

# Research Status and Prospects of Voice Coil Motor Control Technology

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**Abstract.** The voice coil motor (VCM) represents a unique type of direct-drive motor, named for its operational principle. Its working mechanism resembles that of a loudspeaker diaphragm, wherein a voice coil generates motion through the application of a controlled electric current. The fundamental principle involves a current-carrying conductor producing force within a magnetic field, with the magnitude of the force directly proportional to the input current. The resulting motion is typically linear or follows an arc trajectory. As a distinct variant of linear motors, the VCM features a coreless design and operates without a traditional transmission system. This structural simplification enhances system compactness and reduces mechanical complexity. Additionally, VCMs offer numerous advantages, including high stiffness, rapid response, silent operation, excellent linearity, and the absence of cogging and pulsation. These attributes make them well-suited for short-stroke, high-frequency, and highly precise reciprocating movements, contributing to their widespread use in high-precision servo applications. While the removal of transmission components improves efficiency and design simplicity, it also increases the system's sensitivity to external disturbances and variations in load. Moreover, challenges such as low thrust density, mechanical resonance, and the difficulty of developing accurate system models hinder the performance of VCMs in precision control scenarios. This paper focuses on the analysis of several prominent control strategies for VCMs, detailing their operating principles and characteristics. It also summarizes their practical application domains, aiming to provide insight into the implementation of VCMs in advanced servo systems.

**Keywords:** Voice Coil Motor Control, Control Strategies, Engineering Application Scenarios.

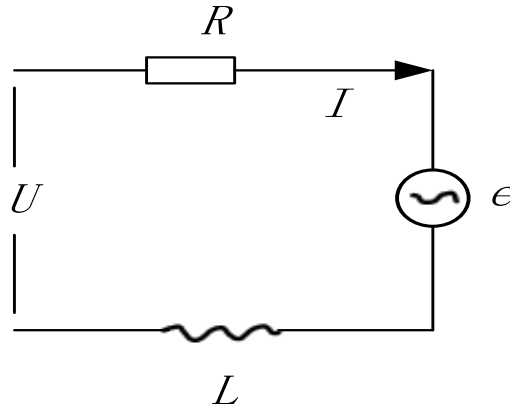
## 1. Introduction

Currently, precision engineering, as an interdisciplinary technology system, covers multiple technical fields such as semiconductor manufacturing processes, microelectronic device processing, optoelectronic testing systems, and submicron precision machining [1]. Among them, precision positioning technology, as a core enabling technology, plays a decisive role in enhancing the performance of precision engineering systems [2]. Taking the motion control system of semiconductor packaging equipment as an example, the positioning accuracy of its core control unit directly determines the quality and yield of chip packaging, and this technical indicator has become one of the important parameters for measuring the technological level of advanced packaging equipment [3,4]. Due to its high dynamic performance, rapid response, and precise control capabilities, voice coil motors are widely used in precision positioning technology in fields such as semiconductor packaging, precision instruments, and medical equipment [5]. As a type of linear motor, voice coil motors are characterized by their small size, simple structure, light mover mass, and low inertia, enabling millisecond-level ( $<1\text{ms}$ ) rapid start-stop, suitable for high-frequency reciprocating motion scenarios [6]. They also feature high acceleration, with instantaneous acceleration up to tens of times the gravitational acceleration ( $>20g$ ), supporting high-speed precision positioning [7]. Due to these characteristics, they are commonly used in precision positioning systems requiring high accuracy and high acceleration performance [8].

## 2. Analysis of Existing Control Strategies

### 2.1. Model of Voice Coil Motor

As shown in **Fig. 1**, it is the internal equivalent circuit diagram of the voice coil motor. The internal permanent magnet of the voice coil motor generates a roughly uniform magnetic field within the range of mover movement. When an external power supply is applied and current flows through the armature circuit, the electrified conductor will be subjected to electromagnetic force in the magnetic field [9]. The mover will move due to the electromagnetic force. When the mover moves under the traction of electromagnetic force, the coil simultaneously cuts the magnetic field lines, generating a counter electromotive force. The external power supply voltage of the motor is  $u$ , the equivalent resistance of the mover winding is  $R$ , the equivalent inductance of the winding coil is  $L$ , the current passing through the winding coil is  $i$ , the back electromotive force generated by the motion of the voice coil motor is  $e$ , the displacement of the motion is  $x$ , and the damping coefficient (friction damping, air damping, etc.) of the motor is  $K_c$ . The back electromotive force coefficient and electromagnetic force coefficient of the motor are respectively denoted  $K_e$  and  $K_m$ .



