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Review

Overview of the Development of Planar Motor Technology

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Abstract: With the rapid development of the semiconductor chip and precision machining industry, there is a growing demand for high-performance planar drive devices, leading to an increasing depth of research on planar motors. Variable reluctance planar motors, induction planar motors, permanent-magnet synchronous planar motors and DC planar motors are discussed in this paper along with their working principles and current research status. The theory of planar motors remains incomplete and immature despite the extensive research conducted by scholars and research institutions on crucial aspects like magnetic field analysis and electromagnetic force calculations. The objective of this paper is to provide a comprehensive review of the research and development status of planar motors in order to positively impact future advancements in this field.

Keywords: planar motor; variable reluctance planar motor; induction planar motor; permanent-magnet synchronous planar motor and DC planar motor

1. Introduction

With the vigorous development of the precision machining manufacturing and semiconductor industry, the processing size required in the production field of electronic components such as microelectronics machining is becoming more and more fine, and the demand for plane drive devices with high precision and high response speed is becoming increasingly strong. Linear motion is converted from spatial rotational motion by using a conversion mechanism in traditional rotary motors that drive mechanical structures. Although two-dimensional planar motion can be realized, due to a series of factors such as assembly errors, friction between the rotating motor and the conversion mechanism, movement, and deformation, the positioning accuracy is difficult to make fine enough, as is usually only on a micron level. With the advancement of linear motor technology, two-dimensional planar motion can be achieved by superimposing and combining multiple sets of linear motors. This eliminates any mechanical assembly influence, resulting in significantly improved positioning accuracy that can reach the nanometer level. However, this approach leads to a significant reduction in space utilization when integrating low-dimensional moving mechanisms into high-dimensional ones. Additionally, meeting the requirements for high response speed becomes challenging. The planar motor, as a device capable of directly inducing actuator movement through electromagnetic action, offers numerous advantages such as high force density and low energy consumption. Due to the absence of additional motion conversion mechanisms and multiple superimposed groups, the planar motor drive device exhibits superior precision and response speed. Therefore, it has increasingly been utilized in high-precision positioning platforms.

Planar motors are classified into variable-reluctance-type, induction-type, permanent-magnet-synchronous-type and DC-type planar motors based on their working principle: the variable reluctance type can be further divided into the stepper planar motor and switched reluctance planar motor. Based on their actuators, permanent-magnet synchronous motors can be classified into coil synchronous planar motors and permanent

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magnet array synchronous planar motors [1–3]. Table 1 shows characteristics and application scenarios of planar motor.

Table 1. Characteristics and application scenarios of planar motors.

Type	Advantages	Disadvantages	Applied Area
Variable reluctance	Low cost and a simple structure	Low positioning accuracy	Electronic assembly line
Induction	High-speed performance and a good dynamic response	Low efficiency and high heat dissipation requirements	Logistics conveying system
Permanent-magnet synchronous	High control accuracy and excellent dynamic performance	Complex control system	CNC machine tools and 3D printers
DC	Good performance at low speeds and simple structure	Large loss and low efficiency	Micromanipulation platforms Surgical robot

The structural principle, characteristics, and potential applications of planar motors with different structural types are presented in a concise way in the present paper.

2. Variable Reluctance Type Planar Motor

2.1. Stepper Planar Motor

Stepper planar motor research was started at an early stage, and its technology has now reached a high level of maturity. The Sawyer motor, as an exemplary product [4,5], effectively addresses the issue of low space utilization in planar actuators composed of multiple groups of linear motors while retaining the inherent characteristics of stepper motors. Each step is independently controlled without cumulative errors. However, its structure imposes limitations on output thrust and torque, making it unsuitable for high-load applications. Stepper flat motors generally employ open-loop control, which may result in out-of-step occurrences and poor resistance to interference at high speeds.

The structure of the Sawyer motor is illustrated in Figure 1, featuring a schematic diagram. The stator consists of a laminated iron core with evenly distributed notches, where the width-to-slot spacing ratio ranges from 7 to 200. The actuator comprises two sets of perpendicular permanent magnets and drive coils. By passing pulse current through the drive coil, the magnetomotive force generated by the phase winding ensures a closed loop magnetic flux along the path with minimal reluctance, thereby driving motion in the moving platform and enabling motor movement. This motor possesses three degrees of freedom: linear movement along both x and y directions, as well as rotational movement around the z axis. Micro-step control is used to minimize possible out-of-step occurrences, as it has a 2-micron linear resolution and a 0.001° rotational resolution.

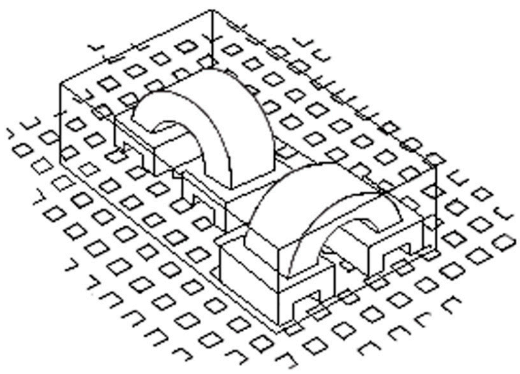


Figure 1. Stepper planar motor.

2.2. Switched Reluctance Type Planar Motor

The planar switched reluctance motor is derived from the rotary switched reluctance motor, and it adheres to the principle of minimal reluctance during operation to ensure that magnetic flux follows the shortest path. Its structure is relatively straightforward, offering reliable performance and easy maintenance. However, it may generate increased noise and vibration during operation, potentially impacting smooth functioning and precise positioning.

Due to the operational principle of planar switched reluctance motors, their electromagnetic force pulsation is generally high. Currently, there are two primary approaches to reducing the electromechanical pulsation: enhancing motor control strategies and improving motor structure. Guangzhong Cao from Shenzhen University, Sudan Huang from Southwest Jiaotong University, and Ji'an Duan from Central South University proposed an enhanced planar switched reluctance motor aimed at minimizing electromagnetic force pulsation (Figure 2) [6]. The motor comprises a base, stator set, X moving platform, Y moving platform, linear encoder, linear guide rail, and other components enabling two-dimensional motion. To minimize the coupling magnetic circuit between the X and Y directions, the stator and actuator have an equal tooth width and slot width of 3.6 mm, an air gap height of 0.3 mm, six teeth per phase, a platform movement range of 330 mm $\times$ 180 mm, an optimized maximum normal force of 502 N, and a thrust capability of up to 40 N. Planar switched reluctance motors now have significantly reduced thrust fluctuations and improved positioning accuracy, with the maximum absolute tracking error in both X and Y directions being reduced to only 0.022 mm.

