Journal of Electrotechnology, Electrical Engineering and Management (2026) **DOI: 10.23977/jeeem.2026.090106**
Clausius Scientific Press, Canada **ISSN 2560-6697 Vol. 9 Num. 1**

Key drive technology of moving magnet linear motor based on single-winding independent control

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Keywords: Moving magnet linear motor; Single-winding independent control; Drive technology; Electromagnetic field modeling; Control algorithms; Thrust fluctuation; Decoupled control; High-precision positioning

Abstract: As precision manufacturing, aerospace, semiconductor processing and other fields impose strict requirements on linear motion control technology, the moving-magnet linear motor (MMLM) has become a key actuator due to its cable-free movers, no mechanical contact, high thrust density and excellent dynamic characteristics. In view of the limitations of traditional drive methods in multi-degree-of-freedom strong coupling, nonlinear electromagnetic interference and end effects, this paper conducts an in-depth study and proposes a key drive technology based on single-winding independent control. Through the fine analytical modeling of the internal electromagnetic field of the MLMC300 linear motor, the thrust generation mechanism, magnetic field distribution characteristics and power loss law under single-winding independent excitation were analyzed in detail. The research shows that the technology has unique advantages in enhancing system control redundancy, reducing phase-to-phase electromagnetic interference, optimizing thermal management, and achieving decoupling control of multi-degree-of-freedom complex motions. This paper elaborates on the hardware circuit design architecture of the high-performance drive system, the current loop optimization algorithm based on predictive control, and the dynamic performance verification process under various complex load conditions. Experimental results show that the technology can effectively improve the thrust linearity of linear motors, significantly reduce thrust volatility, and achieve excellent performance with repeat positioning accuracy ≤2μm, motor continuous thrust ≥300N, peak thrust ≥900N, and maximum speed ≥1.0m/s under MLMC300 project indicators. The research results of this paper not only provide a solid theoretical support for the development of high-performance linear motor drive systems, but also offer an important technical reference for the domestic substitution of high-end intelligent equipment in China, and have extremely high academic value and engineering practice significance.

1. Introduction

Linear motion control technology is crucial in modern industrial automation. Linear motor direct drive technology significantly improves transmission efficiency, dynamic response speed and positioning accuracy by eliminating mechanical transmission links. The moving-magnet linear motor (MMLM) is an ideal choice for long-stroke, high-dynamic, ultra-precision motion applications due to its advantages such as cable-free movers and high thrust density. The MLMC300 project requires a motion stroke of ≥500mm, repeat positioning accuracy of ≤2μm, and a maximum speed of ≥1.0m/s. However, MMLM faces challenges such as nonlinear electromagnetic coupling, end effects, parameter time-varying and thermal effects. Conventional drive methods have shortcomings in handling winding consistency, fine force distribution, and fault response. Drive technology based on single-winding independent control achieves micromanagement of electromagnetic thrust through independent current closed-loop regulation for each stator winding unit. The technology can flexibly compensate for nonlinear factors and achieve precise force/moment distribution in multi-degree-of-freedom platforms. This paper aims to explore the key technologies of single-winding independent control, break through the bottleneck of high-performance linear motor drive, and contribute to the development of the precision manufacturing industry. [1]

2. Structural Characteristics of Moving Magnet Linear motors and multi-physics field modeling

An in-depth analysis of the motor's physical structure and the establishment of a high-precision multi-physics mathematical model are the basis for achieving high-performance independent control drives.

