Overview of Position Servo Control Technology and Development of Voice Coil Motor

Yue Qiao, Tianyi Zhao, and Xianguo Gui

***Abstract*—Voice coil motor (VCM) is a special direct drive linear motor, which can convert electric energy directly into mechanical energy without the use of transmission mechanism. VCM has the advantages of simple structure, good rigidity, fast response, silence, high linearity, no cogging force, no pulsation et al. It is widely used in the field of high-precision control. This paper reviews and summarizes the results of VCM research conducted by scholars from various countries, and summarizes the general situation of VCM servo control technology. Firstly, a basic description of VCM's mathematical model and common control mechanisms is provided. The benefits, drawbacks, and application of control techniques in the field of VCM are all explored in detail; At the same time, the methods to improve control strategy are proposed; Then, combined with the analysis and research of scholars in various countries on VCM, the problems of difficult to establish accurate model, friction disturbance and mechanical vibration of VCM and the solutions to the corresponding problems are summarized; Finally, a summary of VCM's application fields is provided.**

***Index Terms*—Control strategy, Position loop, Position servo control, Voice coil motor.**

I. Introduction

Voice coil motor is a special form of direct drive motor, which is named because of its principle. The principle is similar to that of loudspeaker vibrating diaphragm [1] by exciting voice coil of controlled current. Its working principle is that the energized coil (conductor) will generate force in the magnetic field, and the force is proportional to the current applied to the coil. Straight lines or arcs make up the majority of its motion forms.

As a kind of special linear motor, VCM adopts coreless structure and removes the transmission mechanism. Therefore, the compactness of the motor system is improved, and the structure is simpler. In addition, the VCM also has the advantages of good rigidity, fast response speed, silence, high linearity, no cogging force, no pulsation et al [2], and can realize small-scale, high-frequency and high-precision reciprocating control. Therefore, it is widely used in many occasions where high-precision servo is required.

The elimination of the transmission mechanism makes the structure of the VCM simpler and more efficient, but it also makes the VCM more sensitive to external disturbances and load changes. In addition, VCM also faces problems such as difficulty in establishing accurate models, low thrust density [3], and mechanical resonance, all of which pose challenges to high-precision servo control.

This paper summarizes the research results of servo control technology of VCM. Section II briefly describes the mathematical model, common control strategies, advantages and disadvantages of VCM. Section III introduces the methods of improving the controller by means of feedforward, macro-micro control structure and observer. Section IV summarizes the difficulty of establishing accurate models of VCM, problems such as friction disturbance and mechanical vibration, and solutions to corresponding problems. Section V summarizes the application fields of VCM.

II. Position Loop Control Strategy

As a new type of direct drive linear motor, the design of VCM is based on Ampere force principle. According to different structures, the models of VCM can be divided into two categories: one is mass-spring-damper (MSD) and the other is mass-damper (MD). The mechanical balance equation and voltage balance equation of VCM can be obtained through the mechanical model and circuit model of VCM:

$$k_m i = m\frac{d^2x}{dt^2} + k_f\frac{dx}{dt}(+kx) \tag{1}$$

$$u = Ri + L\frac{di}{dt} + k_e\frac{dx}{dt} \tag{2}$$

Where k_m is Thrust coefficient of VCM, m is the mass of the mover, x is Displacement, k_f is Coefficient of friction, kx is the spring resistance, R and L is total coil resistance and inductance, and k_e is Back-EMF coefficient.

The process of establishing the mathematical model of the VCM is explained in detail in [4].

Because the volume of the VCM is typically tiny, in order to obtain the effect of fast tracking, the servo control system for the VCM often adopts a dual closed loop structure of position and current. The design of the position loop is the

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Yue Qiao is with College of Electrical Engineering and Automationt, Harbin Institute of Technology, Harbin, 150006 China, (e-mail: qiao_yue_hit@163.com).

Tianyi Zhao is with College of Electrical Engineering and Automationt, Harbin Institute of Technology, Harbin, 150006 China, (e-mail: ztybill@163.com).

