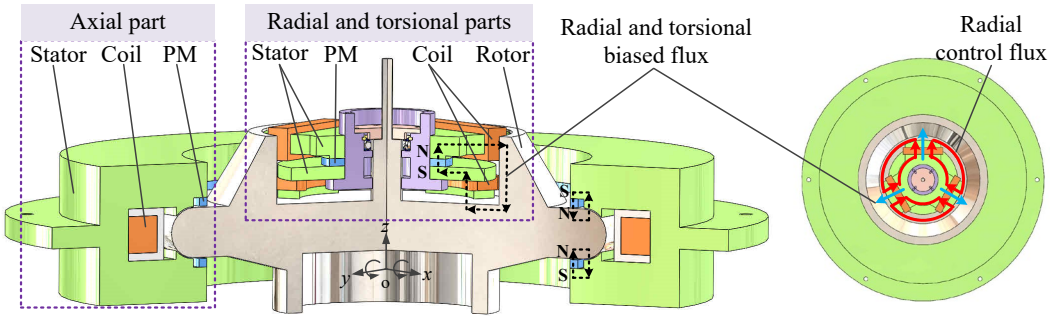
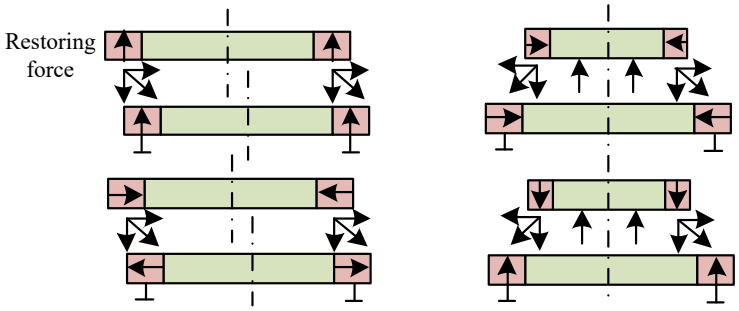


Figure 8. Five-degrees-of-freedom (5-DOF) saucer-shaped magnetic bearing structure [30].

2.1.3. Passive Magnetic Bearings (PMB)

Passive magnetic bearings do not need coils to provide magnetic field force, nor do they need other external energy supply devices, and they rely on their own permanent magnet material characteristics to produce suspension force, which can be generally divided into various superconducting magnetic bearings and permanent magnet bearings [31]. Permanent magnet bearings mainly maintain the relative spatial position of the stator and rotor through the attractive or repulsive force generated by the interaction of the permanent magnets made of NdFeB materials. Figure 9 shows the structure diagram of permanent magnet bearings. The stiffness and bearing capacity of bearings can be adjusted by the stacking of magnets and the change of magnetization direction to adapt to different applications. The suction-type passive magnetic bearing has a relatively simple structure. It does not need an electric drive and control, and has easy operation and low operating costs. However, there are some limitations in the bearing capacity and control accuracy. Nevertheless, they can still provide effective support in some application scenarios.



(**a**) Radial permanent magnet bearing structure. (**b**) Axial permanent magnet bearing structure.

Figure 9. Suction type permanent magnet bearing structure [31].

Figure 9a shows radial permanent magnet bearings, and Figure 9b shows axial permanent magnet bearings. The structure of the suction permanent magnet bearing is composed of two basic forms. (The magnetization direction of the permanent magnet ring is indicated by the arrow.) These four structures can control two degrees of freedom in the radial direction or one degree of freedom in the axial direction. Of course, more structural forms can also be combined on the basis of these four basic structures. Suction-type permanent

magnet bearings are composed of two circular magnets with opposite magnetization directions. A movable magnet is mounted on the rotor and another magnet is fixed on the stator. When the relative position of the movable magnet is shifted, the fixed magnet exerts an attractive force on the migrating magnet in the opposite direction of movement, causing the migrating magnet to return to the right position. It is worth noting that the further the movable magnet is out of position, the less attractive the force it generates.

In order to adapt to more application scenarios, the structure of suction permanent magnet bearings can be improved by a variety of novel permanent magnet magnetization methods, but it is difficult to meet the needs of high-bearing permanent magnet bearings under complex working conditions without changing the structural parameters and the size of remanence.

2.2. Repulsive Magnetic Bearings

2.2.1. Passive Magnetic Bearings (PMB)

Figure 10 shows the structure of repulsive permanent magnet bearings, which are similar in design to suction permanent magnet bearings, but such bearings rely on repulsive forces between magnetic rings to operate. The inner magnetic ring (moving magnetic ring) near the rotor is installed on the rotor, while the outer magnetic ring (static magnetic ring) is installed on the stator. The magnetic characteristics of the bearing will change with the direction of magnetization of any magnetic ring. Since the bearing capacity and stiffness of a single permanent magnet bearing are usually low, multiple magnetic rings will be superimposed during design to meet the needs of practical applications. This superimposed method can effectively improve the bearing capacity and stiffness of permanent magnet bearings to adapt to a wider range of engineering applications.

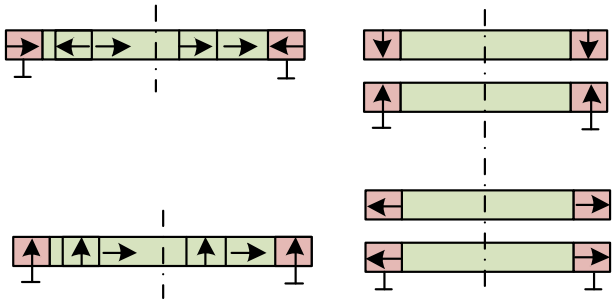


Figure 10. Repulsive type magnet bearing structure [31].

Figure 11 shows four different stacking modes, which can be composed of radial stacking and axial stacking through the form of inner and outer assembly of the magnetic ring [32]. According to the direction of the magnetization of the magnetic ring, it can be divided into axial arrays, radial arrays, or Halbach arrays [33,34]. The structure of the axially and radially stacked Halbach arrays is characterized by an alternating 90° change in the magnetization direction of the magnetic ring between each layer.

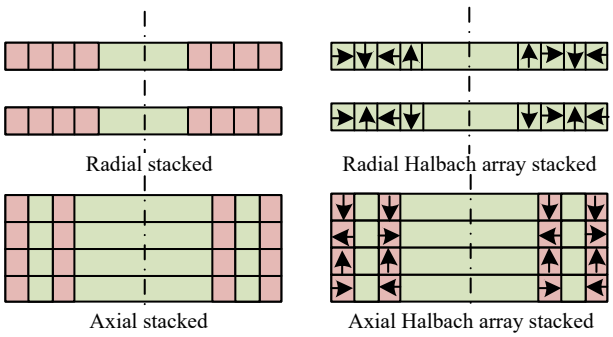


Figure 11. Stacking mode of repulsive magnet bearings [31].

In Ref. [35], a magnetic repulsive force magnetic bearing for supporting a horizontal flywheel battery system is proposed. It uses multiple ring-shaped magnets to generate multiple saddle-shaped magnetic fields. The multi-saddle surface magnetic field is optimized by adjusting the number of circling magnets and the circling radius. Ref. [36] proposes a flywheel energy storage system in which repulsive passive magnetic bearings and hybrid radial magnetic bearings act together, in which the passive magnetic bearings carry the function of counteracting the weight of the rotor and at the same time suppress the rotor deviation under the influence of gyroscope effect. In view of the low magnetic density utilization rate, low suspension height, and low suspension force of the permanent magnet part of the traditional repulsion magnetic suspension system, Ref. [37] introduced the characteristic of a unilateral magnetic field of the Halbach permanent magnet array to improve the magnetic field utilization rate of the bottom main magnetic ring, as shown in Figure 12.

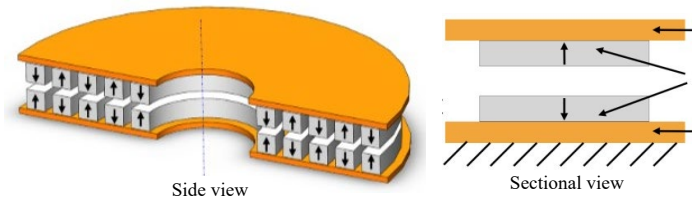


Figure 12. Halbach permanent magnet array bearing structure [37].

2.2.2. Diamagnetic Magnetic Bearings

In 1949, Braunbek's theory [38] was further tested by Arkadiev's successful superconducting magnetic suspension [39]. Since then, scientists from all over the world have begun to study superconductors with properties such as diamagnetism, zero resistance, and quantum tunneling effect, which has opened up a new route for the research of superconducting magnetic suspension and superconducting magnetic bearings, and which has promoted the rapid development of related fields. Superconducting magnetic bearings are magnetic bearings that use the diamagnetism and magnetic flux pinning properties of superconductors to generate magnetic fields contrary to the outside world, and generate repulsive forces with permanent magnets, so as to achieve non-contact suspension of the rotor [40], which is usually used in combination with permanent magnets. Although superconducting suspension technology has made remarkable progress, the practical use of superconducting magnetic bearings will still be limited by the hysteresis loss phenomenon of the material itself and the dependence on a low-temperature environment and cooling system.