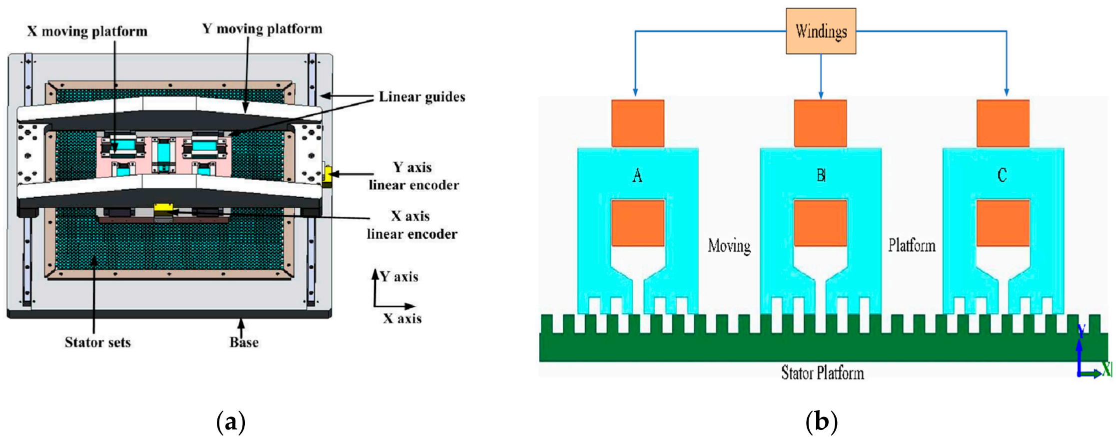
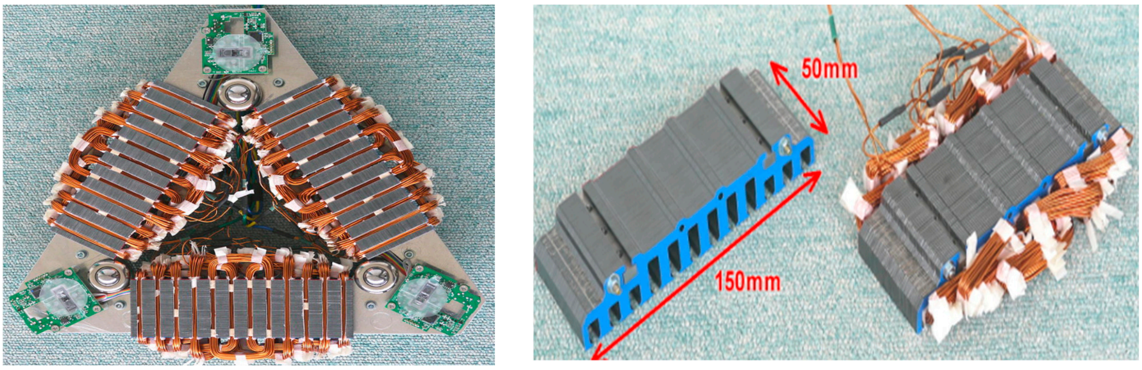


Figure 2. Switched reluctance planar motor: (**a**) three-dimensional structure diagram; (**b**) two-dimensional schematic diagram.

3. Induction Type Planar Motor

Planar induction motor research was not initiated until late, and both domestic and foreign theories and technologies in this field are still in their early stages. However, the inherent advantage of achieving a wider range of motion with a simple secondary plane renders planar induction motors highly adaptable for applications involving heavy loads and extensive movement ranges.

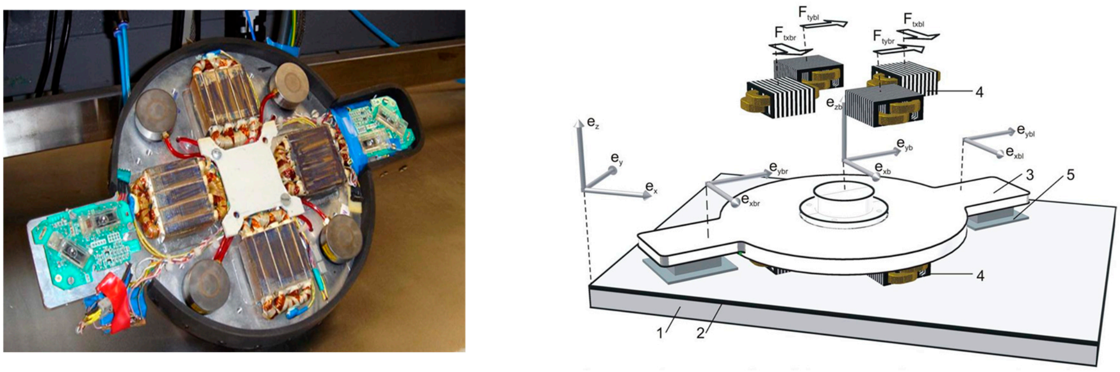
Masaaki Kumagai from Tohoku Gakuin University in Japan and Ralph L. Hollis from Carnegie Mellon University in the United States have created an induction planar motor that has three degrees of freedom [7]. Figure 3 shows the structure of the motor. The stator has three linear induction motor windings, vector control drivers, and three optical mouse sensing units. Three-phase windings are formed by dividing the windings into three groups. By utilizing the optical mouse sensor to measure the converted speed value, the current value of three-phase winding can be calculated for controlling thrust magnitude and achieving linear actuator drive. The windings are subjected to a three-phase alternating current that generates electromagnetic thrust along the circumference to enable the motor to rotate. The motor is capable of delivering a horizontal thrust of 70 N and a torque of 9 N·m, with a response time of up to 10 ms. It can achieve peak acceleration up to 12 m/s^2 and provide rotation angle, translation speed, and angular velocity information; however, due to its nature as an induction-type planar motor that only measures relative motion, it cannot provide precise positioning information. Gradually, positioning errors accumulate over time, resulting in inadequate positioning accuracy.



(a) (b)

Figure 3. Three-degree-of-freedom induction planar motor: (**a**) physical map; (**b**) stator size.

A planar induction motor with three degrees of freedom was designed by Prof. Dr. -Ing. Peter Dittrich from Jena University of Applied Sciences in Germany, as demonstrated in Figure 4 [8]. The motor can move in x and y directions and rotate around the z axis. With a moving diameter of 210 mm and weighing 2.6 kg, the motor is capable of loading 1 kg. The motor is made up of four winding groups. Each group of windings has two optical sensors to detect the position of the motor. The copper sheet was coated with nickel that was sandblasted with glass balls, and has an optical resolution of 63.5 um. The motor's maximum output thrust is 21.5 N, and its thrust density is 0.27 N/cm^2, which is accurately controlled with the relevant motor control strategy.



(a) (b)

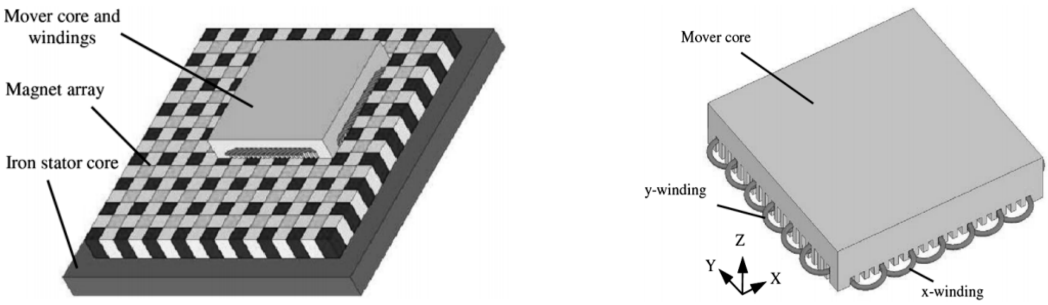
Figure 4. Three-degree-of-freedom induction planar motor: (**a**) physical map; (**b**) schematic diagram.

4. Permanent-Magnet Synchronous Planar Motor

4.1. Moving Coil Permanent-Magnet Synchronous Planar Motor

The moving coil permanent-magnet synchronous motor uses permanent magnets to create a static magnetic field. The sub-coil moves due to the Lorentz force produced when the energized coil moves through the magnetic induction lines. The design of a thin or flat planar motor typically leads to high space utilization. By extending the magnet array, it can extend its motor stroke and provide significant thrust and torque. Moreover, its positioning precision is capable of reaching nanometer levels. Interference with motion accuracy might occur due to the electrical connection between the moving coil and external components. Furthermore, the moving coil presents a significant challenge in terms of heat dissipation [9–11].