**Fig. 1** Equivalent Circuit Diagram of Voice Coil Motor (VCM)

According to Kirchhoff's law, the electronic mechanical equation expression for the armature circuit of a voice coil motor can be derived as:

$$u = e + iR + L \frac{dx}{dt}$$

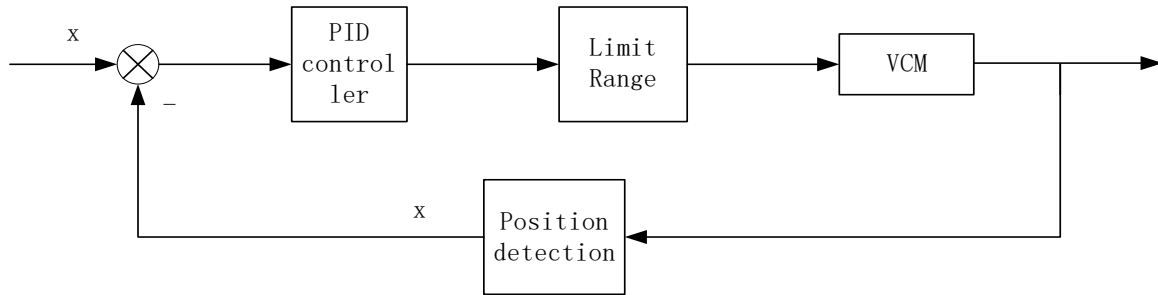
The mechanical equilibrium equation is as follows:

$$F_e = m \frac{d^2x}{dt^2} + K_c \frac{dx}{dt} = K_m \cdot i$$

Due to the typically compact size of voice coil motors (VCMs), their servo control systems often adopt a dual closed-loop configuration—comprising both position and current loops—to enable high-speed tracking performance. Among these, the position loop plays a central role in the overall control architecture. In this section, we provide a concise overview of several commonly implemented controllers used in the position loop of VCM systems.

### 2.2. PID Control

PID control, with its clear structure and convenient parameter tuning, is the most basic and widely used controller in VCM servo control. It exhibits strong reliability and good stability in industrial practice and is suitable for the conventional positioning requirements of VCM. **Fig. 2** shows the control block diagram of PID control.



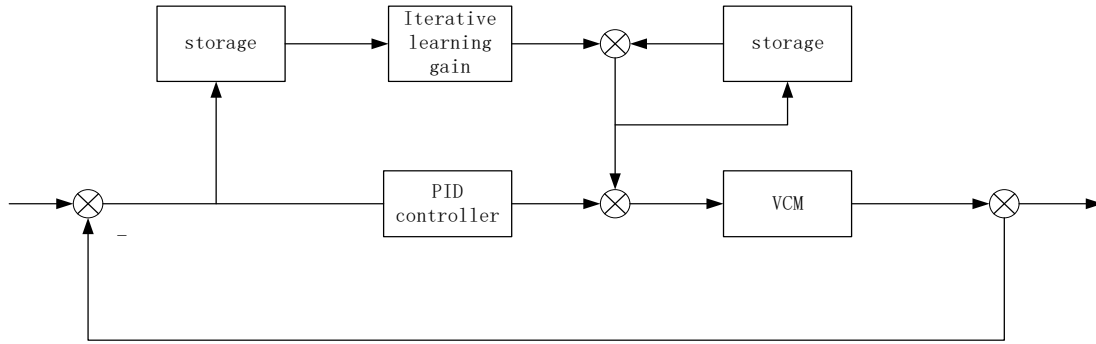
**Fig. 2** PID controller diagram

VCM systems commonly utilize a dual-loop control framework composed of an outer position loop and an inner current loop, with the position loop serving as the central element in control system design. The implementation of a PID controller within the position loop plays a pivotal role in determining the system's tracking accuracy and dynamic response [10]. However, PID control also has many limitations, such as insufficient dynamic performance. When faced with high-frequency response, nonlinear disturbances (such as friction and vibration), or high-precision requirements, traditional PID methods struggle to satisfy the necessary control criteria. Weak anti-interference capability: sensitive to parameter changes (such as load fluctuations) and external disturbances (airflow damping, mechanical resonance).