Xianguo Gui is with College of Electrical Engineering and Automationt, Harbin Institute of Technology, Harbin, 150006 China, (e-mail: guixianguo_hit@163.com).

(Corresponding Author: Yue Qiao)

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most important link to the design of the VCM control structure. The common controllers of the VCM position loop will be briefly summarized here.

A. PID Control

The PID algorithm is widely used in industrial control because of its simple structure, convenient adjustment, reliable work and good stability. It is also widely used in the field of VCM control. The PID controller structure of the VCM is shown in Fig. 1.

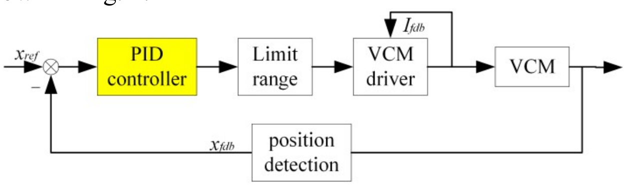

Fig. 1. PID controller block diagram.

According to some differences in the PID structure, PID controllers can be divided into series PID, parallel PID and standard PID. In engineering, parallel PID and standard PID are more widely used. The system structure, model characteristics, parameter characteristics and debugging methods of the PID controller are detailed in [5].

With the improvement in system performance requirements, simple PID control often cannot meet the requirements. Combining PID control with other modern control ideas has formed many valuable control strategies. Combining traditional PID control with fuzzy control [6],[7], neural network control [8], and adaptive control [9] can improve the adaptive ability and anti-interference ability of the VCM servo system when facing interference; In [10]-[12] authors proposed the introduction of predictive compensation in PID control, by analyzing the error at the current moment to change the input at the next moment, thereby improving the positioning accuracy of the VCM; in addition, the use of a two-degree-of-freedom PID controller structure can improve the system The following performance and anti-interference performance [13].

B. ADRC Control

Active Disturbance Rejection Control (ADRC) evolved from PID control and adopted the core concept of PID error feedback control. The proposal of ADRC controller solves the weak links in PID control, such as the error computation; noise degradation; oversimplification and the loss of performance in the control law in the form of a linear weighted sum; complications brought by the integral control [14].

The structure diagram of ADRC controller is shown as in Fig. 2. The ADRC controller turns the control object into an

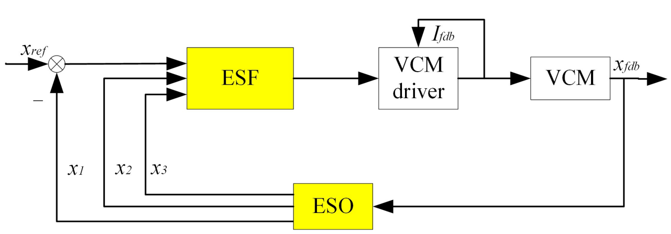

Fig. 2. ADRC controller block diagram.

ordinary integral series control object. The purpose of designing the extended state observer (ESO) is to observe the extended state variables, which are used to estimate the unknown disturbance and the unmodeled part of the control object, and to realize the feedback linearization of the dynamic system. And ADRC use the control law that can be equivalent to the PD structure to compensate the errors of each order, allowing for tracking control of the controlled object. The ADRC controller coefficient is independent of the object's mathematical model.

Since the control object is equivalent to the integral series link in the ADRC controller design process, the controller coefficients often do not depend on the mathematical model of the object. The ADRC controller is used in the VCM to solve the problem of uncertainty in the theoretical model of the system [15]; ADRC parameter tuning is more convenient. Compared with the traditional PID controller, especially when facing the step response, the ADRC controller has smaller overshoot and faster response time [16],[17]; Finally, for real-time interference estimation and compensation can make the system more robust [18],[19].

C. Fuzzy Control

In the traditional control field, the accuracy of the dynamic mode of the control system is the most important key that affects the quality of the control. The more detail the dynamic information of the system, the more precise the control can be achieved. However, because the accuracy requirements for VCM are generally high, the established model cannot meet the requirements of high-precision control, which brings challenges to high-precision control.

Therefore, it is a good attempt to deal with these control problems with fuzzy mathematics. The structure of the fuzzy controller is shown in Fig. 3.