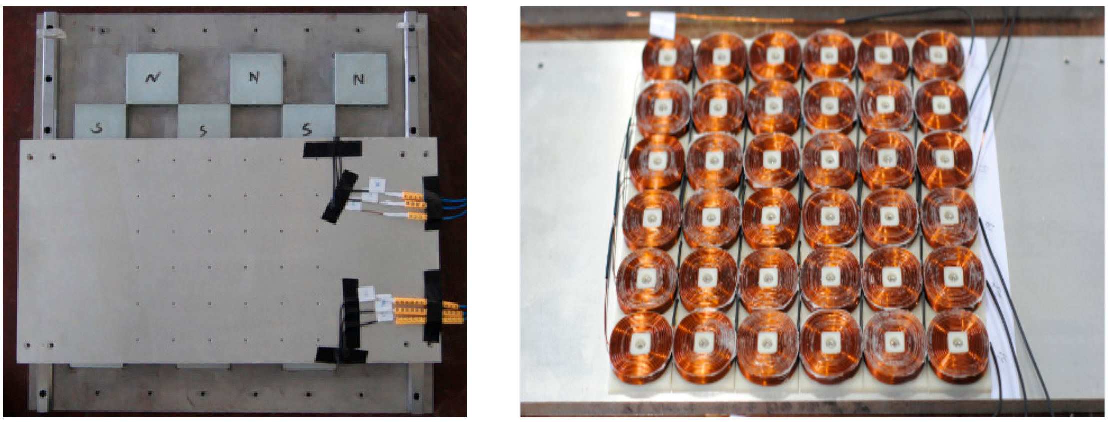
The schematic diagram in Figure 5 illustrates the moving- coil permanent-magnet synchronous planar motor with core slots, which was proposed by Jiayong Cao et al. from Tsinghua University in 2005 [12]. A Halbach permanent magnet array and a ferromagnetic material base make up the stator component of this planar motor. The movable part has a core section, with grooves at the bottom that can be used to insert windings to reduce magnetic circuit resistance. To enhance the continuous force output of the motor, these grooves are arranged very closely together. The X-winding and Y-winding are specifically designed with a three-phase double-layer winding configuration that is depicted in Figure 5b. As a result, thrust forces are produced independently in both x and y directions within the plane motor system. In comparison with non-core permanent-magnet synchronous planar motors, this design enables the continuous provision of larger thrust forces along both x and y axes; however, it also introduces additional thrust fluctuations and reduces positioning accuracy.



(**a**) (**b**)

Figure 5. Permanent-magnet synchronous planar motor with moving core: (**a**) structure diagram (**b**) mover core.

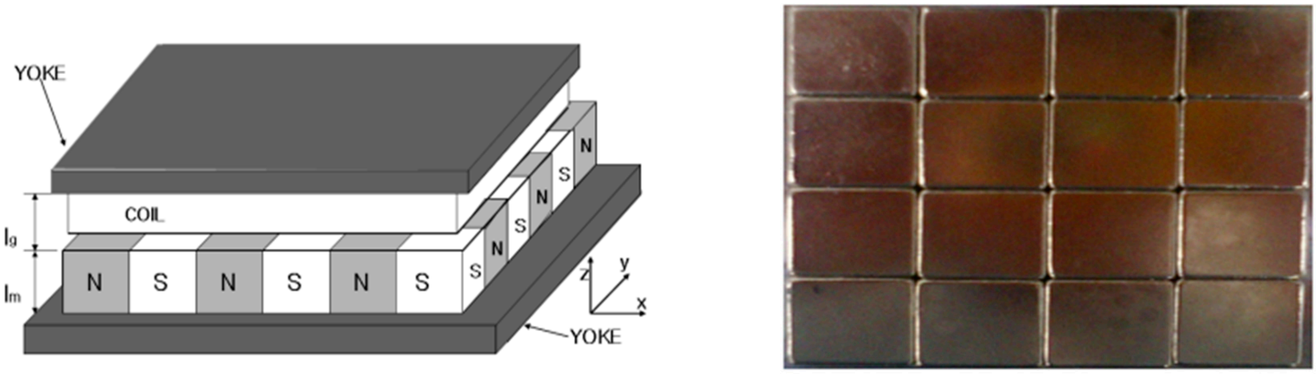
The moving coil permanent-magnet synchronous motor [13], proposed by Zhang Lu of Harbin Institute of Technology in 2010, is depicted in Figure 6. Its stator consists of a two-dimensional Halbach permanent magnet array with a pole distance of 60 mm. The actuator comprises three-phase winding, as shown in Figure 6b. The actuator section includes 36 coils, with each phase containing 12 coils. Utilizing copper wire with a diameter of 0.71 mm and a coil pole distance of 40 mm, this motor belongs to the long-stroke planar motor category and has a maximum motion range of 120 mm × 120 mm. Parameter optimization can result in a thrust of 55.57 N when compared to a current flow of 1.98 A.



(**a**) (**b**)

Figure 6. Moving coil permanent-magnet synchronous planar motor driven by compound current: (**a**) structure diagram; (**b**) moving coils.

The synchronous moving coil moving magnet motor proposed by Huang Rui and colleagues at Shenyang Agricultural University in 2012 can be seen in Figure 7 [14]. The stator component of this motor is replaced by an alternating N-S permanent magnet array instead of the Asakawa and Chitayat permanent magnet arrays. The arrangement of the permanent magnets is visible in Figure 7b. Each magnet unit is 18 mm wide and 10 mm thick, while the rectangular moving coil is 20 mm long, 8 mm wide, and 5 mm thick. The height of the air gap in the center is 1 mm. Comparative analysis reveals that under identical conditions, this magnet array generates a peak flux that is approximately 8.7% larger compared to the Chitayat array and around 31.6% larger compared to the Asakawa array. Moreover, this new configuration generates a back electromotive force that is above the average of 9.8% and 34.1% for both Chitayat and Asakawa arrays. The application of a current of magnitude equal to 1 A results in a force exerted on the moving coil that exceeds that produced by both Chitayat and Asakawa arrays, with increases amounting to roughly 9.1% and 33.4%, respectively. This motor's output thrust can be improved by changing how the permanent magnets are arranged.



(**a**) (**b**)

Figure 7. Moving coil permanent-magnet synchronous planar motor with N-S staggered arrangement: (**a**) structure diagram; (**b**) permanent magnet array.

In 2014, Zhang Lu of Harbin Institute of Technology designed the concentric winding moving coil permanent-magnet synchronous planar motor [15], which is shown in Figure 8. The stator is made up of a Halbach permanent magnet array that is two-dimensional, as shown in Figure 8d. In order to improve dynamic performance and improve thrust density, the actuator uses concentric three-phase winding divided into outer, middle, and inner square coils. This moving coil structure faces a significant challenge in effective heat dissipation due to the ability to generate 900 N thrust. In contrast to traditional series cooling structures, this paper adopts an enhanced series cooling structure, as illustrated in Figure 8c, which ensures more uniform cooling and limits temperature fluctuations on the motor surface within a 2.5 °C range, thereby enhancing temperature distribution uniformity across the electromotor sub-surface.