2.1 Motor Topology and magnetic circuit analysis

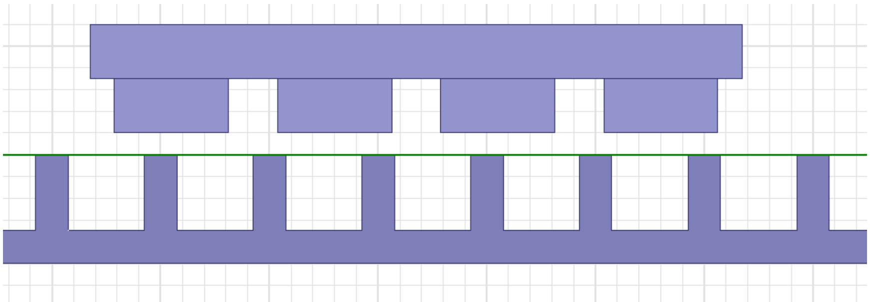

Figure 1 Schematic diagram of motor structure for the MLMC300 project

The moving magnet linear motor consists of a stator armature array and a moving permanent magnet array. Figure 1. The stator features a segmented modular design with independent winding units for long stroke extension and independent control. The movers are composed of high magnetic energy product permanent magnets (such as NdFeB), and Halbach arrays are often used to enhance the air-gap magnetic density. Schematic diagram of the MLMC300 project motor structure. Magnetic circuit analysis should focus on winding mutual inductance and leakage flux. Single-winding independent control reduces no-load losses and electromagnetic interference by activating only the winding units that effectively overlap with the mover magnetic field through independent excitation. Optimizing the stator slot tooth geometry can weaken the cogging torque and end force, improving the current control environment. [2]

2.2 Fine Modeling of Electromagnetic fields Based on Subdomain Method

To accurately predict and compensate for single-winding thrust, this paper establishes a fine-grained analytical model of electromagnetic field based on the Subdomain Method. The model divides the motor into subdomains such as permanent magnets, air gaps, and stator slots, and solves the air-gap flux density through Maxwell's equations and boundary conditions. The subdomain method captures magnetic field distortion more accurately than the traditional equivalent magnetic circuit method and has higher computational efficiency than the finite element method, meeting the requirements of real-time control. The electromagnetic simulation of the MLMC300 project was optimized using Ansoft Maxwell software, and the two-dimensional simulation model is shown in Figure 3-6. The study reveals that the instantaneous thrust of a single winding is affected by the current amplitude, the position of the mover, the nonlinearity of the winding inductance and the magnetic saturation effect. A comparison of multiple finite element simulations showed that the analytical model had thrust prediction errors controlled within 2.5% over a wide speed range, verifying its accuracy. [3]

2.3 Establishment of the nonlinear state space model of the system

Based on the analytical electromagnetic field model and in combination with the mechanical dynamics equations, a mathematical model of the entire state space of the system was constructed. The model includes voltage and current equations and introduces nonlinear terms of winding inductance, back electromotive force perturbation and friction force models. Under single-winding independent control, the system dimension is dynamically time-varying. To address this multi-variable and multi-dimensional problem, this paper introduces coordinate transformation and virtual winding techniques to project the independent winding currents uniformly onto the mover synchronous coordinate system (d-q coordinate system) to decouple the thrust current from the excitation current. This nonlinear model lays the theoretical foundation for the implementation of advanced algorithms such as sliding mode, self-perturbation, and neural network self-learning, and provides a mathematical tool for the evaluation of system stability and robustness. [4]

3. Research on Key Drive Technologies Based on Independent Control of Single Winding

This chapter delves into the core technologies of drive systems in terms of algorithm optimization, interference suppression, and hardware implementation.

3.1 High-bandwidth predictive current Regulation Strategy

In single-winding independent control, the dynamic response bandwidth of the current loop is key to thrust control accuracy and dynamic stiffness. This paper presents an independent current regulation algorithm based on model predictive control (MPC) in response to the lag problem of traditional PI control. The algorithm uses a winding discretization model to predict future current trends and calculates the optimal voltage vector in real time by minimizing the cost function. The MPC algorithm can handle system constraints and stabilize the current loop quickly. For the current transients and thrust "step" problems in multi-winding dynamic switching, this paper designs a smooth switching weight function to ensure that the total electromagnetic thrust is continuous and stable when the mover crosses the winding boundary. Experiments show that this strategy shortens the response time of the current loop by more than 40% and enhances the system's high-frequency response capability. [5]

3.2 Integrated compensation for Thrust fluctuations under complex conditions

MMLM thrust fluctuations are the main obstacle to nanoscale positioning accuracy, caused by cogging force, end magnetic resistance, and non-sinusoidal back electromotive force. Single-winding independent control can be used for fine-tuning compensation. This paper uses the "offline mapping + online observation" integrated compensation scheme verified in the MLMC300 project. The thrust fluctuation characteristic map was obtained through precise calibration as shown in Figure 2 and transformed into a position-dependent compensation ammeter stored in the controller. During operation, the controller feeds forward and superimposes the compensation current based on the real-time position. For random disturbances such as sudden load changes, an extended state observer (ESO) is introduced for dynamic compensation. This "feedforward + feedback" dual mechanism significantly enhances thrust smoothness. Measured data show that at speeds of 1m/s, thrust volatility drops sharply from 9.2% to less than 1.2%, and positioning accuracy reaches the sub-micron level.