Therefore, PID is often integrated with other control techniques to enhance performance: for example, fuzzy PID, which enhances adaptability to nonlinear disturbances (such as friction compensation). Neural network PID, which optimizes parameters online and approximates complex nonlinear characteristics. Predictive compensation, which predicts the next moment's input through current errors to improve positioning accuracy [11]. Two-degree-of-freedom structure, which independently designs set point tracking and disturbance rejection links to enhance dynamic response and robustness.

### 2.3. Iterative Learning Control (ILC)

Iterative learning control is an intelligent control strategy tailored for periodic operational tasks. Its core principle lies in a closed-loop optimization mechanism based on historical operational data. This method involves collecting deviation information between the output feedback of the current control cycle and the preset target trajectory [12]. After processing with an iterative learning algorithm, optimized control inputs are generated, ultimately achieving precise suppression of periodic disturbances and continuous improvement in trajectory tracking accuracy within a finite time domain. Its control architecture typically includes three key elements: a preset reference trajectory generation module; a dynamic error compensation calculation unit; and an iterative learning gain adjustment mechanism. By introducing a memory storage unit, iterative learning control uses the control inputs and error information from previous runs as references for current control decisions, forming a control law with recursive optimization characteristics. This learning mechanism based on historical data enables the control system to continuously improve performance in repetitive tasks, ultimately achieving an exponential improvement in control accuracy. The Block Diagram of Feedback Control with Iterative Learning Control is shown in **Fig. 3**.



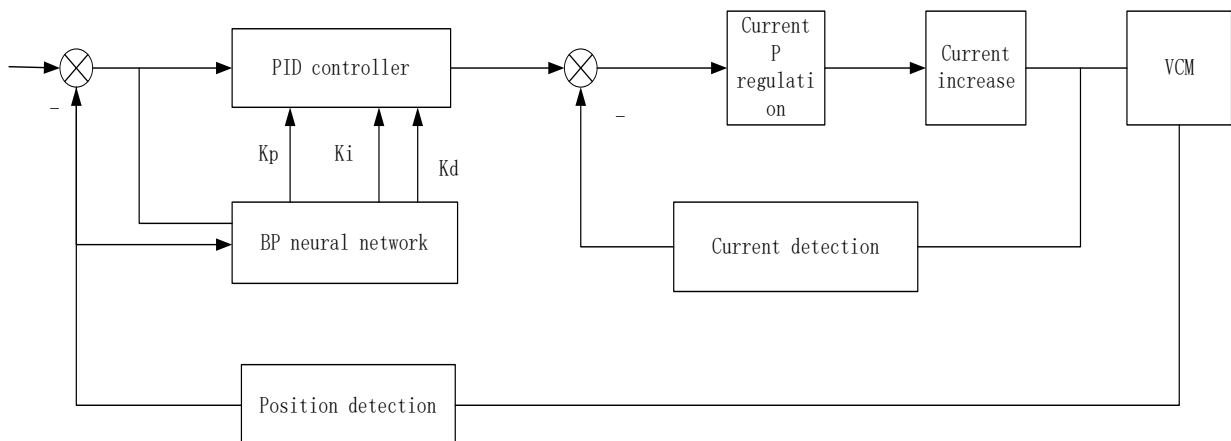
**Fig. 3** Block Diagram of Feedback Control with Iterative Learning Control

In summary, iterative learning control utilizes memory for real-time data update driving, incorporating the previous or current system error into the control system. Compared to traditional control methods, it compensates for the shortcomings of time delay and provides a more sensitive and rapid response to external system disturbances.