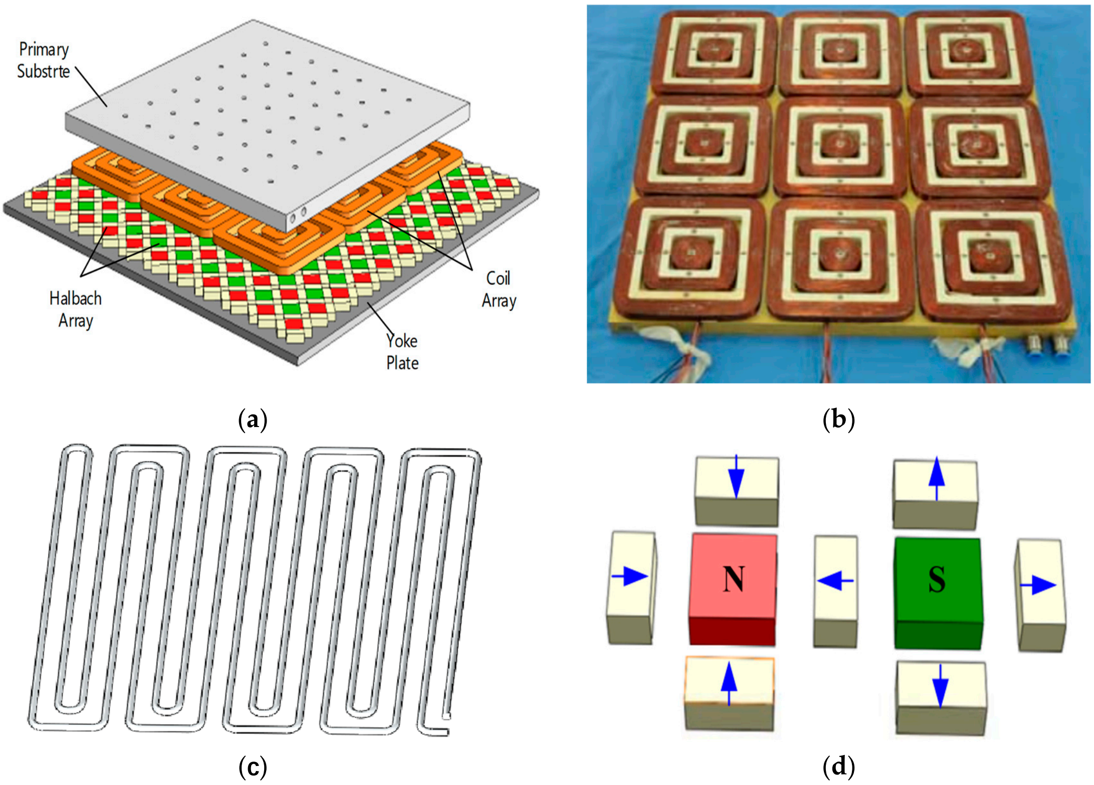


Figure 8. Concentric winding moving-coil permanent-magnet synchronous planar motor: (**a**) structure diagram; (**b**) moving coil; (**c**) improved series cooling structure; (**d**) permanent magnet array unit.

4.2. Moving Magnet Permanent-Magnet Synchronous Planar Motor

The working principle of the moving magnet planar motor is similar to that of the moving coil type, with the exception being that the stator of the moving magnet planar motor consists of an electrified coil, generating a stable and varying magnetic field in its vicinity, while the moving magnet array comprises a permanent magnet. In contrast to the moving coil type, this arrangement ensures that the permanent magnet and external components do not have any electrical connection, which prevents any interference with actuator movement. Moreover, as a result of being a permanent magnet itself, heat dissipation concerns are eliminated; however, controlling this system requires complex strategies due to only the energized coils under the magnet array contributing to thrust generation. To reduce losses, it is essential to control coil activation precisely.

In Figure 9, Jansen, from Eindhoven University of Technology, has proposed a maglev moving magnetic planar motor. The stator component is made up of coils that form a fishbone shape, while the actuator part is separated from a Halbach permanent magnet array [16]. According to Figure 9b, the planar motor has 84 coils, but only 24 of them are powered at once. Also, a coil group that is active is adjusted dynamically based on the position of the moving part. Adopting a coil structure that ensures effective force generation is crucial in minimizing power loss in the planar motor, as demonstrated in Figure 9c. The elongated straight section of the rectangular coil is the main source of the force exerted on it, and its length directly affects the efficiency of the planar motor. In addition, compared to regular square coils, topology structures that have rotating rectangular coils at a 45° angle show lower power consumption and less torque fluctuations compared to regular square coils. These topologies show that their root mean square force fluctuation is below 0.4% during suspension and acceleration, as evidenced by experimental results.

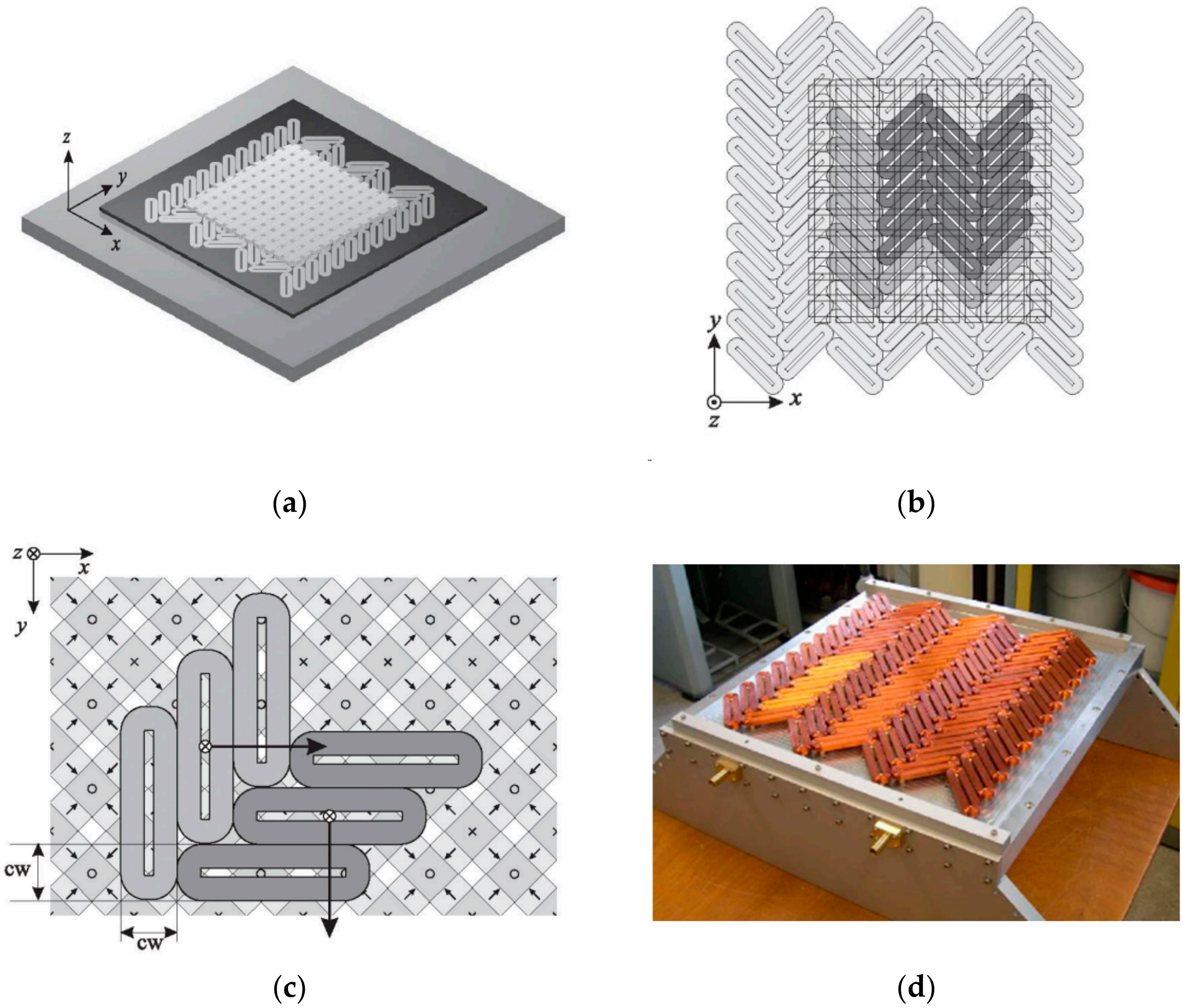
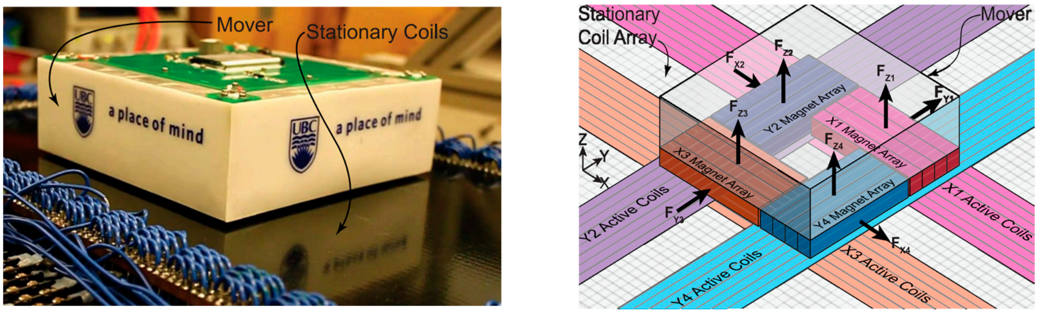