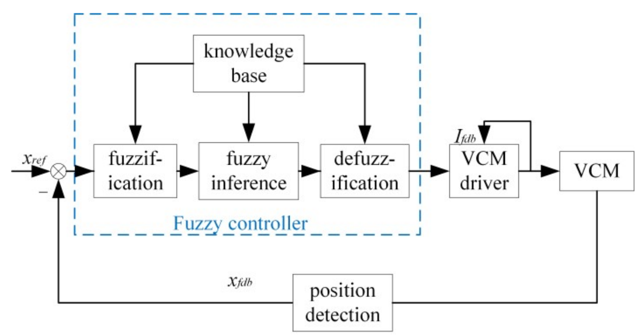

Fig. 3. Fuzzy controller block diagram.

The fuzzy controller fuzzifies the position error, performs fuzzy inference according to the fuzzy rules, and finally defuzzifies the fuzzy value after inference to obtain clear control parameters.

In the early research on fuzzy control, it is necessary to construct fuzzy rules first to achieve design performance through trial and error; however, this adjustment process of trial and error is undoubtedly very tedious and time-consuming. Therefore, how to reasonably design self-learning or adaptive rules to adjust fuzzy rules online is a research point in the application of fuzzy control in VCM [20],[21].

Because fuzzy control is not sensitive to system parameters and environmental parameters, its response to nonlinear control objects is better robust than PID control [22], and model-free control can be implemented to solve the problem of parameter uncertainty and nonlinearity in VCM [23]-[26].

D. Internal Model control and Predictive Control

The internal model control structure is shown in the Fig. 4. The design of the internal model controller uses the principle of internal model, that is, when the internal model is the same as the actual model, it can realize the error-free tracking of the controlled object. However, this structure is limited by the accuracy of the VCM model, so it is of low practical value in engineering and is mainly used for the design of current loops. In [27], authors propose connecting an internal model controller with a stabilizer with a robust structure in parallel to achieve high-precision tracking under a certain range of frequency changes. It is effective to use internal model control to estimate and eliminate periodic interference in [28].

The predictive control is derived from the internal model control structure, as shown in the Fig. 5. It is an optimal control algorithm, which uses the feedback of the current time to determine the future control action by optimizing a performance index.

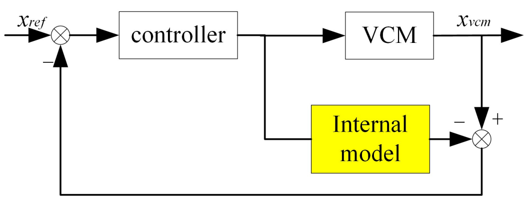

Fig. 4. Internal model controller block diagram.

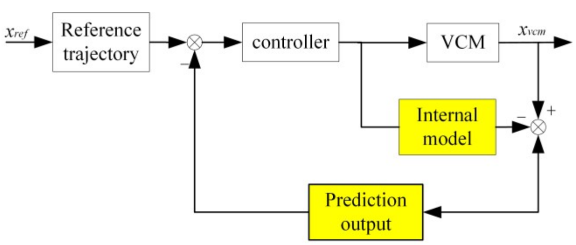

Fig. 5. Predictive controller block diagram

Predictive control is significant in improving the dynamic performance and stability of the system, but it also consumes more computational power, and is weak in nonlinear and uncertain problems. In [29]-[32], the model predictive control of the position error signal of VCM is carried out, which proves that it can reduce the stability time and improve tracking performance in the positioning process of the system; In [33], authors proposes to convert the noise suppression problem into a tracking problem, using model predictive control and generalized prediction Control can suppress the vibration of the ball bearing system rotor.

E. Modern Control Strategy

Taking into account the structure and parameter changes of the VCM servo system, various nonlinear effects, changes in the operating environment, and environmental disturbances and other time-varying and uncertain factors. Other modern control strategies such as adaptive control, neural network control, and robust control, Sliding mode variable structure control has been applied in VCM.