#### 2.4. Neural network PID feed forward control

Error back propagation training neural network, abbreviated as BP neural network, is currently the most widely used method for training neural networks. Using a very widely used neural network, the topological structure of its model. It includes one input layer, one or multiple hidden layers, and one output layer. Layer. Existing research has proven that a 3-layer BP network can achieve. Approximate various nonlinear physical objects with sufficient accuracy, and increasing the number of layers. To further reduce errors and improve accuracy, but also to make the network.

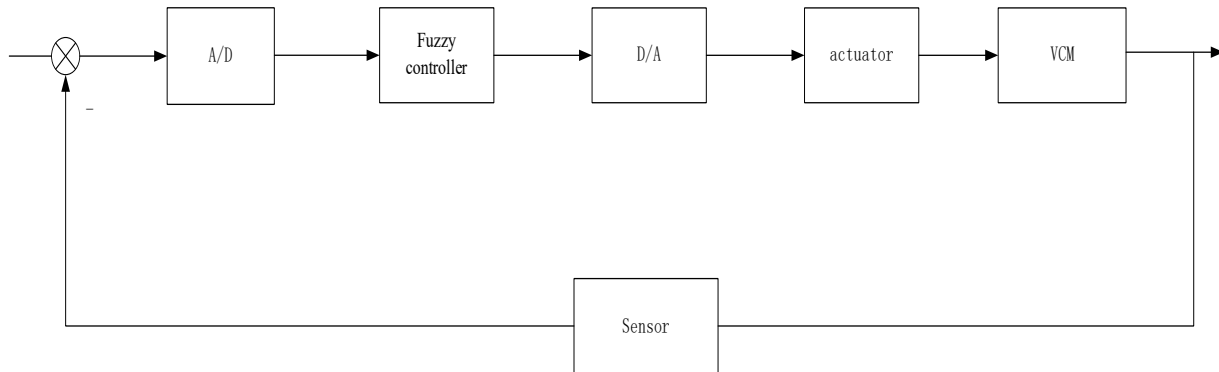
The network is more complex, increasing the training time for network weights and thresholds. BP neural network. The learning process can be divided into forward propagation of signals and error Back propagation has two stages [13]. The forward propagation stage of the signal, and the sample data. Input is fed into the input layer, processed by the hidden layer, and then passed to the output layer. If the actual output of the layer does not match the expected output, proceed to error back propagation. "To the stage of propagation. In the error back propagation stage, the output error is..."Back propagate layer by layer from the hidden layer to the input layer, and allocate the error to each. All nodes in the layer serve as the basis for adjusting the weights of each node. The learning and training process of a neural network involves the forward propagation of signals and the calculation of errors. The back propagation process is carried out iteratively, during which the weights of each layer are continuously updated. Adjust. The learning process continues until the error of the network output becomes acceptable. Or until the preset number of cyclic learning times is reached. BP neural networks are often used to self-tune PID parameters online. The Control model of voice coil motor positioning system is shown in **Fig. 4**.



**Fig. 4** Control model of voice coil motor positioning system

## 2.5. Fuzzy control

Fuzzy control, or fuzzy control system, is an automatic control system that utilizes fuzzy mathematics and fuzzy language. Based on the theoretical foundation of formal knowledge representation and fuzzy logic reasoning, it is a system composed of computer technology with a closed-loop structure [14]. The digital control system of the structure. The structural block diagram of the fuzzy control system, which consists of A/D, D/A conversion interfaces, fuzzy controllers, sensors, and other components. The Block diagram of fuzzy system control structure is shown in **Fig. 5**.



**Fig. 5** Block diagram of fuzzy system control structure

## 2.6. Modern Control Strategy

Taking into account the time-varying and uncertain factors such as the structure and parameter variations of the VCM servo system, various nonlinear effects, changes in the working environment, and environmental disturbances, other modern control strategies such as adaptive control and robust control have been applied in VCM. Here are a few simple examples.