Figure 9. Maglev moving magnetic permanent-magnet synchronous planar motor: (**a**) structure diagram; (**b**) dynamic stator plane diagram; (**c**) stator coils; (**d**) physical drawings.

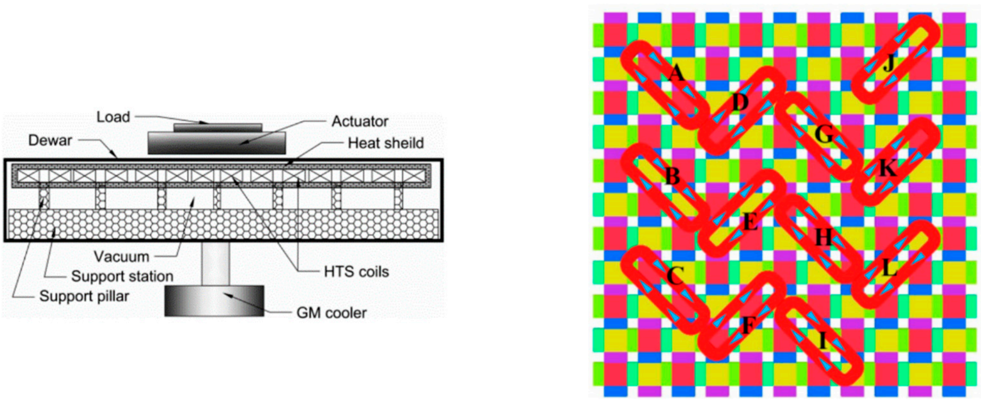
In 2015, Usman et al. of Columbia University designed a six-degree-of-freedom moving magnet permanent-magnet synchronous planar motor, as shown in the schematic diagram in Figure 10 [17]. The movers are made from four individual magnets, while the stator is made up of multiple individual coils integrated on the printed circuit board. The Lorentz force can be divided into two directions by each group of magnet arrays, leading to two degrees of freedom. By combining the forces generated by all four groups of magnet arrays, the motor achieves a total of six degrees of freedom for movement within a motion stroke range measuring 185 mm × 185 mm. One-dimensional magnet and coil arrays are used in this design to effectively simplify both modeling and control processes. Additionally, Usman et al. proposed an innovative concept called the splitting magnet, which optimizes the magnetic circuit and significantly reduces harmonic components. As a result, the force with a frequency equal to six cycles per λ wavelength is ten-fold attenuated, while the position-independent force is attenuated by 5%. These improvements have a positive impact on the positioning accuracy of this motor.



(**a**) (**b**)

Figure 10. Six-DOF PCB moving magnet permanent-magnet synchronous planar motor: (**a**) physical diagram; (**b**) schematic diagram.

In Figure 11, Zhang Yiming and colleagues from the Chinese Academy of Sciences designed and produced a magnetic planar motor that can move magnetically with high load capacity [18], which is shown as a superconducting maglev moving motor with high load capacity. Its core component, the stator part, consists of HTS rectangular coils arranged in a herringbone pattern, which exhibit lower energy consumption and higher current density compared to traditional copper coils. While the actuator part runs at an ambient temperature of 300 K, the high-temperature superconducting coil operates at a temperature of 65 K. To minimize radiant heat, a heat shield wraps around the stator coil. Under critical current density conditions, the actuator's Z-axis force is 2544 N and its dimensions are 230 by 230 mm. Considering that 50% of critical current represents the maximum normal working current, this motor can sustain a maximum carrying capacity of 1267 N with a load per unit area reaching 23950.9 Pa—twice as much as general moving magnetic flat motor products offer in terms of carrying capacity alone. Furthermore, this moving magnetic flat motor has benefits such as no interference with cables and no requirement for cooling its moving parts.



(**a**) (**b**)

Figure 11. High-load superconducting maglev moving magnetic planar motor: (**a**) structure drawing; (**b**) coil and permanent magnet array (A~L are coils).

Researchers from Eindhoven University of Technology, Kleijer et al., proposed a dynamic magnetic permanent-magnet synchronous planar motor optimized for a Halbach permanent magnet array in 2022 to enhance motor acceleration [19]. Figure 12 depicts the motor design, and investigates the impact of altering the magnetization angle and shape of the secondary magnetic steel within the Halbach permanent magnet array on the generated magnetic field intensity and sinusoidal characteristics in the air gap, thereby influencing planar motor acceleration. Block-wise magnetization and a specific magnetization angle are applied to the secondary magnetic steel, as shown in Figure 12c. The transformation of rectangular-shaped secondary magnetic steel to trapezoidal-shaped steel occurs while keeping the total volume constant, as demonstrated in Figure 12d. Increasing the MPP topology from 3 MPP to 9 MPP is shown to result in a higher fundamental wave content of magnetic flux density distribution within the air gap. Square-shaped magnets with a 9 MPP configuration have a 6.65% increase in maximum acceleration, while trapezoidal magnets have a 10.1% increase in maximum acceleration. Overall findings demonstrate that this investigated magnet array enhances planar motor acceleration by up to 10.1%, reduces thrust fluctuation in all directions by approximately 10.2%, and decreases the total harmonic distortion of the suspension force by around 16.2%.