In the research and application of passive magnetic bearings made of normal temperature diamagnetic materials, the magnetic suspension technology is mainly applied within a small range because of the low magnetic properties of the existing normal temperature

diamagnetic materials. Researchers must use magnetic materials large enough to generate magnetic forces that support the stable suspension of the controlled object. The diamagnetic effect is represented by the repulsion between magnets, as shown in Figure 13. In the case that the gravity of the rotor is balanced with the repulsive force, the rotor will remain in a stable suspension state. If the rotor is shifted due to external forces, the magnetic repulsion between the fixed rotors will strengthen as the air gap shrinks, producing the opposite force that pushes the rotor back to the equilibrium position. And vice versa, if the air-gap expands, the magnetic repulsion weakens. In addition, for smaller diamagnetic rotors, their radial displacement is also limited in a potential well composed of a permanent magnet stator. Therefore, this system can effectively provide stable axial and radial support for the rotor. Figure 14 is the basic structure diagram of a diamagnetic bearing. It should be noted that although the structures of the diamagnetic rotor and permanent magnet stator are interchangeable, due to the low magnetic flux density of the diamagnetic body itself, the bearing capacity required by the structure shown in the figure is smaller and it is easier to realize the bearing design.

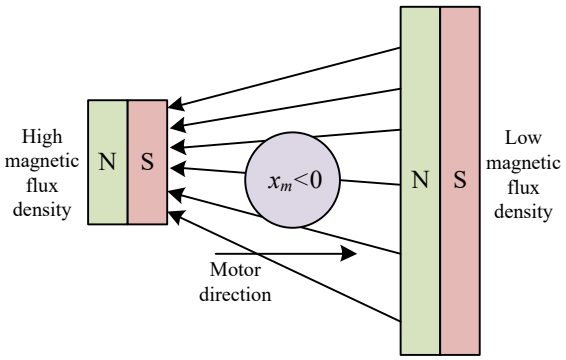


Figure 13. Schematic diagram of diamagnetic effects [41].

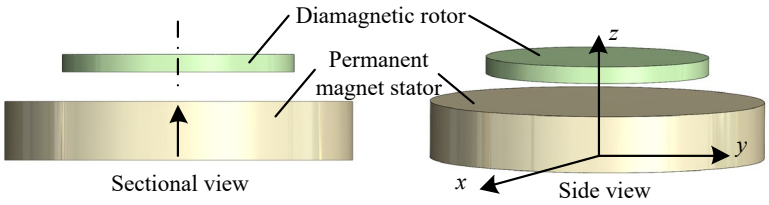


Figure 14. Basic structure diagram of diamagnetic bearing [42].

Figure 15 shows the hybrid diamagnetic bearing structure, which can be used in applications with high bearing capacity requirements. The structure includes a permanent magnet biased magnet, a stable diamagnetic substance, and a suspended rotor, all of which are made of permanent magnet materials. The rotor suspension position is balanced by the force generated between the magnets. The position of the biased magnet is selected with reference to the equilibrium point of gravity, and the radial stability of the rotor is achieved through the ring structure. At the same time, a diamagnetic substance is placed above and below the permanent magnet rotor and its orientation is kept unchanged to achieve a stable suspension in the vertical direction. The adjustment gap of diamagnetic substances must be within a controllable range to ensure the stability of the bearings [43].

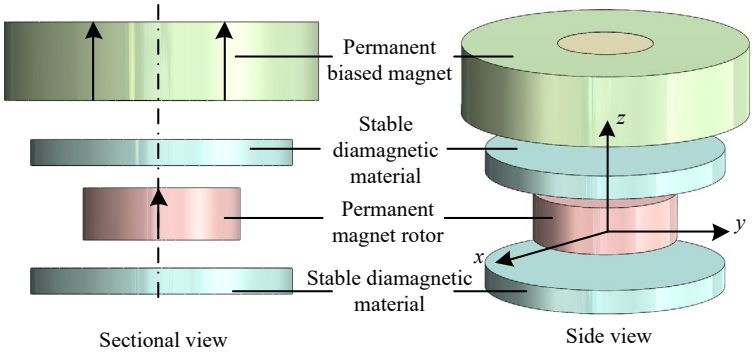


Figure 15. Structure diagram of hybrid diamagnetic bearing [43].

Xu et al. [41] proposed a new configuration of frictionless maglev combined with an electrostatic glass motor. A disc-shaped rotor with a diameter of 12.5 mm was fabricated, which was composed of pyrolytic graphite and glass. As shown in Figure 16, Cansiz et al. [44] designed a test platform for passive suspension with reference to the diamagnetic characteristics of bismuth, and made the rotor of the diamagnetic bearing, which was stably suspended in the air, run at high speed through special gas injection. Moreover, they studied the relationship between its output and input in the stage of gradually decreasing speed. Su et al. [45] used a material called highly oriented pyrolytic graphite (HOPG) to make a suspension rotor and rotated it to 52.3 rad/s by using a special gas injection. In previous studies on maglev experiments, the rotation of the rotor was not an active rotation driven by a motor, but its rotation could be adjusted. Both rely on external devices to spray special gases to turn the rotor.

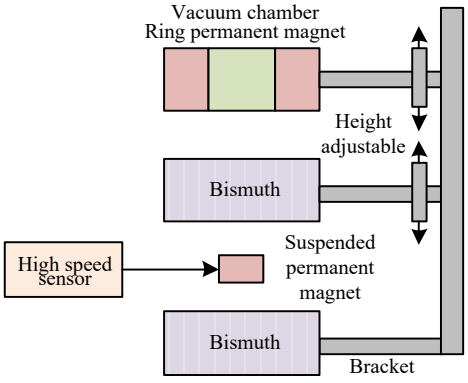


Figure 16. Passive magnetic suspension test platform [44].

2.3. Statistical Comparison Between the Magnetic Bearings

These performance differences of magnetic bearings depend not only on whether they are of the suction type or the repulsive type, but also on multiple factors, such as ferromagnetic materials, the area and thickness of magnetic poles, the configuration of magnetic poles, the bearing clearance, and the structural magnetic circuit. This can be seen from the formulas for deriving the suspension force:

$$F = \frac{B^2 A}{2\mu_0} = \frac{\Phi^2}{2\mu_0 S_r} \tag{1}$$

where the vacuum magnetic permeability is μ_0, A and S_r are both represented as the magnetic pole area, Φ is the total magnetic flux, and B is the magnetic flux density.

Compared with suction magnetic bearings, repulsive magnetic bearings usually have the characteristics of lower magnetic force utilization and more complex structures. This

means that under the same conditions, to achieve the same load-bearing capacity, repulsive magnetic bearings may require more magnetic force or a more complex structure. Table 2 shows the static performance of different magnetic bearings, their applicable fields, and limitations.

Table 2. Statistical comparison between the magnetic bearings.

Type of Magnetic Suspension Bearing		Statical Performance	The Suspension Magnetic Force	Application	Limitations
Suction magnetic bearing	AMB	The electromagnet provides the base suspension force and is adjustable in real time. The stiffness and damping can be flexibly adjusted by the control algorithm. The bearing capacity and stiffness are large.	In [23], when the offset of the rotor in the z direction is 30 mm, the suspension magnetic force is 21 N, the displacement stiffness is 0.7 N/μm. The maximum rate of change of z-axis force is 0.29%.	Aero engines, satellite attitude control, high speed motors, turbomolecular pumps, etc.	High hardware and maintenance costs, high system complexity, and vulnerability to electromagnetic interference.
	HMB	The permanent magnet provides the basic suspension force, and the electromagnet regulates the suspension force. High overall stiffness, stiffness adjustability. The combination of passive damping and active damping can optimize the damping performance.	In [25], when the offset of the rotor in the x direction is 0.2 mm, the suspension magnetic force is 16 N.	High speed motor, aero engine, satellite attitude control, flywheel energy storage., etc.	Complex magnetic field design, high-precision manufacturing requirements, high material, maintenance costs, and complex control systems.
	PMB	Permanent magnet provides suction force, has self-balancing ability in a certain range, nonlinear stiffness, stiffness is closely related to the air gap, the inherent damping is small, dependent on structural damping.	In [32], when the offset of the rotor in the z direction is 2 mm, the suspension magnetic force is 10 KN, the displacement stiffness is 2 N/m.	Small rotary equipment, precision balance, gyroscope, vacuum environment equipment, high-temperature environment equipment, etc.	Limited suspension force and carrying capacity, limited by permanent magnet performance and air gap, stability affected by nonlinear characteristics, lack of active adjustment ability, sensitive to the environment.
Repulsive magnetic bearing	PMB	The repulsion force of permanent magnet produces suspension, the suspension force is strongly related to the distance, the nonlinear stiffness, the stiffness adjustment is difficult, the inherent damping is small, and the damping can be increased by structural design.	In [23], when the offset of the rotor in the z direction is 30 mm, the suspension magnetic force is 21 N, the displacement stiffness is 0.7 N/μm.	Small motor, micro pump, precision balance, optical gyroscope, vacuum environment equipment, radioactive environment, etc.	The limitations are similar to those of suction passive magnetic bearings. Suspension force and load capacity are limited by permanent magnet performance and air gap, stability is affected by nonlinear characteristics, lack of active adjustment ability, and sensitive to temperature and magnetic field.
	DMB	The diamagnetic effect produces the suspension force, which is relatively small and stable, and the stiffness is low. The stiffness is related to the material and magnetic field distribution, and the inherent damping is small, which can be increased by additional structures.	In [41], when the offset of the rotor in the z direction is 3 mm, the suspension magnetic force is 13 KN.	Optical chopper, gyroscope, biochip, crystal holographic interferometer, high precision force sensor, etc.	The suspension force and carrying capacity are limited, the stiffness and stability are insufficient, and the application range is limited.