1) Adaptive Control

Adaptive control is a combination of feedback control and identification theory. It completes the overall adjustment of the controlled object by seeking the best performance indicators. At present, there are two types of self-tuning and model-reference adaptive control [35]. By designing the adaptive parameter adjustment law, the error signal tends to zero while ensuring the stability of the system [36]. The advantage of adaptive control is that it is effective and easy to implement when dealing with parameter changes and internal and external disturbances [37]-[39]. However, it will be limited by the measurement accuracy. In the field of VCM, adaptive control is usually used to deal with uncertain problems such as friction and vibration.

2) Neural Network Control

Neural network control uses reward or penalty mechanisms to accurately model certain parameters that are difficult to obtain with conventional tools, or act as a controller and optimize calculations. Neural network control has strong robustness, learning ability and adaptive ability. However, the optimization process of the neural network takes time, and it is difficult to meet the real-time performance of the position servo with the neural network as the controller. Therefore, the neural network control is often used to approximate certain parameters in the application of the VCM servo system [8],[39]-[40] , Or cooperate with adaptive control or fuzzy control to optimize adaptive control law [42]-[43] or fuzzy rules [24],[25].

3) Robust Control

Robust control configures the controller through the state space method, so that the control system maintains certain performance under a certain (structure, size) parameter perturbation.

Robust control has stronger anti-interference ability and stability. However, because the robust control system generally does not work in the optimal state, the steady-state accuracy of the system is poor. Therefore, robust control is especially suitable for those systems with large variation range of uncertain factors and small stability margin[44]-[46]. In [47], H∞ robust control is used to solve the problem of assembly errors in the center of mass and force of VCM; In [48], robust control is used to reduce the impact of load resonance changes; some scholars also propose to use robust control to solve the problem uncertain external disturbance [49]-[51] and the problem of uncertain system model [52], thereby improving the stability and tracking effect of the system.

4) Sliding Mode Variable Structure Control

Sliding mode variable structure control (SMVSC) is essentially a special kind of nonlinear control, and nonlinearity manifests itself as control discontinuity. The difference between this control strategy and other controls is that the "structure" of the system is not fixed, but it can change purposefully and continuously according to the current state of the system in a dynamic process, forcing the system to follow a predetermined "Sliding surface" State trajectory movement.

Sliding mode variable structure control not only has good control effect on nonlinear system, but also has the advantages of simple algorithm and fast response speed. Due to the characteristics of the sliding film control structure[53], the determination of sliding surface and the elimination of buffeting [54],[55] are the difficulties of research. In VCM control, sliding mode control is used to compensate for non-linear, time-varying, hysteresis characteristics such as friction [56],[57] or to improve robustness in the face of parameter changes or external disturbances [58].

5) Optimal Control

The settling time is an important parameter in the VCM control system. In order to realize the rapid positioning problem, people usually consider time-optimal control (TOC), that is, the system can move with maximum acceleration and deceleration (that is, bang-bang control). In [59], this method is used, by planning the acceleration and deceleration action time, the energy optimal solution for a fixed time is realized.

Despite its excellent dynamic performance, TOC has poor robustness. When there are differences in models or disturbances in the system, the control performance of the system will deteriorate. Proximate time-optimal control (PTOC) introduces a linear working area based on TOC control law. When the error is small, the linear control law is used instead of the switching function, which makes the system more robust. In the field of VCM, optimal control greatly improves the dynamic performance of the system. In [60],[61], the PTOC method is used to realize the tracking and resetting process of HDD, and the stabilization time and overshoot are better than PID controller. In [62]-[64], a reference trajectory compensation method is proposed to shorten the action time and improve the residual vibration.

III. Position Loop Improvement Strategy

The above introduces more common controllers for VCM position loops, and by carefully selecting and cooperating with the controllers, VCM control performance can be enhanced. However, the simple feedback strategy still has its limitations, which limits the further improvement of VCM performance. Therefore, many scholars have proposed a series of methods to improve the control strategy. Several common methods are introduced below.

A. Feedforward Compensation

The VCM may be subject to external disturbances such as airflow damping, friction damping, internal mechanical vibration, dead zone, hysteresis, and various nonlinear characteristics in the system. Such problems are difficult to handle with conventional controllers, posing a challenge for VCM's high-precision servo control. The feedforward control is an effective method to solve the internal or external disturbance of the VCM.