Adaptive control integrates feedback mechanisms with system identification theory to adjust the dynamics of the controlled system based on the pursuit of an optimal performance criterion [15]. It is generally categorized into two main approaches: self-tuning regulators and model reference adaptive control. By formulating appropriate parameter adaptation laws, the control error can asymptotically converge to zero while preserving system stability. This control technique is valued for its practicality and effectiveness in coping with time-varying parameters and various internal or external disturbances. In the context of VCM applications, adaptive control is commonly utilized to mitigate uncertainties such as frictional effects and mechanical vibrations [16].

Robust control, on the other hand, relies on state-space techniques to design controllers capable of maintaining desired performance levels in the presence of parameter uncertainties—whether structural or parametric. It is characterized by its strong disturbance rejection capabilities and inherent system stability. However, due to its conservative nature, robust control systems may not always achieve optimal steady-state accuracy. As a result, this method is particularly advantageous in systems subject to wide-ranging uncertainties and narrow stability margins [17]. In the field of VCMs, robust control has been proposed as a viable strategy to counteract unknown external influences and model inaccuracies, thereby improving both system stability and trajectory tracking accuracy.

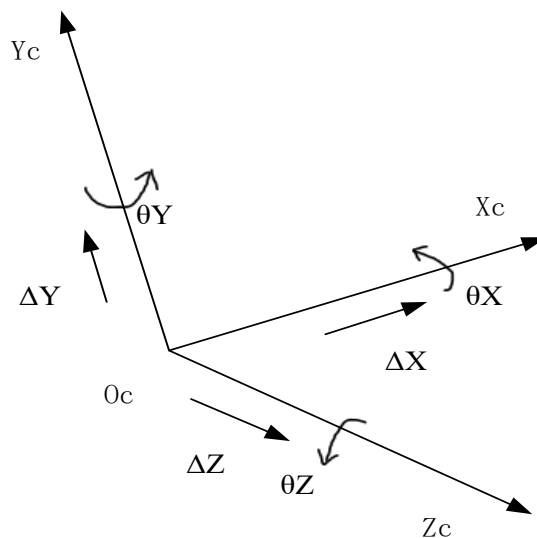
Optimal control, which places significant emphasis on time-response characteristics, is often employed in VCM positioning systems to achieve fast and precise motion. Time-Optimal Control (TOC), for example, guides the system through maximum acceleration and deceleration phases, resembling bang-bang control strategies. While TOC offers outstanding dynamic behavior, its sensitivity to modeling errors and disturbances can undermine performance [18]. To enhance robustness, Proximate Time-Optimal Control (PTOC) introduces a linear control region around small error values, softening the switching action of TOC and thereby increasing resistance to model uncertainties. Within VCM applications, optimal control approaches—particularly PTOC—have demonstrated notable improvements in motion responsiveness and dynamic control performance.

### 3. Analysis of engineering application scenarios

Although the voice coil motor position servo drive system eliminates some of the adverse effects brought by traditional mechanical transmission. The design difficulty of its drive controller has also increased significantly. It is necessary to comprehensively consider the direct drive system of the voice coil motor. Take into account and design reasonably based on its specific application, while also considering the many uncertain factors that may affect the control. The impact of the control system. By combining the voice coil motor drive system with the closed-loop control system, it can greatly improve the rapid response capability and position servo control accuracy of the feed system, in various high-speed and precision machining equipment. It has broad application prospects. In recent years, with the development of micro-motor technology, power electronics technology, sensor technology, permanent magnet material technology, and automatic control. With the advancements in manufacturing technology, microcomputer application technology, as well as various modern control technologies and intelligent control technologies, there has been a surge in the development of various high-performance technologies. Performance-driven control systems are constantly emerging, and the development of direct drive systems for voice coil motors has entered a new stage. Voice coil motors play an important role in many fields.