2.4. Chapter Summary

According to the different classification methods, action principles, and characteristics of magnetic bearings, the suspension force generation methods are summarized, as shown in Table 3.

Table 3. Magnetic bearing classification characteristics.

Type of Magnetic Suspension Bearing		Action Principle	Characteristics
Suction magnetic bearing	AMB	The rotor is supported by the suspension force generated by the electromagnet, and the position of the rotor is precisely located by the displacement sensor. The control system adjusts the magnetic force by adjusting the current intensity to correct and maintain the stable operation of the rotor on the predetermined trajectory. The device is mainly composed of an electromagnet, a displacement sensor, a rotor, a power amplifier and a controller.	Inverter drive, small size, strong nonlinear, mature technology.
	HMB	The bearing integrates the technical characteristics of active and passive magnetic bearings, and takes the active magnetic bearings as the core in the structural design, adding a permanent magnet or superconductor to form a biased magnetic field to provide auxiliary suspension force, and is equipped with mechanical protection bearings.	The structure is slightly complex, but due to the reduction of the number of turns of the electromagnetic coil, the overall bearing volume is reduced and the cost is saved.
	PMB	By controlling the attraction between the stator and the rotor, the rotor can realize the stable suspension without contact by using the suspension force generated by the permanent magnet.	Simple structure, no need to control and consume electric energy, easy to use, small bearing capacity, low precision.
Repulsive magnetic bearing	PMB	The rotor is suspended by repulsive forces generated by the magnetization direction arrangement of different permanent magnets, including axial array, radial array, and Halbach array.	A design similar to the suction-type permanent magnet bearing is proposed. However, this type of bearing operates by relying on the repulsive force between magnetic rings. Multiple magnetic rings need to be stacked to increase the load-bearing capacity and stiffness.
	DMB	By using the diamagnetism and flux napping properties of superconductors or normal temperature diamagnetism materials, the magnetic field opposite to the outside world is generated, and the repulsion force is generated with the permanent magnet, so as to realize the rotor non-contact suspension magnetic bearing.	Passive and completely contactless friction, simple structure, variable stiffness, superconducting magnetic bearings require low temperature environment. Ambient diamagnetic material magnetic bearings require light load weight.

3. Modeling of Magnetic Suspension Bearing

3.1. Modeling of Suction Magnetic Bearings

3.1.1. Modeling of Electromagnetic (Active) Magnetic Bearings

The active magnetic suspension bearing adopts the design without a permanent magnet and completely relies on the electromagnetic attraction of the electromagnet to stabilize the suspended rotor. At the same time, the load capacity of the system depends on the maximum electromagnetic attraction provided by the electromagnet. Therefore, it is very important to accurately derive the expression of electromagnetic suction force for bearing structure design and parameter calculation of the control algorithm. At present, the mathematical modeling methods of active magnetic bearings mainly include the virtual displacement method, equivalent magnetic circuit method, and Maxwell tensor method. In order to simplify the analysis, Ref. [46] selected a magnetic circuit for derivation, ignoring the effects of leakage flux, hysteresis loss, and eddy current loss. The magnetic circuit diagram is shown in Figure 17. According to the virtual displacement theorem, the magnetic field energy at the air gap also changes with the increase of the air gap, and the change of magnetic field energy is provided by the work performed by electromagnetic suction. The expressions of electromagnetic attraction F_1 and F_2 are:

$$F_1 = F_2 = \frac{dW}{d\delta_0} = \frac{1}{2}BHS_0 = \frac{B_0^2 S_0}{2\mu_0} = \frac{\mu_0 S_0 N^2 i_0^2}{2\delta_0^2} \quad (2)$$

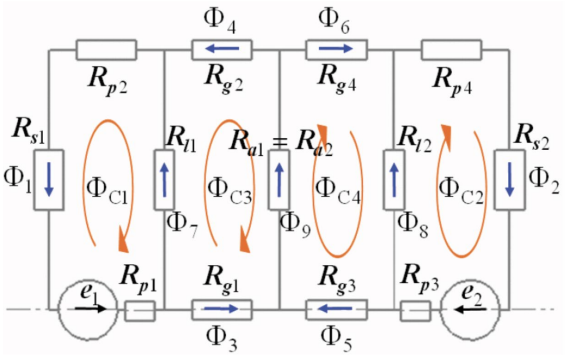


Figure 17. Magnetic circuits of an axial active magnetic bearing [46].

The resultant force F of the rotor in the y-axis direction is:

$$F = \mu_0 S_0 N^2 \cos\alpha \left[((i_0 + i)/(\delta_0 + x\cos\alpha))^2 - ((i_0 - i)/(\delta_0 - x\cos\alpha))^2 \right] \tag{3}$$

In the control of the magnetic bearing system, the bias current is much larger than the control current, and the rotor offset x is very small. At $x = 0$, $i = 0$, taylor expansion is carried out on the relevant function, and the higher order term is ignored, and the expression form of rotor displacement x and bias current i_0 can be obtained, that is:

$$\begin{cases} F = k_x x + k_i i_0 \\ k_x = -4\mu_0 S_0 N^2 i_0^2 \cos\alpha/\delta_0^3 \\ k_i = 4\mu_0 S_0 N^2 i_0 \cos\alpha/\delta_0^2 \end{cases} \tag{4}$$

where k_x is the stiffness coefficient of rotor displacement, and k_i is the current stiffness coefficient.

In Ref. [23], the analytical formula of the magnetic force of the tapered active magnetic bearing with the claw structure is derived by using the magnetic circuit method and the principle of virtual displacement. Magnetic force f_m can be calculated using the principle of virtual displacement, i.e.:

$$f_m = \frac{B^2 A}{2\mu_0} = \frac{\mu_0 n^2 i^2 A}{2\delta^2} = \frac{1}{2} k \left(\frac{i}{\delta} \right)^2 \tag{5}$$

In addition to the above common methods, active magnetic bearings also use sub-domain methods. The Fourier series is the basis of the sub-domain method. Based on the relevant magnetic-field boundary conditions, the sub-domain problem can be solved by using the vector magnetic potential in each sub-domain. In Ref. [47], AMB is divided into several sub-domains, and the magnetic flux field distribution of the corresponding sub-domains is obtained by the superposition of the 0-order and 1-order components of the magnetic field considering the rotor eccentricity using the perturbation theory.

In Ref. [48], based on the sub-domain and perturbation methods, the active magnetic bearing is divided into two regions: the air-gap and the stator-groove (as shown in Figure 18). At the same time, the zero-order equations and first-order equations in polar coordinates are obtained and solved by the method of variable separation. According to the perturbation method, the first order solution is superimposed on the zero order solution, and the magnetic field distribution is obtained. By using Maxwell's stress tensor theory, the

unbalance magnetic force is calculated and the displacement stiffness and current stiffness are obtained. The components of the x and y magnetic forces are obtained by integrating:

$$\begin{aligned} F_x &= \int_{-L/2}^{L/2} \int_{-\pi}^{\pi} f_x r \mathrm{d}\alpha \mathrm{d}z = L \int_{-\pi}^{\pi} f_x r \mathrm{d}\alpha \\ F_y &= \int_{-L/2}^{L/2} \int_{-\pi}^{\pi} f_y r \mathrm{d}\alpha \mathrm{d}z = L \int_{-\pi}^{\pi} f_y r \mathrm{d}\alpha \end{aligned} \tag{6}$$

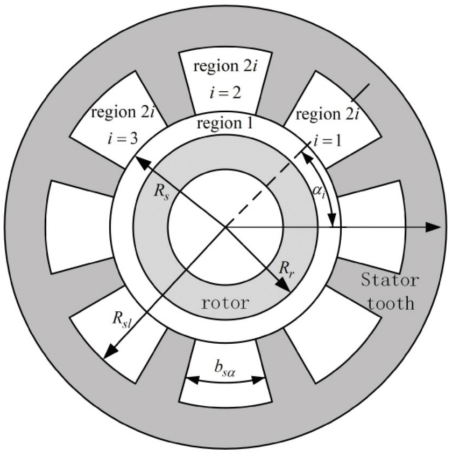


Figure 18. Symbols and two types of sub-regions [48].