At present, most studies on external disturbances such as friction in VCM use feedforward to compensate [50],[65]; in [66], multi-rate adaptive feedforward was used to suppress Nyquist frequency and higher frequency interference; In [67], authors using feedforward to compensate the hysteresis characteristics of VCM; A control strategy combining feedforward and feedback is proposed in [68]. The feedforward controller adopts an iterative control algorithm based on zero-phase filter, which effectively improves the system's following accuracy and response speed.

B. Macro-micro Control Structure

Due to the simple structure and light weight of VCM, it can easily reach a positioning accuracy of 10um. However, it is difficult to further improve its accuracy, and it often requires the cooperation of appropriate control strategies. The piezoelectric actuator (PZT) has the advantages of high control accuracy, high response frequency, high electrical and mechanical energy conversion efficiency, and can achieve a positioning accuracy of 1-10nm. But the stroke of PZT is only tens of microns [2].

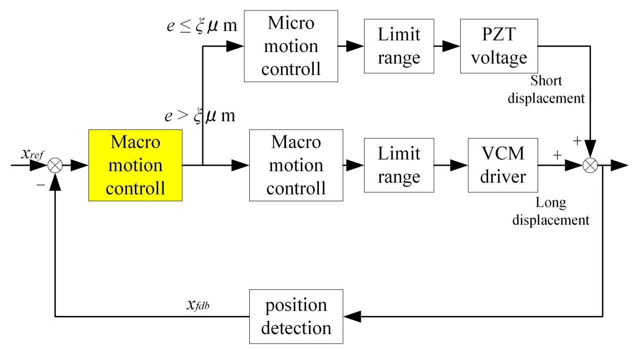

Fig. 6. Macro-micro control structure block diagram.

In order to overcome the shortcomings of PZT short stroke, an effective method is to combine VCM and PZT to form a macro and micro control structure, as shown in Fig. 6. Where ξ represents the boundary point between the macro controller and the microcontroller. When the position error $e > \xi$ um, the macro controller will act; when the position error $e \le \xi$ um, the microcontroller will act.

This kind of control structure with VCM as macro controller and PZT as micro controller was first applied to the positioning mechanism of hard disk read/write, and it is also the most widely used in this field [69]-[72]. In [42], a macro-micro control structure composed of a permanent magnet linear motor (PMLM) and a VCM is also proposed, which can achieve a positioning accuracy of 0.1um in a larger stroke range.

C. Observer

The observer can be used to supplement or replace the sensor in the control system, and can be used to calculate the state or parameter that the sensor is difficult to measure. Observers in VCM can be roughly divided into parameter-oriented observers and disturbance observers (DOB) according to their purposes.

1) Observer Recognizes The Motor Parameters

VCM contain a large number of time-varying and non-linear parameters, which are difficult to measure using traditional methods. Many scholars use observers to calculate these parameters. This part of the content will be explained in more detail in Section IV, the introduction of VCM parameter identification and friction parameter identification.

2) Observer Reduces Disturbance

The basic idea of the disturbance observer is to equate the difference between the actual model and the ideal model output caused by external disturbance and model parameter changes as control input, that is, to observe the equivalent disturbance. And equal compensation is introduced in the control to realize the interference Completely inhibited [73],[74]. The basic structure diagram of the disturbance observer is shown in the Fig. 7 (a). In practice, the order of GP(s) is not 0, and the inverse cannot be realized. At the same time, considering the influence of the measurement noise ξ, the principle block diagram of the disturbance observer is shown in the Fig. 7 (b).

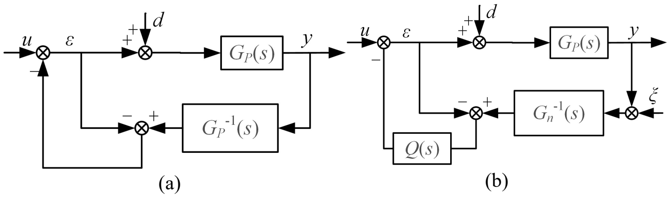

Fig. 7. (a) DOB theoretical structure (b) DOB basic structure.