#### 3.1. Mobile phone camera module

In the production process of packaging mobile phone camera modules, it is necessary to utilize voice coil motors to position the camera pose on a six-degree-of-freedom (6-DOF) work platform. During the adjustment process, precise positioning is required to ensure product quality; meanwhile, rapid adjustment is necessary to enhance production efficiency. During the production of mobile phone camera modules, the camera pose needs to be adjusted, and then the camera is fixed to the frame using adhesive. First, a macro world coordinate system is established, where  $\theta_X$ ,  $\theta_Y$ , and  $\theta_Z$  represent the rotation angles of the camera coordinate system relative to the X-axis, Y-axis, and Z-axis of the world coordinate system, respectively;  $\Delta X$ ,  $\Delta Y$ , and  $\Delta Z$  represent the offsets of the origin of the camera coordinate system relative to the origin of the world coordinate system in the X-axis, Y-axis, and Z-axis directions, respectively. The Camera coordinate system is shown in **Fig. 6**



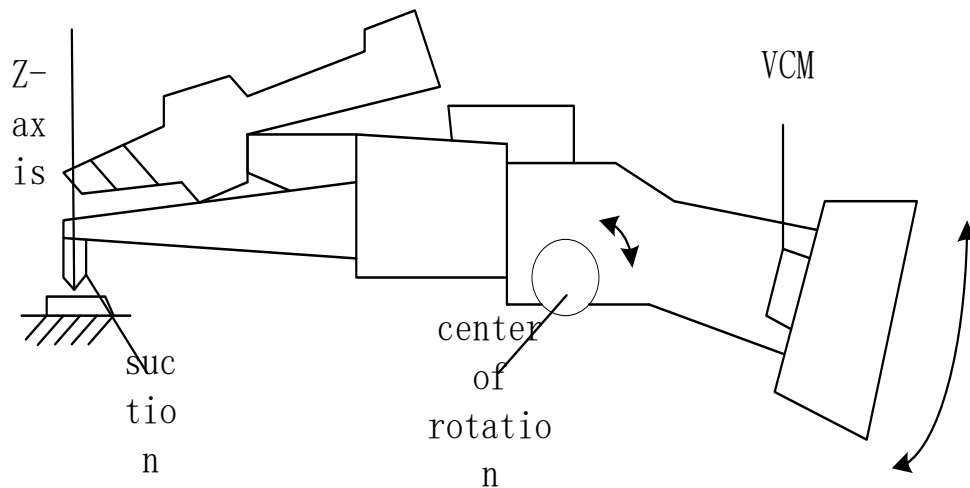
**Fig. 6** Camera coordinate system

The rotation amounts  $\theta_X$ ,  $\theta_Y$ , and  $\theta_Z$  of the camera coordinate system on the three axes are adjusted to make the camera coordinate system parallel to the three axes of the world coordinate system; the translation amounts  $\Delta X$ ,  $\Delta Y$ , and  $\Delta Z$  of the camera coordinate system on the three axes are adjusted to position the origin of the camera coordinate system at a given location in the world coordinate system. The camera is connected to the 6-DOF work platform through a fixture, and six

voice coil motors are used to adjust the six degrees of freedom ( $\theta_X$ ,  $\theta_Y$ ,  $\theta_Z$ ,  $\Delta X$ ,  $\Delta Y$ , and  $\Delta Z$ ) to achieve camera pose correction [19]. During the adjustment and positioning process of the voice coil motors, there are no external disturbances, and the mass of the work platform connected to the voice coil motor mover is fixed. It is required to adjust and position quickly and accurately according to the given adjustment amounts of the six degrees of freedom to improve production efficiency and ensure product quality.

### 3.2. Trajectory tracking

The wire bonding process of a wire bonding machine includes: forming a gold ball through electronic sparking, driving the cleaver down to the bonding point at high speed using a voice coil motor and performing contact detection for wire bonding, followed by arc pulling operation, and finally repeating the process of searching for bonding points and wire bonding. It can be seen that the wire bonding process is a high-precision, repetitive motion process, where the most critical steps are the position search and arc pulling processes, that is, the ability to track the planned trajectory. To improve the trajectory tracking capability of the control system, a feed forward + fuzzy feedback control algorithm was initially proposed for trajectory tracking of wheeled mobile robots. Its control effect was improved compared to standard inverse control, but the formulation of its fuzzy rule table relied too much on prior conditions. Another approach adopted adaptive neural sliding mode control to eliminate chattering and improve the robustness of the system during trajectory tracking. The above methods have limited effect on reducing the error of trajectory tracking, slow convergence to the expected trajectory, or involve overly complex processes leading to too many design variables [20]. The PD-type iterative learning control algorithm with a forgetting factor is very suitable for such highly repetitive and high-precision motion processes, and theoretically can achieve high-precision, error-free trajectory tracking. The Simplified Z-axis Model of Wire Bonder is shown in Fig. 7.