In Ref. [49], an analytical model using sub-domain and conformal mapping methods is established, and its accuracy is verified by finite element methods (FEM) and experiments. Although the above method is highly accurate in its calculation, it is relatively complicated to calculate when the rotor is eccentric. On top of that, sub-domain methods can scarcely handle saturation effects. The dynamic magnetic circuit method can dynamically update the reluctance through the B–H curve in the magnetic potential equation, thus taking the saturation effect into account. In Ref. [50], the improved Langmuir method is used to obtain the exact expression of the magnetization curve and establish the magnetic circuit equation of AMB, but the strong nonlinear relationship is not conducive to the numerical solution. The magnetic circuit diagram is shown in Figure 19. In addition, Ref. [51] adopted a new analysis and calculation method based on the distributed magnetic circuit method. The magnetic circuit diagram is shown in Figure 20. It can not only consider magnetic saturation, but can also avoid calculating complex magnetic field equations caused by rotor eccentricity. In the distributed magnetic circuit method, there is no need to write the node magnetic potential equation and calculate the resistance, and there is no need to make major adjustments to different structures. At present, the distributed magnetic circuit method is mainly used in the design of polyphase induction motors. It mainly uses multiple magnetic circuits and iterative calculations to achieve accurate magnetic circuit calculations, so it actually belongs to the dynamic magnetic circuit method. It is worth noting that, due to the differences in the motor, before applying the distributed magnetic circuit method, the rotor eccentricity, and the divergence caused by zero magnetic potential should be considered.

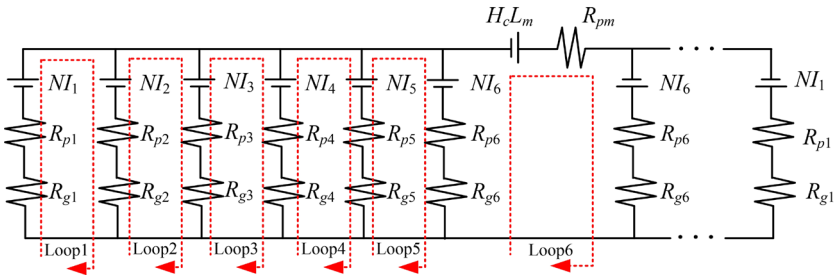


Figure 19. 1-D magnetic circuit model of homopolar magnetic bearing [50].

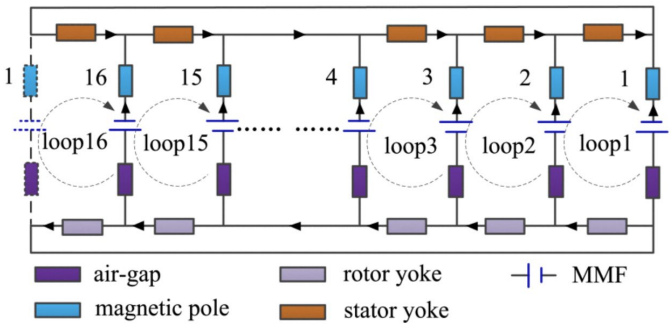


Figure 20. Magnetic circuit model of AMB [51].

3.1.2. Modeling of Hybrid Magnetic Bearings

As a traditional modeling method, the equivalent magnetic circuit method is often employed, and it uses the commonality between the magnetic circuit and the circuit to analogize the magnetic potential, magnetic permeability, and magnetic flux into the resistance, electromotive force, and current in the circuit, respectively. In this way, an equivalent magnetic circuit diagram can be drawn for further analysis. As shown in Figure 21, in Ref. [52], this method is applied to a three-pole radial-axial hybrid magnetic bearing to build an accurate radial two-degree-of-freedom suspension force model. The researchers considered the leakage permeability and the gap permeability, and drew the equivalent magnetic circuit diagram to derive the mathematical model of the suspension force:

$$\begin{cases} \begin{bmatrix} F_x \\ F_y \end{bmatrix} = \frac{3}{2} k_{xy} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} + \sqrt{\frac{3}{2}} k_{ir} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} i_x \\ i_y \end{bmatrix} \\ k_{xy} = \frac{\mu_0 F_m^2 S_r}{2\delta_r^3}; k_{ir} = \frac{\mu_0 N_r F_m S_r}{2\delta_r^2} \end{cases} \tag{7}$$

where the total magnetomotive force is F_{pm}. The vacuum permeability is expressed by μ_0. The radial magnetic pole area, air gap length, and coil turns are S_{r}, δ_{r}, and N_{r}, respectively.

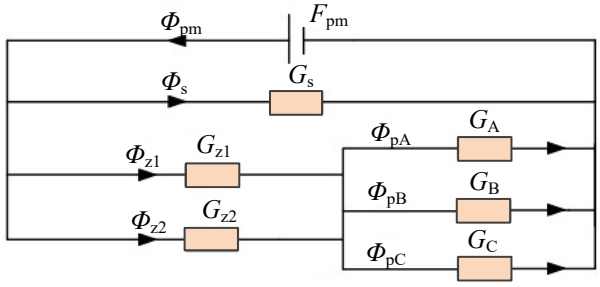


Figure 21. Equivalent biased magnetic circuit diagram [52].

In Ref. [53], the equivalent magnetic circuit method is further used to estimate the leakage flux, thus improving the practicability of flywheel control. A dynamic performance

analysis method of magnetic suspension bearing based on the equivalent circuit model and considering the eddy current effect and leakage effect is proposed to predict the dynamic performance of the magnetic suspension bearing and guide the design of the magnetic suspension bearing. Firstly, the equivalent magnetic circuit of bias flux, axial control flux, and radial control flux is established (as shown in Figure 22). Then the eddy current effect of different materials is modeled. The influence of the leakage effect on static stiffness and dynamic stiffness is analyzed, and the influence of the eddy current effect on leakage coefficient is analyzed. Further, as shown in Figure 23, Ref. [24] also adopted the equivalent magnetic circuit method to propose a suspension force modeling method based on accurate magnetic field segmentation and accurately calculated fringing flux and leakage flux, obtaining a more accurate model.

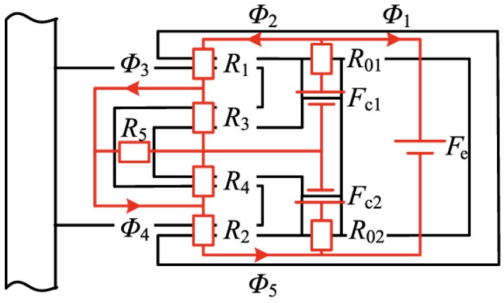


Figure 22. Equivalent magnetic circuit of axial magnetic bearing [53].

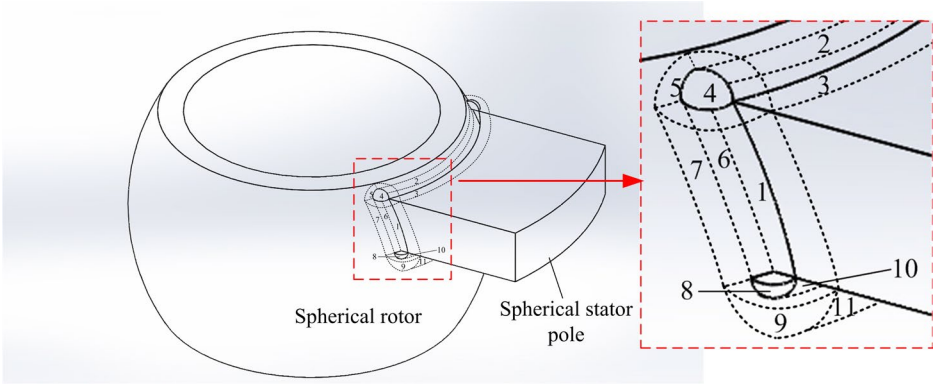


Figure 23. Sub-regions of flux [24].