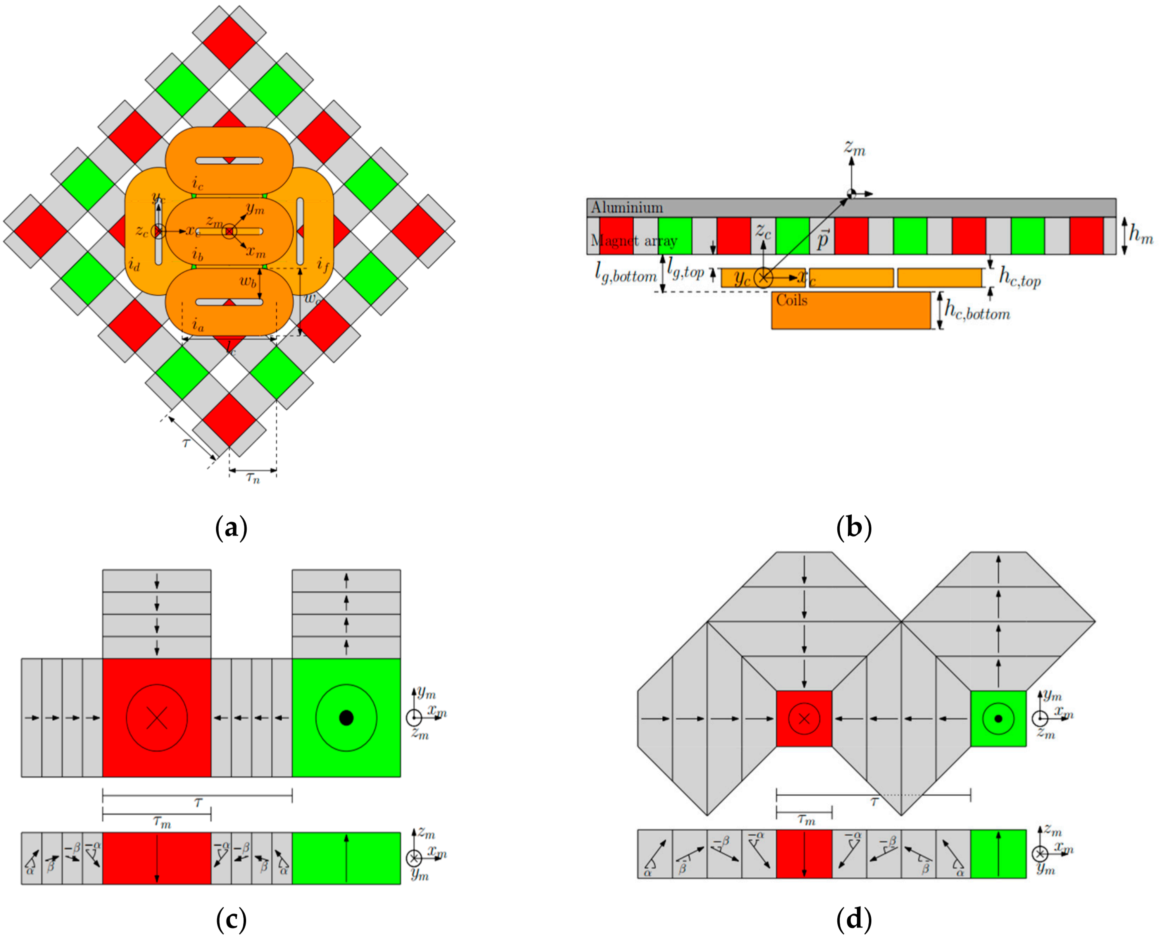


Figure 12. Halbach array optimized moving magnetic permanent-magnet synchronous planar motor: (**a**) structure diagram; (**b**) sectional drawings; (**c**) rectangular 9 MPP magnet topology; (**d**) trapezoidal 9 MPP magnet topology.

5. DC Planar Motor

The DC planar motor's working principle is similar to that of the conventional DC motor. Thrust for motor movement is achieved by the actuator experiencing a Lorentz force within a stable magnetic field generated by the stator. The DC planar motor demonstrates a straightforward mechanical and electrical relationship, offers high utilization of aluminum space, and can be customized based on shape and size requirements, making it suitable for various MEMS systems. Despite its low power density, its operation may still lead to more pronounced electromagnetic interference.

In Figure 13, Zhang He et al. from Harbin Institute of Technology propose a three-degree-of-freedom Lorentz force-driven planar motor for nanoscale positioning systems [20]. The stator section consists of three rectangular coils arranged at equidistant intervals of

120° around the center of mass, aiming to enhance force and minimize force variation with horizontal displacement, as illustrated in Figure 13c. Figure 13d shows that the actuator is divided into a Halbach permanent magnet array with varying thicknesses to modulate the magnetic field at the motor's end. Compared to a Halbach permanent magnet array solely possessing vertical magnetization and a central magnet with horizontal magnetization or an end magnet within the Halbach permanent magnet array, the newly proposed Halbach permanent magnet array with unequal thickness increases force amplitude by 5.5% while reducing the force within a ±2 mm range of horizontal displacement by 29%. In some instances, this three-degree-of-freedom short-stroke permanent-magnet synchronous planar motor, which utilizes a Halbach permanent magnet array with varying thickness, reduces thrust fluctuations.

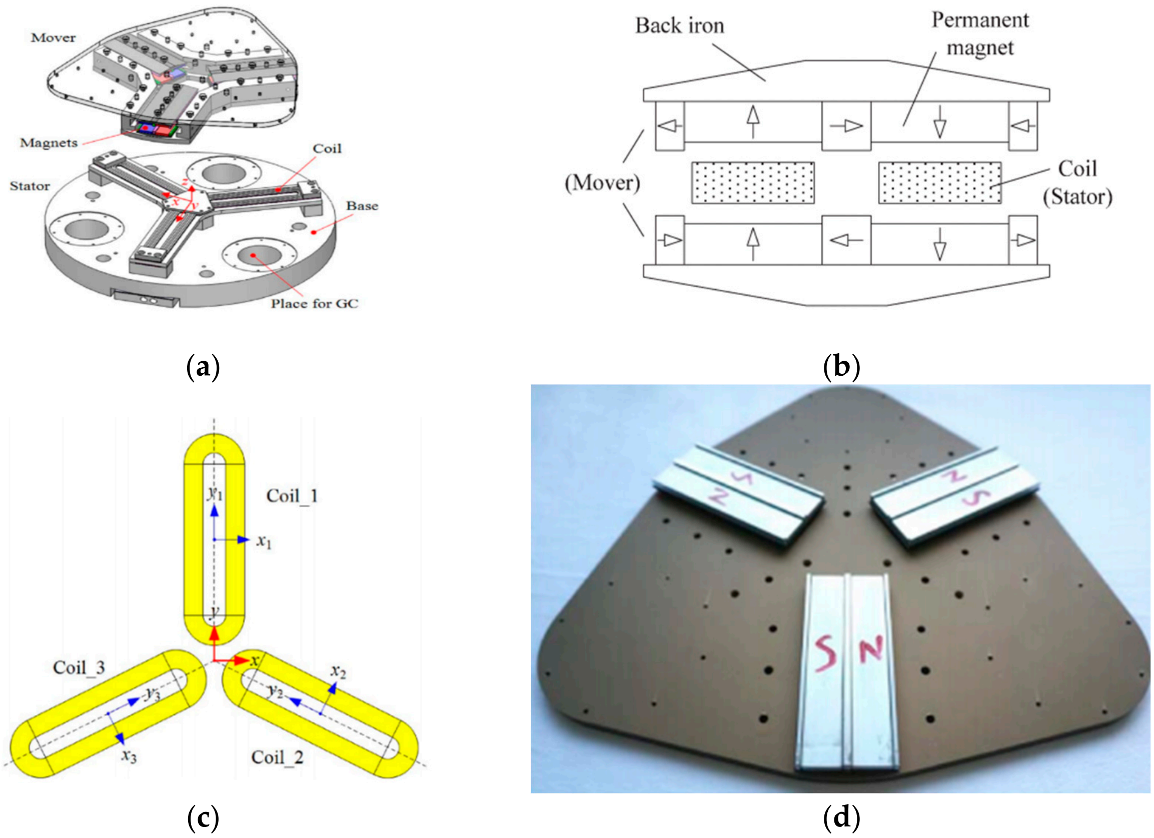
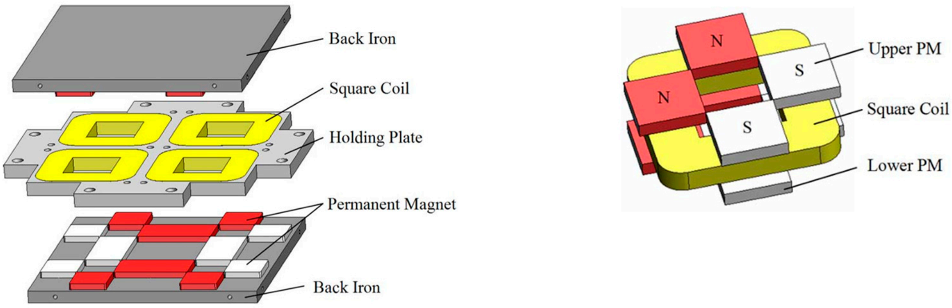


Figure 13. Three-DOF short-stroke permanent-magnet synchronous planar motor: (**a**) structure diagram; (**b**) Lorentz motion unit; (**c**) stator coil; (**d**) moving permanent magnet.