In VCM, a disturbance observer can be used to estimate and compensate the errors caused by uncertain disturbances and nonlinear parameters [75],[76]; A friction compensation method based on GMS model and DOB is proposed in [77]. DOB compensates the residual friction outside the friction model.

IV. Main Research Difficulties

A. Difficulty of Establishing Accurate Model

For the controlled object, accurate modeling and identification are crucial. The more accurate the model, the easier the feedback controller design. On the other hand, analyzing the complex characteristics of multiple nonlinear factors helps to improve the positioning accuracy of motion control systems, especially in nano-level positioning control systems.

In [78], the accurate mathematical model of VCM is established through time domain and frequency domain analysis, and the friction and nonlinear factors are compensated; A neural network is used to identify the nonlinearity in the VCM online Parameters in [8],[40]; In [79], a fuzzy observer with simple self-learning ability is used to approximate the unknown nonlinearity of the VCM system dynamics online; For the change of VCM resistance, It is also suggested that using the least mean square error algorithm or RROs characteristics is a method to estimate the VCM resistance in [80].

In [23]-[26], an adaptive dynamic sliding mode fuzzy CMAC (ADSFC) system with cerebellum is proposed to realize model free control of network or compensation controller; In [81], an adaptive structure based on dynamic surface control is proposed to deal with the uncertainty of VCM motor parameters.

B. Friction Disturbance

Friction damping is one of the main disturbances of VCM. Because friction is a very complex nonlinear process, it also includes such characteristics as friction lag under changing speed, disengagement force, nonlocal memory characteristics and so on. It brings challenges to friction compensation, especially when the speed crosses zero. The traditional model-based friction compensation is mainly divided into three steps.

1) Friction Disturbance

At present, researches on friction model are mainly divided into two categories: static model and dynamic model. The static model is shown in Fig. 8, which is a combination of Coulomb friction, viscous friction, and Strebeck effect. The dynamic model includes dahl model, Bliman-Sorine model, lugre model [82], leuven model [83], Maxwell-slide (GMS) model [84] et al.

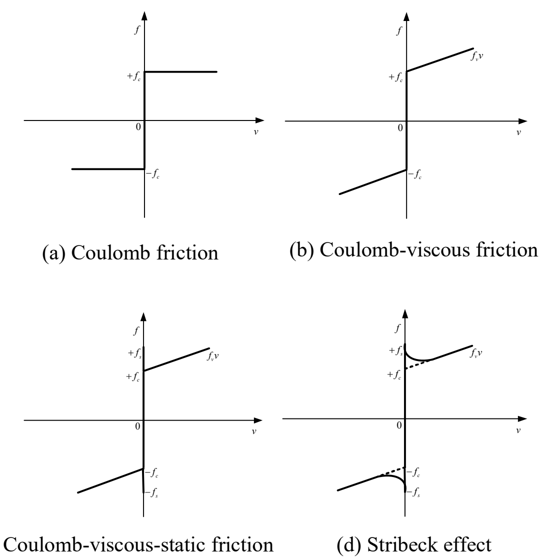

Fig. 8. Static friction model.

2) Identification of Friction Parameters

For the static friction parameter identification method, the applied speed can be given, and the friction model can be obtained through the time domain or frequency domain response of the system[85]-[87]. The parameter identification methods of LuGre model and GMS model are introduced in more detail in [88]. In addition, a method of simulating pivot friction using Prandtl operator is proposed in [89].

At present, the most commonly used model-based friction compensation is feed-forward compensation. The structure diagram is shown in Fig. 9. Feed-forward compensation can usually be divided into the following two types: one is the compensation at the system control signal, and the other is superimposing the motor output a signal on the force, both of which can reduce the influence of friction. When making compensation, some scholars use the desired speed as input, and some scholars use the actual speed of feedback as input.