Based on the similarities in structure and function between the AC magnetic bearing and bearing-less motor's suspension subsystem, Ref. [54] developed a new modeling method for radial suspension force of the AC magnetic bearing based on the Maxwell tensor method by referring to the mathematical model construction of the radial suspension force of the bearing-less motor. Compared with the radial suspension force model of the AC two-degree-of-freedom hybrid magnetic bearing established by the equivalent magnetic circuit method, it is found that the suspension force expressions obtained by the two methods are identical in form, and the difference is only in the coefficient. Moreover, the accuracy and practicability of the new model and method are verified.

3.1.3. Modeling of Passive Magnetic Bearings

At present, the modeling theory of the permanent magnet suspended bearing is not mature. In research and design, the crucial step is to calculate its bearing capacity and stiffness. Researchers usually adopt general and simplified mathematical models. They also use different modeling methods, such as the equivalent magnetic circuit method and the equivalent magnetic charge method [55–59]. Each of these methods has its own

advantages and limitations. Researchers choose and improve the method to model and analyze bearings according to specific application scenarios and needs.

Yonnet has established a general mathematical model of permanent magnet suspension bearings, which can be used not only as a mathematical model of radially magnetized magnetic bearings, but also as a mathematical model of axially magnetized magnetic bearings, so it is universal. In order to establish the feasibility of this general mathematical model, the following basic assumptions need to be satisfied:

(1) Assume that the remanent magnetization of the permanent-magnet material is high;
(2) Ignore the influence of curvature on calculation accuracy;
(3) Assume that the two parallel magnets are infinitely long.

In this case, the magnetic field lines are confined to the cross-section of the magnets, thus simplifying the problem to a two-dimensional one. The simplified mathematical model is based on the general model. In addition, the coaxial toroidal magnet is regarded as an infinitely long bar magnet. Combined with the equivalent magnetic charge method, a simplified model of axially magnetized radial magnetic suspension bearing is constructed based on the static magnetic energy between two magnets per unit length and the first and second derivatives of this energy with respect to coordinates x and y [55]. Based on the general model, Dellinger regarded the ring magnet as a combination of two cylindrical magnets and established a mathematical model of axially magnetized radial magnetic suspension bearings by using the equivalent magnetic charge method [56]. Based on the general model, Ref. [57] developed a numerical integral model of radially magnetized radial magnetic suspension bearings by establishing the relationship expression of magnetic charge interaction at each pair of points. Based on the general model, Ref. [58] developed the numerical integral model of axially magnetized radial magnetic suspension bearings by constructing the relationship expression of magnetic charge interaction at each pair of points. The calculation model of magnetic force is shown in Figure 24. In accordance with the theory of equivalent magnetic charge, the axial magnetic force between the inner and outer magnetic sleeves can be formulated as:

$$\begin{cases} F_a = \dfrac{B_{r1}B_{r2}}{4\pi\mu_0}\int_0^{2\pi}\int_0^{2\pi}\int_{R_1}^{R_2}\int_{R_3}^{R_4} A_1 r_1 r_2 \mathrm{d}r_1 \mathrm{d}r_2 \mathrm{d}\alpha \mathrm{d}\beta \\ A_1 = \dfrac{2\delta_0}{\left(A_2+\delta_0^2\right)^{3/2}} + \dfrac{\delta_1-\delta_0}{\left(A_2+(\delta_1-\delta_0)^2\right)^{3/2}} + \dfrac{\delta_2+\delta_0}{\left(A_2+(\delta_2+\delta_0)^2\right)^{3/2}} \\ A_2 = (r_2\sin\beta - r_1\sin\alpha)^2 + (r_2\cos\beta - r_1\cos\alpha)^2 \end{cases} \tag{8}$$

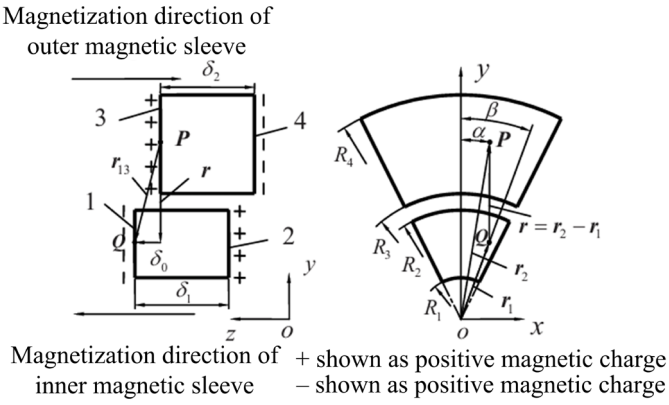


Figure 24. The calculation model of magnetic force [58].

Ref. [59] further used the magnetic charge method and virtual work method to quantitatively analyze Halbach permanent magnet bearings and they established a model.

3.2. Modeling of Repulsive Magnetic Bearings

3.2.1. Modeling of Passive Magnetic Bearings

At present, the general analytical modeling methods of repulsive passive magnetic bearing magnetic force include the equivalent magnetic charge method, the equivalent current method, and the Fourier analysis method, or the magnetic field analytic curve can be directly obtained by using the finite-element simulation method. Current research focuses on double-ring permanent-magnet bearings. Determining their magnetic force usually relies on complex numerical calculation methods or empirically-based formulas [60–62]. In Ref. [60], based on the molecular current hypothesis of Ampere's, the space magnetic field around a rectangular permanent magnet is simulated by the surface current method, and then the expression of the space magnetic field is derived. Finally, the magnetic field calculation formula of the Halbach array is obtained by using the superposition theorem and coordinate transformation. Ref. [61] conducted a comparative analysis of the axial magnetic force of Halbach permanent magnet bearings composed of permanent magnet rings with rectangular sections, and found that 90° rotation magnetization is more feasible when meeting specific force and stiffness requirements (as shown in Figure 25). In Ref. [62], an analytical model is further constructed, which is used to evaluate the axial magnetic force on the rotor of Halbach permanent magnet bearing composed of rectangular section permanent magnet ring during assembly (as shown in Figure 26). This study provides important theoretical support for the design and optimization of magnetic bearings. The formula of axial suspension force is:

$$F = \frac{B_{r1}B_{r2}L \times 10^{-6}}{4\pi\mu_0}\left[\sum_{i=1}^{n}(n-i-1)\Theta(c_{i1}) + \sum_{j=2}^{n}(n-i-1)\Theta(c_{j1})\right] \quad (9)$$

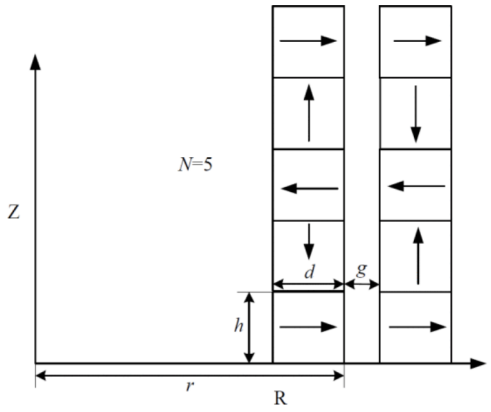


Figure 25. A passive axial magnetic bearing with Halbach magnetic field [61].

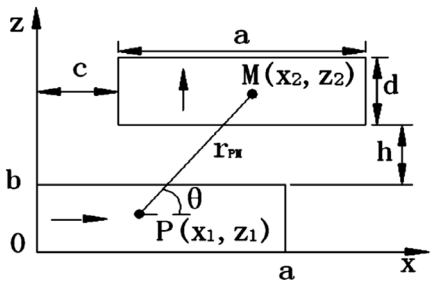


Figure 26. Model of magnetic force for axial stack permanent magnet bearings [62].

3.2.2. Modeling of Diamagnetic Bearings

The static characteristics of HTS magnetic bearings, including suspension force and lateral restoring force, are generally analyzed using the Bean critical state model. The Bean model is more accurate in the analysis of stability, bearing capacity, and AC loss, etc. The vector control model can be used to calculate the interaction force between the superconductor and the magnet. Additionally, the suspension force model can also be simplified to the force between the permanent magnet and its mirror image. This simplification has the advantage of facilitating easier analytical solutions. The finite element method can be used when the relative permeability of high temperature superconducting materials is set to low. Ref. [63] used a method based on the magnetization curve of superconducting materials to calculate the suspension force, but this method is not universally applicable because the magnetization curve changes with different sizes. Based on the Kim model of macroscopic electromagnetic field of superconductors, Ref. [64] simulated and analyzed superconductors with the method of electric vector potential, and established a nonlinear electromagnetic field model. Through the quantitative simulation of the designed experimental process, the accurate simulation of the hysteresis of the suspension force is realized quantitatively. In the analysis of permanent magnets, Ref. [41] used a current model. In this model, the magnet is equivalent to the current distribution, and then the standard current calculation method is used to solve the magnetic field. The force provided by the magnetic field H on a diamagnetic body of diamagnetic material can be written as follows:

$$\vec{F} = \mu_0(\mu_r - 1)\int_V \nabla \vec{H}\vec{H}\mathrm{d}V \tag{10}$$

On the other hand, Simon used the magnetic dipole method [65] to explore the suspension force of bearings, and simplified the model structure and established analytical formulas to characterize the bearing capacity and stiffness. Because the effect of the structure on performance is not taken into account in the modeling, the method is easy to calculate, but there is a big difference between the results obtained by this method and the actual situation, and it cannot accurately reflect the dynamic changes of the suspension force and stiffness in the case of rotor-position migration. Cansiz et al. [42] obtained the elliptic integral expression of the magnetic force under axisymmetric conditions through the magnetic field image method, and built the analytical model of bearing capacity and stiffness with the help of the polynomial approximation method. However, this modeling method cannot be widely applied to a more general bearing model description. The suspension force is as follows:

$$F(I_1, I_2, x, z) = \frac{\mu_0 I_1 I_2 R_2}{2\pi}\int_{-\pi/2}^{\pi/2}[F_s(r_1, x, z) - F_s(r_2, x, z)]\mathrm{d}\Phi \tag{11}$$