Kou Baoquan and his colleagues at Harbin Institute of Technology came up with an innovative planar DC motor that has three degrees of freedom and is powered by the Lorentz force [21]. Figure 14 shows that the stator is composed of coils and the actuator is made up of a permanent magnet array. The magnetic field within the air gap is improved by using a double-sided structure. Regulating currents in the four coils allows for a ±1 mm translation along both x and y axes and ±3° rotation around the z axis. Linearity in the motor's output force with respect to current magnitude ensures minimal force fluctuations (less than 1%). Furthermore, positioning accuracy is enhanced through the use of a precision measurement system composed of a laser interferometer and capacitance probe.



(**a**) (**b**)

Figure 14. Three-DOF planar DC motor: (**a**) structure drawing; (**b**) dynamic stator fit.

6. Planar Motor Products

Planar motors are becoming more common in high-precision products due to their exceptional positioning accuracy and high dynamic response performance. As a semiconductor equipment manufacturer headquartered in Eindhoven, the Netherlands, ASML Company provides cutting-edge integrated key equipment to complex integrated circuit manufacturers worldwide.

In 2023, ASML unveiled the world's first 2 nm extreme ultraviolet lithography machine, wherein the positioning and driving platform serve as core components that directly dictate the performance of the lithography machine. Figure 15 reveals ASML's products for measuring and detecting wafers. ASML has developed the most advanced electron beam system in the world, HMleP5, which has an impressive pixel size of 1 nm, a CD measurement accuracy below 0.1 nm, and a capability for defect detection under 5 nm. The provision of dimension measurement and defect detection is crucial for chip development and production monitoring purposes. It is impossible to understate the importance of planar motors in this situation.

(**a**) (**b**)

Figure 15. ASML high-precision electron beam system: (**a**) HMleP5-type products; (**b**) electron beam systems.

7. Key Technology of Permanent-Magnet Synchronous Planar Motor

7.1. Design Technique of Permanent-Magnet Synchronous Planar Motor

Preliminary research on the design of a permanent-magnet synchronous planar motor has been conducted by scholars both at home and abroad. A series of studies were conducted on the commonly utilized fishbone, square, concentric coil array, and two-dimensional Halbach permanent magnet array. Their progress in magnetic field analysis, electromagnetic force and torque calculation, and parameter optimization of permanent magnet arrays has been significant. There is still a lack of a general theory. People have put a lot of effort into determining how to reduce the thrust fluctuation of permanent-magnet synchronous planar motor and reduce the influence of the end effect on the planar motor [22–25]. However, problems related to how we can achieve high thrust and high dynamic response still need to be solved. Planar motors' design requires the study of the heat dissipation structure as an important component. During operation, there is a significant amount of heat generated due to the large current density in the general coil with high thrust. Planar motors' motion accuracy is directly influenced by their excellent heat dissipation structure.

7.2. Technique of Sustaining Permanent-Magnet Synchronous Planar Motors

Friction, deformation, and other factors make the traditional contact support significantly affect the accuracy of motion. The demands of permanent-magnet synchronous surface motors in the precision and ultra-precision field are challenging to meet. To prevent friction, air suspension and magnetic suspension [26] support have become the most common support methods for permanent-magnet synchronous planar motors. The implementation mode for air suspension support is relatively straightforward, and it also has low friction and better structural stability. Adding gas pipes and mechanical components to the actuator of the permanent-magnet synchronous planar motor is necessary for the air suspension support mode. Interference with the motion accuracy of the actuator parts will result in an impact on the dynamic characteristics of the system. Furthermore, the air suspension support method is not applicable in vacuum environments, like in the extreme ultraviolet lithography machine. An absence of mechanical friction, good structural stability, and an absence of external mechanical components like gas pipes are necessary. Therefore, the magnetic suspension support will not interfere with the operation of a permanent-magnet synchronous planar motor. Due to its simplicity in achieving high precision, it has become the most promising support mode.

7.3. Control and Decoupling Technique of Permanent-Magnet Synchronous Planar Motor

With regard to controlling permanent-magnet synchronous planar motors, the planar motor in the electromagnetic coupling end causes coupling between the two directions of planar motion due to its non-linearity. The planar motor's positioning accuracy and dynamic characteristics will suffer due to the end effect's impact on the stationarity of the electromagnetic force. Adopting appropriate decoupling and control technology is necessary to decouple motion from the influence of parameter changes and external interference. The planar motor can be utilized to achieve high positioning accuracy and dynamic performance [27–31].

Most planar motor control systems currently utilize the current control mode, and the coil current is believed to be able to accurately monitor the reference value. The AC current always has an inductance in the coil that prevents a significant change in the current. There is a significant discrepancy between the actual current and the reference current of the coil. The planar motor's control accuracy will be impacted by the former. The permanent-magnet synchronous planar motor system shows a complex relationship between the electromagnetic force and the electromagnetic torque in various directions. To control a planar motor accurately, it is crucial to have good decoupling between variables. The majority of decoupling methods are currently based on mode force and dq coordinate transformation. The previous is employed for a permanent-magnet synchronous plane motor that is supported by different executive parts for its suspension and driving forces. The latter applies to a permanent-magnet synchronous plane motor that has its suspension and driving force provided by the same executive part. The actuator is the one in charge of both the suspension and driving forces in a permanent-magnet synchronous planar motor. The decoupling method that relies on dq coordinate transformation is no longer applicable. Finding a new decoupling method is necessary. In addition, the development of planar motor control technology should also fully take advantage of control principles and methods of rotary motor and linear motor control technology, such as vector control theory and the thrust pulsation suppression method.

8. Conclusions

Precision positioning platform components are becoming increasingly necessary as the size of components continues to shrink with the rapid advancement of integrated circuits. The high performance of planar motors, which are the core components of these platforms, has been extensively researched. Although many scholars and research institutions focus on magnetic field analysis and electromagnetic force calculation in this area, the theory behind planar motors remains incomplete and immature. Both domestic and international research on planar motors still face several challenges: reducing thrust fluctuations caused by tooth grooves in iron core-based planar motors, addressing motion interference and efficient heat dissipation resulting from actuator and external connections in moving coil planar motors, and developing effective control strategies for moving magnetic planar motors, as well as minimizing noise and vibration levels. Mainstream approaches to tackle these issues include enhancing field intensity and sinusoidal properties of air gap magnetic fields through improving permanent magnet arrangement and topological structures, and optimizing the coil array structure and commutation modes, as well as refining motor structures to mitigate edge effects associated with magnet arrays. Overall, there are still many obstacles that need to be overcome in order to improve the positioning accuracy and response speed of planar motors—advancements that can significantly propel precision machining development forward. Consequently, research on planar motors has garnered increasing attention, with the aim of expediting their development progress.