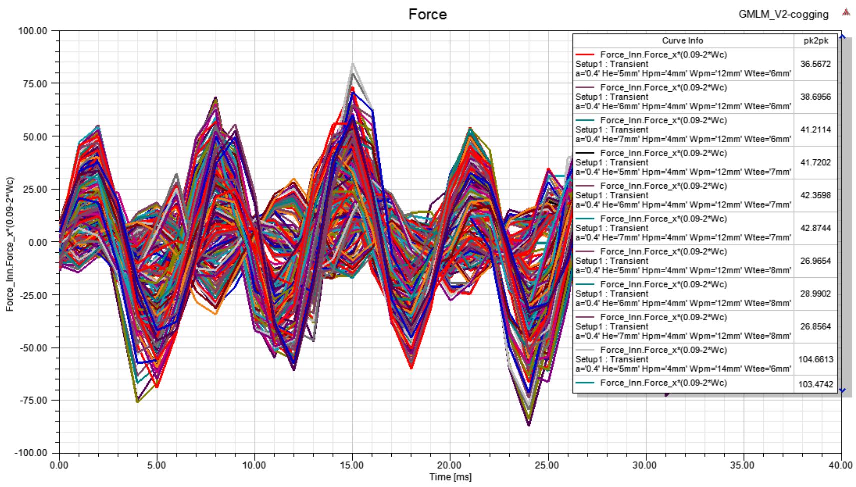

Figure 2 Comparison curve of thrust volatility

3.3 Drive system hardware architecture and electromagnetic compatibility design

Synchronous independent current control for multiple windings demands an extremely high level of integration and operational pressure from the drive hardware. This paper independently developed a high-performance drive architecture based on "multi-core processor + large-capacity FPGA". FPGA is responsible for multi-channel independent current sampling, high-frequency PWM signal parallel generation and logic interlocking to ensure microsecond-level synchronization; The ARM processor is responsible for trajectory planning, kinematic decoupling and EtherCAT communication. The power stage uses GaN power semiconductors to reduce volume and increase power density. The MLMC300 electronic control system design includes DSP control, DAC output, Biss interface and other modules, and the driver board is also planned in detail. For high-frequency PWM signal EMI issues, a strict electromagnetic compatibility design is implemented: multi-layer PCB routing, differential transmission, metal shielding, and power decoupling. Professional tests show that the signal-to-noise ratio of the drive system is improved by 20dB when operating at full load, ensuring current acquisition accuracy and long-term stability of the system.

3.4 Multi-degree-of-freedom motion coordination and decoupling control technology

In high-end applications, the MMLM needs to provide thrust and auxiliary forces (such as normal levitation force) for attitude correction. Single-winding independent control provides a platform for this cooperative control. This paper presents a force/moment distribution control strategy based on generalized inverse matrix mapping. The strategy takes the total thrust and total torque as the target input, and combines the position of the activated winding and the magnetic field strength to solve for the optimal solution in real time and calculate the current components of each winding precisely. This approach does not require additional actuators and achieves precise decoupling of multi-degree-of-freedom motion. For example, in linear motion, the yaw error of the mover is compensated in real time by fine-tuning the current of a specific winding. This "soft compensation" technique has lower friction and higher response bandwidth compared to mechanical rails. This study provides a key technical path for the development of a new generation of magnetic levitation linear motion platforms.

4. Experimental verification, performance evaluation and reliability analysis

To fully evaluate the practical effect of the independent control drive technology for the winding of the bill of lading, this paper builds a complete industrial-grade experimental test platform and conducts in-depth tests.