Ref. [44] studies the statics and dynamics of diamagnetic bearings, which consist of disc-shaped rotor magnets. Based on the discussion of dipole approximation and the magnetic image method, as well as the simple model calculation, the stable suspension of diamagnetic bearing is explained, and some parameters of diamagnetic bearing are understood. As a general numerical analysis method, the finite element method is widely used to analyze the magnetic field of various geometric structures, especially in dealing with three-dimensional structures and nonlinear magnetic field problems. However, the finite element method consumes relatively a large amount of computational resources, and the analysis process is time-consuming, which limits the application of the finite element method in dynamic system response analysis and structural optimization design.

3.3. Chapter Summary

At present, the modeling method of magnetic suspension bearing is still developing and improving. The modeling methods of different types of magnetic suspension bearings are summarized in Table 4.

Table 4. Modeling method of suspension force of magnetic suspension bearings.

Type of Magnetic Suspension Bearing		Modeling Approaches	Literature
Suction magnetic bearing	AMB	Virtual displacement method, equivalent magnetic circuit method, Maxwell tensor method, Sub-domain method, Perturbation method, Dynamic magnetic circuit method, Distributed magnetic circuit method.	[23,46–51]
	HMB	Equivalent magnetic circuit method, Maxwell tensor method, Considering eddy current effect to establish the mathematical model of suspension force.	[24,52–54]
	PMB	General mathematical model, Simplified mathematical model, Equivalent magnetic circuit method, Equivalent magnetic charge method.	[55–59]
Repulsive magnetic bearing	PMB	Equivalent magnetic charge method, Equivalent current method, Fourier analysis, Finite Element analysis method, Lorentz force method.	[60–62]
	DMB	Analysis of magnetic field model, Suspension force model, In-plane electromagnetic force model, Magnetic dipole method, Magnetic field image method, Finite element analysis method.	[41,42,44,63–65]

4. Magnetic Bearing Control Strategies

4.1. Suction Type Magnetic Bearing Control Strategies

4.1.1. Low Power Control Strategies

In the practical application of the magnetic suspension bearing system, power consumption is a key performance index. When the power consumption increases, the coil in the bearing may heat up and cause the temperature to rise, which may not only cause the thermal expansion of the rotor, but may also cause the temperature drift of the sensor. These thermal effects will eventually affect the control accuracy of the rotor [66]. The loss of magnetic bearings mainly includes four aspects: rotor loss, stator magnet loss, power amplifier loss, and coil loss. In the design phase, once the loss of the rotor and coil are determined, they are usually fixed and difficult to further adjust. However, the loss of the power amplifier can be reduced by reducing the switching frequency or using soft switching technology. Therefore, the main energy dissipation part is the loss in the stator magnet, which mainly includes copper loss and iron loss. In order to reduce power loss, Tsiotras et al. [67] implemented a low bias current control strategy. They adjusted the flux density by fine-tuning the control current and developed a matching nonlinear controller for this purpose. Because power consumption is one of the main obstacles limiting its development towards portability, how to reduce the energy consumption of the system under the premise of ensuring the stable suspension of the rotor has become a key issue that needs to be overcome in the field of magnetic suspension artificial heart pumps.

The aim of zero-power control technology is to minimize the current in the electromagnetic coil while ensuring that the rotor remains suspended. When the allowable static force is applied, the current is maintained within a small fluctuation range close to zero by precisely adjusting the suspension gap. This design makes the zero-power control strategy the preferred solution for low-energy magnetic suspension artificial heart pumps. At present, this control strategy has been applied to the vibration isolation system and

maglev traffic field. Mizuno et al. [68] elaborated on the design and experimental process of zero power control. The equation of motion of the floator is as follows:

$$M\ddot{z}(t) = F_z - Mg \tag{12}$$

The state equation with a zero-power controller is as follows:

$$\begin{cases} \dot{\hat{x}}(t) = \hat{A}\hat{x}_v(t)\hat{b}_u(t) \\ \hat{x} = \begin{bmatrix} x \\ i_{int} \end{bmatrix}, \hat{A} = \begin{bmatrix} & & A & & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \hat{b} = \begin{bmatrix} b \\ 1 \end{bmatrix} \end{cases} \tag{13}$$

The control system block diagram with zero power controller is shown in Figure 27.

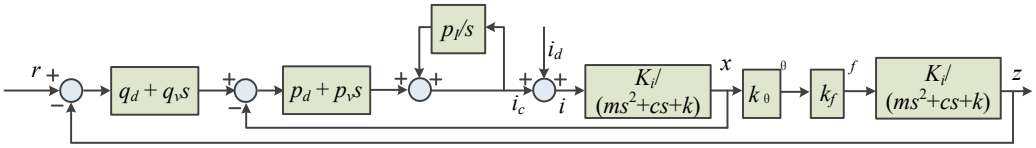


Figure 27. The method of zero-power control [68].

Takeshi et al. [69] designed a zero-power controller under voltage control and current control in vibration isolation systems. For hybrid magnetic bearings, reducing the bias current is also a strategy to reduce energy consumption. It can be achieved by introducing a variety of nonlinear control algorithms, such as the TSK fuzzy controller, variable bias current controller, hyperbolic linear bias controller, or PWM-modulated PID controller. These algorithms can adjust the bias current intelligently and help build an intelligent bias controller based on the switching control strategy. Another method is to control the current integral term as an outer loop independently, and to use the fastest current loop feedback, so that the coil current can respond quickly to the change of the control voltage, thereby reducing the hysteresis effect of the inductance. At the same time, considering the optimal control parameters under different loads and the characteristics of the zero-power suspension state gap, an adaptive mechanism can be designed. This mechanism can adjust the PD-ring parameters under variable load quality conditions to achieve the best control effect.

4.1.2. Zero Displacement Control Strategies

The zero-displacement control strategy, which is also referred to as unbalance compensation, is specifically designed to minimize the displacement of the rotor. This strategy aims to enhance the active control ability of the magnetic bearing and improve the dynamic stiffness of the system. It does so by increasing the control current through specific measures or compensation algorithms. Through this method, the rotor rotates around the geometric center of the magnetic bearing stator as much as possible. As a result, the displacement and vibration of the rotor are effectively reduced, minimizing the rotor vibration amplitude. There are two main methods of displacement minimum compensation: current compensation and displacement voltage compensation. Both methods reduce rotor vibration by increasing the control current.

With the progress of control theory, scholars have effectively integrated a variety of control strategies, including pole assignment, feedforward, and feedback adjustment methods. Lum et al. [70] proposed an adaptive centering control to adjust the control of various degrees of freedom of magnetic bearings. In order to minimize the impact in displacement compensation and reduce the dependence on model accuracy, Kim et al. [71] proposed an adaptive algorithm to estimate the magnitude of unbalance. They also developed a method

to detect the rotor displacement of magnetic bearings based on the extended influence coefficient method. This strategy obviates the need for the traditional compensation algorithm in a three-point sensor configuration, preventing compensation failure. Moreover, it can automatically identify and adjust rotor vibration.