**Fig. 7** Simplified Z-axis Model of Wire Bonder

Since the bonding head module of the wire bonding machine is a high-precision, high-speed motion module, using only a feedback controller cannot guarantee a sufficiently fast response speed under high acceleration conditions, which will result in time delay. Pure feed forward control can only compensate for specified disturbances and cannot improve the existing deviations in the control system. Therefore, a two-degree-of-freedom control system combining feed forward and feedback is adopted. Compared to the inevitable errors in feedback control, feed forward control can theoretically achieve completely error-free control of the system. The movement of the bonding head of the wire bonding machine not only requires high response capability, but its trajectory tracking ability also has a significant impact on the quality of wire bonding. Therefore, the control requirement is preferably to achieve complete tracking of the desired trajectory, and iterative learning is a good control method that can meet the requirement of complete trajectory tracking. Therefore, iterative learning feed forward control is now widely used to achieve complete trajectory tracking.

Overall, voice coil motors have achieved multi-dimensional penetration in the field of precision motion control, leveraging their core advantages of direct drive without a transmission chain, millisecond-level dynamic response, and high linearity output. From nanometer level positioning of hard disk drive (HDD) heads to anti-vibration and anti-shake capabilities for mobile phone lenses, from submicron synchronization of lithography platforms to micro-force manipulation of microscopic instruments, the technological value of VCMs continues to break through the triangular performance limits of "precision-speed-disturbance resistance". The differentiated needs of different application scenarios (such as HDD resistance to vibration disturbances and semiconductor manufacturing pursuit of multi-axis collaborative precision) not only drive the evolution of key technologies such as macro-micro composite structures and intelligent control algorithms, but also reveal the trend of VCMs transitioning from single actuators to electronic mechanical integrated intelligent modules. In the future, as precision engineering advances towards the nanometer/quantum scale, VCMs will further integrate embedded sensing, AI real-time optimization, and new material technologies, expanding irreplaceable application boundaries in emerging fields such as biomedical robots and space optical payloads.

#### **4. Conclusion**

Initially, the research on voice coil motors was quite backward due to the limitations of knowledge at that time and various social factors. However, with the advancement of science and technology, voice coil motors have become a crucial presence in various modern industrial fields due to their structural characteristics and various performance advantages. The research on voice coil motors has gradually gained attention, which has also accelerated the technological development of voice coil motors.

Based on research on VCM control systems conducted by researchers from various countries, this article summarizes various VCM control technologies. This article comprehensively introduces the principles and characteristics of some common control systems. Currently, most mainstream control technologies are based on traditional PID control. However, these technologies have many drawbacks, such as susceptibility to external interference, information time lag, and mechanical friction. These factors can lead to control errors. Consequently, a number of advanced technologies have been developed to address these issues. For example, iterative learning control uses the previous output as the input signal to continuously reduce tracking error, ultimately achieving perfect tracking through increasing iterations. Of course, there are many other approaches, such as fuzzy control, neural networks, and other modern control methods. Furthermore, this article introduces common VCM application areas, such as bond head control in wire bonders, primarily addressing bond head trajectory tracking, where iterative learning control is used to eliminate tracking errors. This article also discusses applications in mobile phone camera modules, and summarizes the key issues that need to be addressed in each application scenario. Now, as the application fields of voice coil motors are becoming more and more, even covering our daily lives such as mobile phone cameras to some high-end precision equipment, more and more problems are exposed in their use, so more control methods are constantly being created.

The main challenges currently facing VCMs are improving positioning accuracy and timing, as well as enhancing anti-interference capabilities. In various working environments, external interference factors such as temperature, air pressure, friction, and so on, may pose challenges. In the future, it can be reasonably anticipated that as the application of VCMs in various fields gradually increases, and as research deepens and widens, the performance of VCM control systems will continue to improve.

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