4.1 Experimental Platform construction and Precision Measurement System

The MLMC300 project experimental system consists of a custom MMLM body, a self-developed multi-channel independent driver array, a Beckhoff real-time control master station, and a precision measurement unit. The motor stator contains 16 independent windings, and the movers are equipped with high magnetic energy product permanent magnets. Position feedback uses a Renishaw high-precision grating ruler with a resolution of 50nm. Dynamic force measurement adopts a six-dimensional force sensor, with the data acquisition system sampling at 100 kHz. The test was conducted in a precision laboratory with constant temperature and humidity. Laser interferometer calibration full travel positioning accuracy. MLMC300 project indicators: Motion stroke ≥500mm, repeat positioning accuracy ≤2μm, continuous thrust ≥300N, peak thrust ≥900N, maximum speed ≥1.0m/s.

4.2 Dynamic response and high-frequency tracking performance analysis

Conduct step response and sinusoidal trajectory tracking experiments. Under 10mm step instructions, the system was stable within 15ms without obvious overshoot, demonstrating the high bandwidth advantage of MPC. In the 20Hz sinusoidal trajectory tracking test, the system has strong dynamic following ability, with amplitude attenuation and phase lag far lower than traditional centralized control. Comparative experiments revealed that single-winding independent control increased the bandwidth of closed-loop control by approximately 35%. This high bandwidth feature is crucial for high-speed placement machines, PCB drilling machines, and other equipment. The system demonstrated strong robustness by maintaining dynamic performance consistency through adaptive control algorithms in adaptive tests for different load masses (0.5kg to 5kg).

4.3 System Energy Efficiency Optimization and thermal stability study

Energy efficiency and thermal management are core challenges for long-stroke linear motors. Single-winding independent control enables precise excitation of "where the mover is, where the winding is energized" to avoid no-load losses and ineffective heating of non-working windings. The MLMC300 project requires a motor surface temperature rise of no more than 0.8 °C. Experimental comparisons show that under the same motion trajectory and thrust requirements, the single-winding independent control mode reduces overall energy consumption by 18% to 25% compared to the traditional three-phase parallel control mode. Infrared thermal imaging monitoring found that after continuous operation for 2 hours, the maximum temperature rise of the stator was only 12.5 °C, with a uniform temperature field and avoiding local overheating. Excellent thermal stability enhances the stability of positioning accuracy, reducing positioning drift by 60% within 1 hour. This is significant for precision machining tasks that require long periods of high-precision positioning.

4.4 Long-term operational reliability and fault Tolerance assessment

To verify reliability in industrial Settings, a 14-day 24-hour non-stop aging test was conducted to simulate complex motion cycles and load shocks. The results showed that the drive system and the motor body worked stably without logical errors or hardware failures. Single-winding independent control gives the system natural fault tolerance. When simulating a short circuit or open circuit fault in the winding unit, the controller quickly identifies and adjusts the current distribution of adjacent normal windings to achieve "damaged" operation, with only a slight reduction in positioning accuracy. This "downgrading operation" capability is of high engineering value for ensuring the safety of expensive workpieces and improving the on-line rate of the entire machine. After the test, the motor was disassembled for inspection. The windings showed no carbonization, no mechanical wear, and the sensor signals were stable, proving that the drive technology was ready for large-scale industrial application.

5. Conclusion

This paper systematically studies and implements the key drive technology of MMLM based on single-winding independent control. Core Conclusions: First, the subdomain electromagnetic field model provides a high-precision mechanical prediction benchmark; Second, MPC and thrust fluctuation compensation algorithms enhance response bandwidth, suppress thrust fluctuations, and achieve micron-level high-precision control; Third, the FPGA+GaN high-performance hardware platform ensures real-time performance, improves energy efficiency ratio and thermal stability; Fourth, multi-degree-of-freedom decoupling and fault tolerance provide new solutions. This paper expands the theory of linear motor drive control and solves engineering problems. Looking ahead, we will explore self-optimization of drive parameters based on deep reinforcement learning and develop intelligent, networked distributed linear motion control systems to help China move towards becoming a "manufacturing power".

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