After improving the influence coefficient method, Ref. [72] proposed a generalized influence coefficient method and tested the unbalance amplitude. The method evaluates whether an equilibrium state has been reached after each increase in mass. Compared with the traditional influence coefficient method, this optimized method can provide better vibration suppression balance under the high speed working condition of the magnetically suspended rotor. In addition, Ref. [73] also introduced an influence coefficient method based on active magnetic bearings, and the compensation method is shown in Figure 28. The unbalance force of the rotor and the compensation signal are as follows:

$$\begin{cases} F_d(t) = me\omega^2 \angle(\omega t + \theta) = me\omega^2 \cos(\omega t + \theta) + jme\omega^2 \sin(\omega t + \theta) \\ U_c(t) = \alpha \cos \omega t - \beta \sin \omega t + j(\alpha \sin \omega t + \beta \cos \omega t) \end{cases} \tag{14}$$

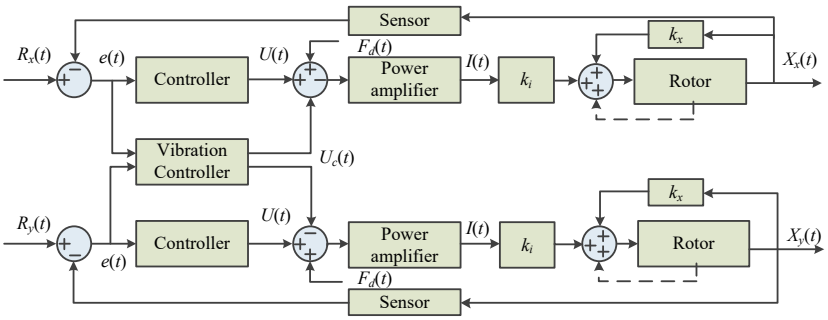


Figure 28. Compensation rotor unbalance vibration method [73].

This method uses an active magnetic bearing to generate a current consistent with the displacement frequency and phase in front of the rotor during alignment, thus replacing the traditional operation of increasing and decreasing the counterweight in the process of dynamic balancing. The current value used to reduce the rotor's unbalanced vibration is determined by calculation, and the real-time unbalanced vibration correction can be realized to ensure the stable operation of the rotor. The influence coefficient method is a method to determine the test quality through an iterative process, but there are other methods to choose from when calculating the unbalance force of the rotor.

Ref. [74] proposed an iterative algorithm based on variable step size, which extends and optimizes the iterative algorithm with fixed step size. The algorithm integrates signal processing, iterative calculation, and output module, and realizes accurate iterative calculation of unbalance force amplitude effectively. Compared with other algorithms, the variable step size algorithm has significant advantages in accuracy and convergence speed. The LMS algorithm is widely used in the phase estimation of rotor unbalance compensation because it can be regarded as a trap for a specific frequency signal. In addition to the LMS algorithm, many filtering techniques are applied to the unbalance compensation phase estimation of magnetic bearing rotors. Schuhmann et al. Ref. [75] used the Kalman filter method to extract the unbalance displacement and enhanced the stiffness with a linear Gaussian state feedback controller to reduce vibration. Ref. [76] applied a synchronous rotating coordinate system (SRF), which is widely used in motor control, to magnetic bearing control, as shown in Figure 29. In this study, a feedforward control loop is used to generate two orthogonal signals by generating single-phase displacement error signals, which are used as inputs for the super regenerative frequency (SRF) transformation. This

method can convert the displacement error of the same frequency into the direct flow rate, and can then realize the tracking and control of the transformed direct flow rate without static error. The transfer function of this novel notch filter is as follows:

$$g_n(s) = \frac{1}{1 + \hat{g}_n(s)} = \frac{1}{1 + g_f(s - j\Omega)e^{-j\theta}} \tag{15}$$

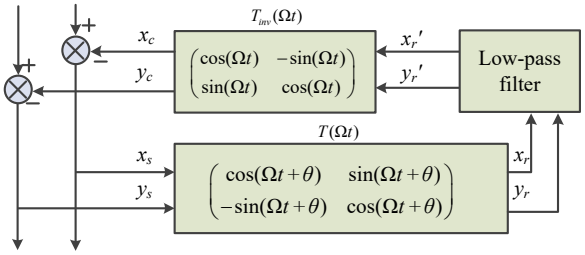


Figure 29. The structure of the SRF transformation [76].

In Ref. [77], Han B.C. et al. proposed a new algorithm based on frequency domain adaptive LMS. This method uses harmonic vibration force as the input to the filter. It also introduces a sinusoidal signal as the reference input, which has the same component as the sensor pulsation. At the same time, a convergence factor of the step update strategy is proposed to improve the harmonic convergence rate. The simulation results show that the proposed method can effectively suppress the harmonic vibration force of the magnetic suspension rotor system. Ref. [78] proposed a novel decoupling control method, which is based on the inverse system construction of fuzzy neural network, and its structure is shown in Figure 30. The coupling characteristics of nonlinear multi-input–multi-output systems can be linearized by the inverse system method, which first converts the system to approximate linear form and then adopts the linear control theory to control synthesis. By collecting the input and output data of the hybrid magnetic bearing's inverse model and using these data to train the fuzzy neural network, the network can approximate the inverse model of the hybrid magnetic bearing. Finally, the inverse model of the fuzzy neural network is connected with the original system in series to achieve the purpose of decoupling control of the magnetic bearing. The experimental results show that the control strategy has good decoupling performance.

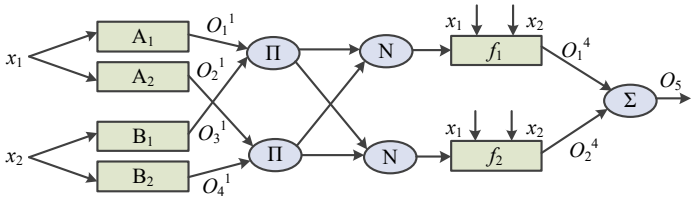


Figure 30. Fuzzy neural network control [78].

4.1.3. Robust Control Strategies

There are many kinds of control methods for magnetic suspension bearings, among which PID control, LQR control, and robust control are common choices. In the current application practice, PID control occupies a dominant position in the magnetic suspension bearing system because of its simple and easy-to-implement characteristics. However, when only PID control is used, the rigidity of the system may be insufficient, resulting in heightened sensitivity to external interference, while increasing the proportional gain can enhance the rigidity of the system and introduce excessive overshoot. In addition, facing parameter changes and model uncertainties, PID control often needs to be combined

with other control strategies to achieve better control performance. Therefore, researchers are constantly exploring more advanced control methods to improve the stability and reliability of magnetic bearing systems. LQR control is designed to find a control strategy that optimizes a specific performance metric. However, in order to solve the uncertainty of parameter fluctuations and model dynamics, LQR control often needs to be combined with other control techniques. Similarly, the two control methods do not deal with the problem of parameter change directly, which brings some challenges to the system to achieve the established function.

Ref. [79] proposes a new method which combines traditional PID control with fuzzy control. By building a fuzzy PID controller, this method is mainly based on a simple mathematical model, fuzzy processing the difference between the reference value and the actual value and its change rate, and then reasoning according to the fuzzy control rules to realize the online adaptive adjustment of PID parameters. The results show that the whole system has good robustness and anti-interference ability. Ref. [80] proposes the linear/nonlinear active disturbance rejection switching control strategy. Nonlinear active disturbance rejection control has advantages in anti-interference and tracking accuracy, while linear active disturbance rejection control makes it easier to set parameters. Both have advantages and disadvantages.

With the continuous development of digital control technology and control algorithms, methods such as robust control and nonlinear control have developed rapidly in dealing with parameter uncertainty and nonlinearity. Robust control theory pays special attention to the deviation between the mathematical model and the actual system, and strives to maintain the stability and robustness of the system under an uncertain environment. Among many robust control methods, H-∞ control and μ integrated control are particularly prominent. Especially in the control of the magnetic suspension bearing-rotor system, the H-∞ control method has been widely used. An H-∞ control strategy is proposed in Ref. [81], as shown in Figure 31. The control strategy is applied to the active magnetic suspension bearing system and can effectively resist external interference. Through these advanced control methods, the performance and reliability of the magnetic suspension bearing system can be significantly improved. The simplified linear model is as follows:

$$F = K_j i + K_s x \tag{16}$$

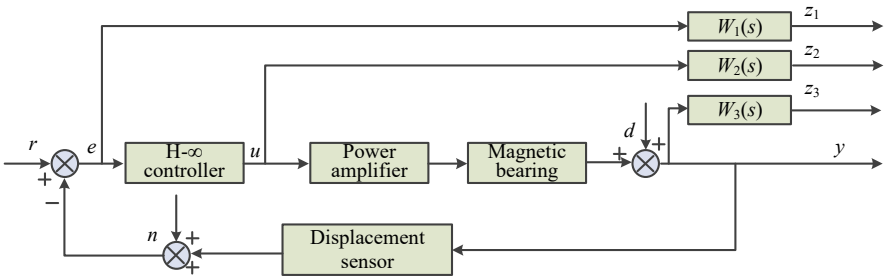


Figure 31. H-∞ Control policy [81].