3) *Compensation of Friction*

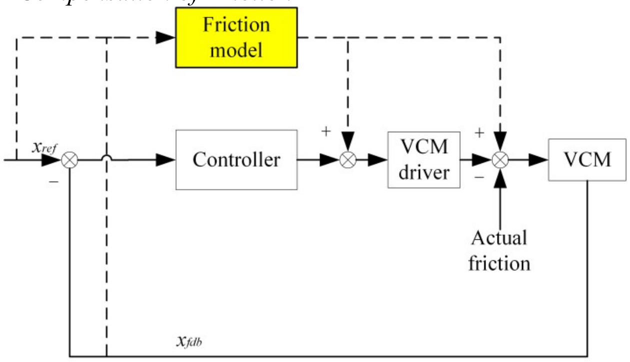

Fig. 9. Structural diagram of friction feedforward compensation.

The above introduction is the friction correction of the fixed model. This method relies on the accuracy of the friction model. During the compensation process, it will be affected by the uneven friction parameters or the changes of the friction parameters of the environment, which will affect the compensation results. An effective method is to use the observer to identify and compensate online, as shown in Fig. 10. For example, in reference [90]-[92], adaptive control is used to adjust some parameters in the friction model. And a method using sinusoidal tracking controller to estimate Coulomb friction, viscous friction, static friction and strebeck effect in VCM is proposed in [93]; In addition, a method of using a disturbance observer outside the model to compensate the residual friction is also proposed in [77].

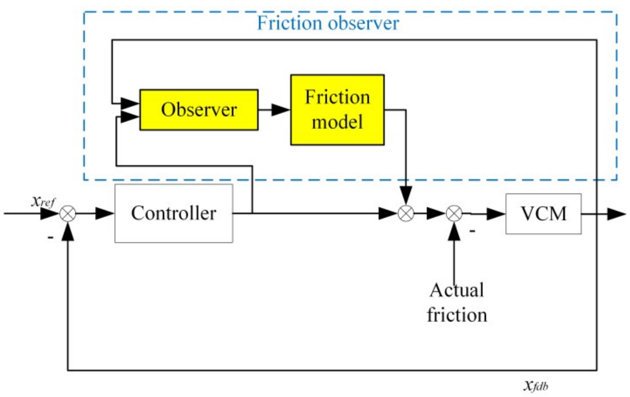

Fig.10. Structure diagram of friction compensation based on observer.

C. *Mechanical Resonance*

VCM are often disturbed by friction damping and airflow damping when they are in motion. At the same time, assembly errors may occur due to process limitations during assembly, that is, spindle eccentricity or deviation of center of mass and force. All of these may cause the VCM to produce mechanical resonance, which seriously affects the positioning accuracy and steady-state performance of the VCM.

Since the vibration frequency of mechanical resonance is relatively fixed and generally higher than the servo bandwidth of the controller, a multi-rate notch filter with band stop function is a simple and effective solution to rescue mechanical resonance [94]. However, notch filters usually result in a decrease in phase margin and robustness. In addition, proper positive speed and positive position feedback can effectively eliminate the first-order and second-order system vibrations [95]. Some scholars measure the vibration of the actuator according to this idea and inject reaction commands to design vibration suppression controllers. For example, in [96], [97], the vibration model is obtained through vibration sensor and modal test respectively, and the vibration is eliminated through positive feedback, the structure is shown in Fig.7(a). In [98], piezoelectric sensors are used to detect vibration, and an active vibration suppression (AVR) method to eliminate vibration is proposed. The structure is shown in Figure 11 (b). In addition, in [99], [100], it is recommended to design a feedforward compensator to compensate for vibration. In order to reduce the influence of uncertain vibration, robust control is also an effective method.

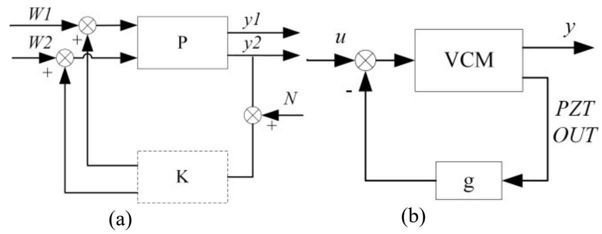

Fig. 11. Structural diagram of vibration compensation controller. (a) Vibration compensation block diagram in [96],[97]. (b) Actuator with AVR in [98].