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References

1. Kou, B.; Zhang, L.; Li, L.; Zhang, H. The Review of Planar Motor Technology Development. *Micromotors* **2010**, *43*, 66–72+85.
2. Kou, B.; Zhang, H.; Pan, D.; Zhang, L.; Li, L. Development of 2D Planar Motors. *Micromotors* **2011**, *39*, 67–71.
3. Wu, W.; Si, J.; Yue, S.; Liu, Q.; Feng, H.; Li, Y. An Overview on Development of Multi-Degree-of-Freedom Planar Induction Motor. *Micrommotors* **2018**, *46*, 88–92.
4. Ish-Shalom, J. Modeling of Sawyer planar sensor and motor dependence on planar yaw angle rotation. *Int. Conf. Robot. Autom.* **1997**, *4*, 3499–3504.
5. Soltz, M.A.; Yao, Y.L.; Ish-Shalom, J. Investigation of 2-D planar motor based machine tool motion system. *Int. J. Mach. ToolsManufacture* **1999**, *39*, 1157–1169. [CrossRef]
6. Cao, G.-Z.; Fang, J.-L.; Huang, S.-D.; Duan, J.-A.; Pan, J.F. Optimization Design of the Planar Switched Reluctance Motor on Electromagnetic Force Ripple Minimization. *IEEE Trans. Magn.* **2014**, *50*, 1–4. [CrossRef]
7. Kumagai, M.; Hollis, R.L. Development and Control of a Three DOF Planar Induction Motor. *Int. Conf. Robot. Autom.* **2012**, *14*, 3757–3762.
8. Dittrich, P.; Radeck, D. 3—DOF Planar Induction Motor. In Proceedings of the 2006 IEEE International Conference on Electro/Information Technology, East Lansing, MI, USA, 7–10 May 2006; pp. 81–86.
9. Hao, X.; Peng, B.; Chen, Y.; Xie, G. Transient thermal model of a permanent magnet synchronous planar motor considering spreading thermal resistance. *Appl. Therm. Eng.* **2015**, *81*, 1–9. [CrossRef]
10. Rovers, J.; Stöck, M.; Jansen, J.; van Lierop, C.; Lomonova, E.; Perriard, Y. Real-time 3D thermal modeling of a magnetically levitated planar actuator. *Mechatronics* **2013**, *23*, 240–246. [CrossRef]
11. Zhou, Q.S.; Huang, S.R.; Zhang, Q. Calculation and Analysis of Temperature Field for Planar Motor Based on 3D FEM. In Proceedings of the 2011 Second International Conference on Digital Manufacturing & Automation, Zhangjiajie, China, 5–7 August 2011; pp. 277–279.
12. Cao, J.; Zhu, Y.; Wang, J.; Yin, W.; Duan, G.; Cao, J. Novel Synchronous Permanent Magnet Planar Motor and Its Model for Control Applications. *IEEE Trans. Magn.* **2005**, *9*, 2156–2163.

13. Lu, Z. *Basic Research on Composite Current Driven Permanent Magnet Synchronous Planar Motor*; Harbin Institute of Technology: Harbin, China, 2011.
14. Rui, H.; Shihong, W.; Qiuying, Z.; Chunling, C.; Fengli, J.; Bo, H. Characteristics Analysis of the Synchronous Permanent Magnet Planar Motor with New Permanent Magnet Array. In Proceedings of the International Conference on Mechatronics and Automation, Chengdu, China, 5–8 August 2012.
15. Lu, Z. *Basic Research on Synchronous Permanent Magnet Planar Motor with Concentric Winding*; Harbin Institute of Technology: Harbin, China, 2016.
16. Jansen, J.W.; van Lierop, C.M.M.; Lomonova, E.A.; Vandenput, A.J.A. Magnetically Levitated Planar Actuator with Moving Magnets. *Trans. Ind. Appl.* **2008**, *44*, 272–278. [CrossRef]
17. Usman, I.-U.-R.; Lu, X. Force Ripple Attenuation of 6-DOF Direct Drive Permanent Magnet Planar Levitating Synchronous Motors. *IEEE Trans. Magn.* **2015**, *51*, 1–8. [CrossRef]
18. Zhang, Y.; Ding, K.; Du, S. Design Study of a High Loading Superconducting Magnetically Levitated Planar Motor. *IEEE Trans. Appl. Supercond.* **2021**, *31*, 3601504. [CrossRef]
19. Kleijer, M.; Jansen, J.W.; Lomonova, E.A. Optimization of Quasi-Halbach Topologies to Maximize the Acceleration of Moving-Magnet Planar Motors. *Int. Conf. Electr. Mach.* **2022**, *47*, 942–948.
20. Zhang, H.; Kou, B.; Zhang, H.; Jin, Y. A Three-Degree-of-Freedom Short-Stroke Lorentz-Force-Driven Planar Motor Using a Halbach Permanent-Magnet Array with Unequal Thickness. *Trans. Ind. Electron.* **2015**, *62*, 3640–3650. [CrossRef]
21. Kou, B.; Zhang, H.; Li, L. Analysis and Design of a Novel 3-DOF Lorentz-Force-Driven DC Planar Motor. *IEEE Trans. Magn.* **2011**, *47*, 2118–2126. [CrossRef]
22. Lee, M.G.; Gweon, D.G. Optimal design of a double-sided linear motor with a multi-segmented trapezoidal magnet array for a high precision positioning system. *J. Magn. Mater.* **2015**, *281*, 336–346. [CrossRef]
23. Zhang, L.; Kou, B.; Li, L.; Zhao, B. Modeling and design of an integrated winding synchronous permanent magnet planar motor. In Proceedings of the 2012 16th International Symposium on Electromagnetic Launch Technology, Beijing, China, 15–19 May 2012; pp. 1–6.
24. Zhang, L.; Kou, B.; Xing, F.; Luo, J. Modeling and analysis of a magnetically levitated synchronous permanent magnet planar motor with concentric structure winding. In Proceedings of the 2014 17th International Symposium on Electromagnetic Launch Technology, La Jolla, CA, USA, 7–11 July 2014; pp. 1–6.
25. Jansen, J.W.; Smeets, J.P.C.; Overboom, T.T.; Rovers, J.M.M.; Lomonova, E.A. Overview of Analytical Models for the Design of Linear and Planar Motors. *IEEE Trans. Magn.* **2014**, *50*, 1–7. [CrossRef]
26. Jung, K.S.; Baek, Y.S. Precision stage using a non-contact planar actuator based on magnetic suspension technology. *Mechatronics* **2003**, *13*, 981–999. [CrossRef]
27. Yang, J.; Song, C. Sensorless control of surface permanent magnet synchronous motor at low speed. In Proceedings of the 2008 International Conference on Electrical Machines and Systems, Wuhan, China, 17–20 August 2008; pp. 1621–1624.
28. Wang, Z.; Hu, C.; Zhu, Y.; Zhang, M. Precision LARC motion controller design for a magnetically levitated planar motor. In Proceedings of the 2015 IEEE International Conference on Information and Automation, Lijiang, China, 8–11 August 2015; pp. 1359–1364.
29. Pan, J.; Cheung, N.; Yang, J. High-precision position control of a novel planar switched reluctance motor. *IEEE Trans. Ind. Electron.* **2005**, *52*, 1644–1652. [CrossRef]
30. Huang, S.D.; Cao, G.Z.; Peng, Y.; Wu, C.; Liang, D.; He, J. Design and Analysis of a Long-Stroke Planar Switched Reluctance Motor for Positioning Applications. *IEEE Access* **2019**, *7*, 22976–22987. [CrossRef]
31. Liu, M.; Wang, M.; Li, J.; Zhang, C.; Li, L. Dynamic Decoupling Compensation for Six Degrees of Freedom Maglev Planar Motor Based on Nonlinear Extended State Observer. In Proceedings of the 2023 26th International Conference on Electrical Machines and Systems (ICEMS), Zhuhai, China, 5–8 November 2023; pp. 157–162.