In Ref. [82], in order to improve the stability of an active suspension system with uncertain energy feedback, a robust controller is designed and its obvious vibration reduction effect is demonstrated. Kuseyri [83] researched and developed three active magnetic bearing controllers based on multivariate H-∞ control strategies, and evaluated and compared the performance of these three controllers. *M*-integrated control technology effectively deals with the parameter uncertainties and structural changes in the system, and also solves the conservative problem in the H-∞ control method, so that the stability and robustness

of the system can be evaluated more deeply. In Ref. [84], researchers developed a robust control strategy based on μ analysis for the nonlinear characteristics of the electromagnetic force in the magnetic suspension bearing system and uncertain factors, such as the temperature drift of the displacement sensor. The experimental data show that the control algorithm improves the robustness of the system effectively and enhances its ability to resist disturbance. Through this advanced-control method, the overall performance of the magnetic suspension bearing system is significantly optimized.

4.1.4. No Sensing Detection Control Strategies

At present, the self-detection technologies of sensor-less magnetic bearing systems mainly include the high-frequency signal injection method, the salient pole tracking method, the duty cycle compensation method, the state observation method, and the Kalman filtering method [85]. Among these, the high-frequency signal injection, salient pole tracking, and duty cycle compensation methods require additional circuit support and special signal processing techniques to achieve a displacement estimation. Methods such as state observation and Kalman filtering rely on accurate system models and have high performance requirements for controllers. Because the magnetic bearing system is susceptible to external interference, nonlinearity and parameter uncertainty, these methods' effect in practical application is not always ideal, and often faces the problems of insufficient robustness, poor dynamic performance, and a low signal-to-noise ratio. In order to solve these problems, some researchers have proposed using neural network technology to self-detect displacement, but the neural network method also has its limitations, such as relying on sample data and easily falling into local optimal solutions. In contrast, the Support Vector Machine (SVM) method does not depend on the model of the tested object, has the advantages of a simple structure and strong generalization ability, and is especially suitable for the fitting problems of small samples, nonlinear, and high-dimensional functions. In the field of magnetic bearing displacement prediction modeling and rotor position estimation, SVM shows wide application potential and can provide high prediction accuracy.

4.2. Repulsive Magnetic Bearing Control Strategies

In the repulsive passive magnetic bearing control strategy, the traditional PID is still the most widely used. In Ref. [86], a digital PID controller is used to control axial passive radial active hybrid suspension bearings, the design process of the control parameters is analyzed, and the hardware and software of the controller are developed. Repulsive magnetic bearings using zero power control strategy are widely used. According to the research in Ref. [87], when the zero-power control strategy is applied to the repulsive permanent magnet biased axial magnetic bearing, the system can automatically sense the magnitude and direction of external forces acting upward on the axis, and adapt to these changes by adjusting the balance position of the rotor core. In this way, the magnetic force generated by the biased magnetic field counteracts the external force, thus achieving the control current approaching zero in a steady state. The zero-displacement and zero-current controls are applied to the identification algorithm of magnetic center shift and high-speed automatic balancing algorithm. Common implementation methods include the Least Mean Square (LMS) adaptive method, notch filter, and universal notch filter [88,89].

4.3. Chapter Summary

With the progress of control technology, the control of magnetic bearing system has covered a variety of methods from traditional to modern control theory. At present, single high-performance controllers, such as PID, H-∞, μ, sliding mode, neural networks, fuzzy and decoupling controllers, are still the mainstream choice in practical applications. Of course, the composite high-performance controller that combines a variety of single

controllers has been widely concerned, representing an inevitable trend in the development of controllers. This composite controller can combine the advantages of multiple single controllers, overcome the shortcomings, and realizing the complementary advantages. It is expected that more innovative composite controllers will be developed in the future to meet higher performance requirements. The comparison of different control strategies is summarized in Table 5.

Table 5. The comparison of different control strategies.

	Control Strategies		Advantages	Disadvantages
Suction Type Magnetic Bearing Control Strategies	Low Power Control Strategies	1. Introduce a variety of nonlinear control algorithms; 2. Use the current integral term as an external loop independent control.	Reduce energy consumption, Reduce heat, Improve system efficiency, Facilitate equipment miniaturization and portability.	The control algorithm is complex, High precision of sensors is required, Stability and robustness face challenges.
	Zero Displacement Control Strategies	1. Current compensation; 2. Displacement voltage compensation.	High precision positioning, Reduced vibration, Fast response, Optimized system energy.	High sensor requirements, Complex control algorithms, System stability challenges, High cost.
	Robust Control Strategies	PID control, LQR control, Other robust control.	Strong anti-interference ability, Adaptability to parameter changes, Improve system reliability, Broaden application scenarios.	Eclectic control performance, Difficult design, conservative, Complex debugging.
	Sensor-less control Strategies	High-frequency signal injection method, Salient pole tracking method, Duty cycle compensation method, State observation method, Kalman filter.	Cost reduction, Anti-interference ability, Fast response speed, Avoid sensor error.	High model-dependence, Limited estimation accuracy, Difficult fault diagnosis, Complex control algorithms
Repulsive Magnetic Bearing Control Strategies	PID, LMS adaptive method, Notch filter, Universal notch filter.		PID: Simple control, good robustness. LMS: Strong adaptive ability, does not depend on the exact model. NF: Strong adaptive ability, versatility, and scalability	PID: limited anti-interference ability, complex parameter setting. LMS: convergence speed contradicts steady-state accuracy. NF: High dependence on specific frequency, limited system adaptability, design and debugging difficulty.

5. Conclusions and Future Perspectives

Magnetic bearings, an advanced bearing technology using magnetic force to suspend the rotor, play an increasingly important role in modern industrial fields. Magnetic bearing technology has been widely used in many industries, such as medical, aerospace, flywheel energy storage systems, power grids, and air compression.

In development, magnetic bearings have come a long way from theoretical breakthroughs to wide applications. In 1842, Earnshow's theory that stable suspension in the magnetic field of permanent magnets was impossible hindered its progress. In 1937, Kemper's proposal of a controllable electromagnet plan opened up a new path. Since then, researchers worldwide have advanced the technology, leading to its applications in multiple fields.

In classification, magnetic bearings are mainly divided into suction and repulsive types by suspension force generation. Among suction magnetic bearings, electromagnetic (active) magnetic bearings stabilize the rotor with the attraction of electromagnets. They can be classified into DC and AC types by driving method. Hybrid magnetic bearings combine the features of active and passive ones, using permanent magnets for bias magnetic fields. Passive magnetic bearings generate suspension forces from permanent magnet materials. Among repulsive magnetic bearings, passive ones work with the repulsion between permanent magnets, and diamagnetic magnetic bearings achieve suspension through the diamagnetism of superconductors or room-temperature diamagnetic materials.

Modeling is crucial for optimizing magnetic-bearing performance and formulating control strategies. For suction magnetic bearings, different types use methods like the virtual displacement method and the equivalent magnetic circuit method to accurately obtain the electromagnetic attraction formula, providing a basis for structure design, parameter calculation, and precise control. Modeling of repulsive magnetic bearings is also important. For instance, passive magnetic bearings often use the equivalent magnetic charge method for magnetic force calculation, and diamagnetic magnetic bearings use the Bean critical state model to analyze static characteristics.

The choice of control strategies directly impacts magnetic bearing performance. Suction magnetic bearings have diverse control strategies. The low-power control strategy reduces energy consumption and thermal effects. The zero-displacement control strategy cuts down rotor displacement and vibration by increasing control current. The robust control strategy enhances system stability and reliability against uncertainties. The sensorless detection control strategy solves sensor-related issues. In repulsive magnetic bearing control, the traditional PID control is widely used, and there are also strategies such as zero-power control.

Despite remarkable progress, magnetic bearings face challenges. Their structure design is complex, control strategies require high precision, and production costs are high. In the future, research will focus on developing new magnetic materials, optimizing structure design, perfecting system modeling, innovating control strategies, and exploring energy-efficient driving technologies.

During the structural design optimization stage of magnetic suspension bearings, a permanent-magnet-biased hybrid structure can be introduced, combined with a radial and axial hybrid design, as well as a hexagonal radial-symmetry layout method (which has been proven to reduce manufacturing costs and decrease the equipment volume), to improve the overall operating efficiency. When establishing the dynamic model, the fringe flux and leakage flux effects, the saturation characteristics of magnetic media, loss factors, and vibrations caused by imbalances must be considered. Meanwhile, the combination of matrix converters and intelligent control algorithms represents the trend and core of the future development of driving and control technologies.

These research directions aim to simplify the design of magnetic bearing systems, enhance their intelligence and reliability, and further improve the energy–efficiency ratio. Breakthroughs in research also provide more solutions to the common and specific problems existing in various magnetic bearings currently. With the development of technology, the applications of magnetic bearings will be more extensive in the future and provide important support for high-tech fields.

Author Contributions: Project administration, W.Z.; Writing—original draft, W.Z. and T.W.; Conceptualization, W.Z.; methodology, T.W.; software, T.W.; validation, T.W.; All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported in part by the National Natural Science Foundation of China under Grant 52077099, and in part by the Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions.

Data Availability Statement: Not applicable.

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

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