V. Application of VCM Position Servo System

A. *Camera Focus*

In smart phone camera modules, VCM have advantages over stepper motors and piezoelectric materials. Most cameras use VCM, which control the current of the VCM to achieve the autofocus function of the phone lens. In [9,101,102], Hall sensors are used to detect the position of the mover to achieve closed-loop control of the lens position. Due to the characteristics of mobile phone camera application scenarios, how to improve the robustness of the VCM in the face of external interference is the main research difficulty of the position servo system in this field. An adaptive fuzzy PID control algorithm is proposed in [9], which compensates for the disturbance changes of movable parts, load and gravity changes; In [101], a digital lag lead compensator is used to compensate for vibration and maintain the stability of the camera image.

B. *Hard Disk Drive*

The VCM was first used in the hard disk read/write head positioning system, and it is also the most widely used in this field. At present, the hard disk drive usually uses a macro-micro control system composed of a VCM and a PZT [103]-[105]. The specific control structure is described in Section III. There are many researches on hard disk drives. The main research areas are the suppression and elimination of friction and vibration, the improvement of servo bandwidth [106]-[108], and the design of multi-level controller loops [109].

C. *Multi-axis Precision Motion Stage*

X-Y precision motion stage is the core component of semiconductor device manufacturing and packaging equipment such as photoetching machine, wire bonding machine, PCB drilling and so on. Two VCM respectively controls the positioning of the x and y axes. Based on this idea, many multi-axis motion stages are also designed.

The workbench has extremely high requirements for the speed and accuracy of driving equipment. VCM has the advantages of fast response speed, high accuracy and good Nano positioning linearity[110]. It is widely used in ultra precision positioning systems such as semiconductor manufacturing equipment, high-grade CNC machine tools and optical electron microscopy [111].

In research on the XY working platform, positioning accuracy and tracking performance are the primary goals of the research. In [42], it was proposed to achieve high-precision positioning through a macro-micro control structure composed of a permanent magnet linear motor and a VCM; The fractional order fuzzy PID control structure is adopted in [7], which proves that the controller has good robustness and good tracking performance for high-precision contour; Problem of quadrant burr when the speed crosses zero is solved in [77].

VI. Conclusion

This article summarizes VCM servo control technology based on the position servo system of VCM by researchers from various nations. This article gives a comprehensive introduction to the principles, characteristics and application scenarios of some common position controller structures. The methods for improving the position loop servo based on feedforward control, macro-micro control structure, observer are summarized. At the same time, it introduces the main research difficulties in the process of VCM research, such as the difficulty of establishing accurate models, friction disturbance, and mechanical resonance, and analyzes and discusses the research of related scholars in these fields. Finally, this article introduces common application areas of VCM and summarizes the main problems that need to be solved in each application scenario.

The future development trend of VCM servo system may continue focus on improving positioning accuracy and time, as well as improving anti-interference ability. It is reasonable to expect that as research progresses, the performance of the VCM servo system will increase.

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Yue Qiao received the B.S degrees in electrical engineering from Harbin Institute of Technology, and he is pursing the M.S degree in electrical engineering,Harbin Institute of Technology.

His current research interest is Voice coil motor servo control, friction identification and compensation.

Tianyi Zhao received the B.S and M.S degrees in electrical engineering from Harbin Institute of Technology, and he is pursing the Ph.D degree in electrical engineering.

His current research interest is high precision position control of permanent magnet linear synchronous motor.

Xianguo Gui received the B.S. M.S. and Ph.D. degrees in electrical engineering from Harbin Institute of Technology (HIT), Harbin, China, in 1994, 1996, and 2000, respectively. In 2000, he joined the Department of Electrical Engineering, HIT, as a Lecturer, where he has been an Associate Professor of electrical engineering since 2009. He was a Postdoctoral Fellow with Ryerson University, Toronto, ON, Canada, from 2011 to 2013. He is the author of more than 30 technical papers.

His current major research interests include optimized design of permanent-magnet synchronous motors, control and drives of electrical machines.