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The precise modeling and active disturbance rejection control of voice coil motor in high precision motion control system

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ABSTRACT

In this paper, the improved active disturbance rejection control (ADRC) method is discussed firstly. This method is applied to the high precision positioning table, which is driven by the voice coil motor (VCM). Compared with the conventional ADRC, the proposed ADRC has been improved for its tracking differentiator (TD) is replaced by the reference trajectory optimization (RTO), which is based on 5 order S-shaped curve (FOS). An extended state observer (ESO) of the ADRC can observe disturbances and uncertainties of the system, and cancel them dynamically. Secondly, the hybrid cascaded H-bridge (HCHB) seven-level inverter topology structure is proposed to make sure that the current could possess high power and low ripple at the same time. However, the HCHB inverter has its own drawback that its current flows backwards in it. Therefore, the hybrid frequency carrier-based PWM (HFPWM) modulation method is put forward to solve this problem. Thirdly, the mathematical model of VCM is established accurately, which takes the air damping, eddy current damping and elastic stiffness into consideration. Finally, the experimental and simulation results show that the improved ADRC control method can effectively improve positioning accuracy and robustness; the FOS curve can reduce the impact of shocks and residual vibration; the HCHB inverter resolves the contradiction between high power and low ripple.

1. Introduction

The ultra-precision positioning technology has become a key technology in the precision engineering field. Many other fields are deeply concerned with this technology, such as ultra-precision machining, nanotechnology, IC device manufacturing, and so on. At present, the ultra-precision positioning technology is advancing towards high-precision, high acceleration and large stroke.

From the perspective of actuators, the traditional piezoelectric actuators and magnetostrictive actuators can hardly meet the requirements of ultra-precision positioning technology for their small stroke. The VCM has been widely applied to high-speed and high-precision positioning systems, because it is of simple structure, high speed, high acceleration, fast response and other advantages. It also can resolve the contradiction between the accuracy and large stroke, so it is widely applied to high-precision positioning system, for example, Hard-Disk-Drive (HDD) [1,2], precision machining [3–5], digital cameras [6,7], lithography machine [8].

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From the perspective of high-precision motion control, the VCM is a kind of direct drive servo system, which means that external disturbances and changes act on the system directly. Therefore, the VCM is not easy to control. For this reason, many new control methods come into being. For instance, an adaptive dynamic sliding-mode fuzzy CMAC control method [9,10] is proposed for trajectory tracking control of VCM, a nonlinear model predictive control (NMPC) [11] is put forward to control a single stage VCM of HDD. The disturbance decoupling strategy [12] is used to improve the disturbance rejection and the tracking performance, and a robust backstepping control approach [13] is applied to the stewart platform to solve the active vibration isolation problem. Han puts forward the ADRC method for the first time [14]. This method is based on the error-driven control law rather than the model-based control law, and it could suppress the disturbances effectively. Many problems in high precision motion control field could be solved by the ADRC, including load disturbance resistance speed control [15], motion control with disturbance observers [16] and sensorless control of induction motors [17]. .

From the perspective of the power converter, it can be divided into two kinds: the linear power converter and the PWM power converter. The linear power converter has two obvious advantages: small current ripple and fast response. The disadvantages of it are that it is inefficient, of low efficiency, and only suitable for low-power applications. The conventional PWM power converter is of many merits: the low power consumption, high power and high efficiency. The serious switching interference and large current ripple are its drawbacks. However, the current, in the high-precision motion control, should possess both high power and low ripple. In order to solve this problem, the hybrid multi-level concept [18] is proposed, compared with conventional cascaded H-bridge (CHB) inverter, there are more levels by use of hybrid PWM modulation methods in the hybrid multi-level inverter [19,20].

In a word, in order to solve the problems of the VCM in high speed and high precision motion control system, the improved ADRC strategy is adopted for VCM. To reduce the impact and suppress the residual vibration, the reference trajectory is designed based on the FOS curve. The HCHB seven-level inverter topology structure is proposed to resolve the contradiction between the high-power and low ripple. Finally, the simulation and experimental results are verified.

The structure of this paper is as follows. In Section 2, the mathematical model of the VCM is established. The FOS reference curve is designed in Section 3. In Section 4, the HFPWM modulation method of the HCHB inverter is presented. The modified ADRC positioning control strategy is put forward in Section 4. The simulation and experimental results are verified in Section 5. Finally, the conclusion of the present study is drawn in Section 7.

2. The precise mathematic model of VCM

The mechanical structure of the VCM is shown in Fig. 1, the primary winding of the motor is fixed to the base frame by using two cooling plates, its secondary structure is fixed to the base frame by the springs.

Therefore, the mathematical model of the VCM is MFK type, the dynamics of VCM can be described by,

$$\begin{cases} u = k_e \frac{dx}{dt} + iR + L\frac{di}{dt}, \\ F = m\frac{d^2x}{dt^2} + c\frac{dx}{dt} + kx, \\ F = k_m i, \end{cases} \tag{1}$$

where u, i, x and F are motor voltage, current, position and the developed force, respectively; c is the damping coefficient, k, k_m and k_e are the spring coefficient, the thrust coefficient and the back EMF coefficient, respectively.

The transfer function from the input voltage to the output position is an essential third order, as shown in formula (2),

$$\frac{Lm}{k_m}\frac{d^3x(t)}{dt^3} + \left(\frac{Lc + Rm}{k_m}\right)\frac{d^2x(t)}{dt^2} + \left(\frac{Lk + Rc + k_e k_m}{k_m}\right)\frac{dx(t)}{dt} + \frac{kR}{k_m}x(t) = u(t). \tag{2}$$

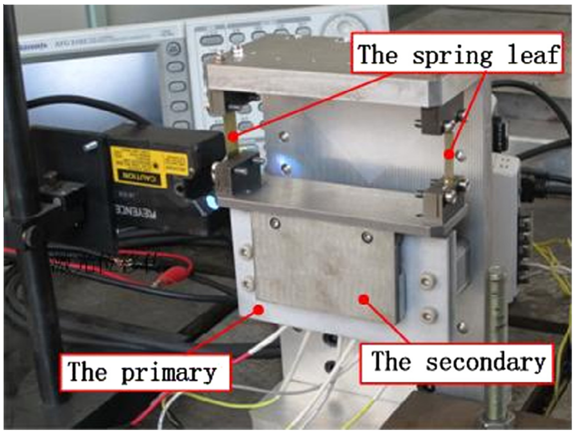

Fig. 1. The prototype of VCM.

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