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# Fractional Order Sliding Mode Control of Linear Motor for Wood Cutting CNC Machine Tools Based on Particle Swarm Optimization

**Lei Yang[1] , Chuansheng Tang[2*]**
[1]School of Information Engineering, Nanyang Institute of Technology, Nanyang, Henan, China
[2]School of Intelligent manufacturing, Nanyang Institute of Technology, Nanyang, Henan, China
*Corresponding Author.

***Abstract:***

In order to improve the control performance of the system and solve the problem of the lack of single control method of linear motor in wood cutting CNC machine tools, this paper combines fractional PID algorithm with sliding mode variable structure algorithm. In order to avoid the complexity and uncertainty of the parameters manually, particle swarm optimization is used to optimize the parameters of the sliding mode variable structure algorithm. In this paper, the sliding mode variable structure controller of fractional PID is optimized and improved to improve its control accuracy. This paper applies the new algorithm to the single-phase full bridge inverter of linear motor in wood cutting CNC machine tool. The simulation results are compared with the fractional PID sliding mode variable structure control function (PID SMC) and the sliding mode variable structure control (SMC) method. The results show that the particle swarm optimization algorithm can find the optimal solution in a short time because of its fast convergence rate. The static error of the algorithm is small and the rising speed is fast. The method makes the linear motor control system of CNC machine tool have strong ability of buffeting and strong robustness.

***Keywords**: Control performance, wood cutting, CNC machine tools, linear motor, particle swarm optimization.*

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## I. INTRODUCTION

Machine tool industry is the basic industry of equipment manufacturing industry. Numerical control machine tool has attracted worldwide attention for its excellent flexible automation performance, excellent and stable precision, agile and diversified functions. It has created a precedent for mechanical products to develop into mechatronics. Therefore, numerical control technology has become a core technology in advanced manufacturing technology [1-2]. With the development of advanced manufacturing technologies such as ultra-high speed cutting and ultra precision machining, higher and higher requirements are put forward for the performance indexes of machine tools, and higher requirements are also put forward for the servo performance of machine tool feed system: high driving thrust, fast feed speed and high fast positioning accuracy [3]. High speed, high acceleration and high precision are the requirements and development trend of modern CNC servo drive. Although the performance of the world's advanced AC / DC servo (rotary motor) system has been greatly improved, due to the limitation of the traditional mechanical structure (i.e. rotary motor + ball screw) feed transmission mode, it is difficult to make a breakthrough in the improvement of its servo performance index (especially the fast response). As a kind of transmission device which directly converts electric energy into linear motion mechanical energy without any intermediate conversion mechanism, linear motor has obvious advantages in speed and precision compared with traditional transmission mode. Therefore, linear motor plays an important role in modern manufacturing equipment [4-5].

Linear motor direct drive system has been applied in the world manufacturing equipment industry, and its prospect is attractive. In addition, the linear motor direct drive system has been applied in automation equipment, information engineering, instrumentation, aerospace, medical equipment, etc. However, there are many problems to be solved in the application of the linear motor direct drive system [6]. For example, because the linear motor drive system is driven by the linear motor directly, the system does not have any intermediate buffer process, the influence of uncertain factors such as parameter perturbation and load disturbance will be directly reflected in the motion control of the linear motor. As a result, the difficulty of control is increased. There are also problems such as forced cooling system, braking system, so-called heating problem, normal magnetic attraction problem, magnetic separation problem, edge effect problem, etc. when linear motor is applied to machine tool, heating problem and normal magnetic attraction problem are key technical problems, which seriously affect the machining accuracy of machine tool and produce various errors. Therefore, how to improve the thermal performance and structural performance of the machine tool, reduce the deformation of the machine tool, and then improve the machining accuracy, has become one of the most important topics in the machine tool design and performance analysis [7-9].

## II. RESEARCH ON NORMAL FORCE OF PERMANENT MAGNET LINEAR SYNCHRONOUS MOTOR FEED SYSTEM

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2.1 Causes of normal force of permanent magnet linear synchronous motor

The secondary material of permanent magnet linear synchronous motor is rare earth permanent magnet. It can keep its magnetism for a long time, and has strong magnetization effect on the surrounding ferromagnetic materials. It can absorb 400-500 times of the weight of white body. Therefore, its magnetic force is very large. As shown in Figure 1, the permanent magnet linear synchronous motor not only generates an electromagnetic thrust parallel to the direction of linear motion, but also generates a normal magnetic suction perpendicular to the direction of linear motion. In fact, there is normal force in the commonly used rotating motor, but because the geometric structure of the rotating motor is symmetrical, its normal force is not shown. In the permanent magnet linear synchronous motor, because of its asymmetric mechanism, the normal force is particularly obvious, its value is about 2-5 times of the thrust. The larger normal magnetic suction will cause the deformation of the machine tool structure and affect the machining accuracy of the machine tool [10].

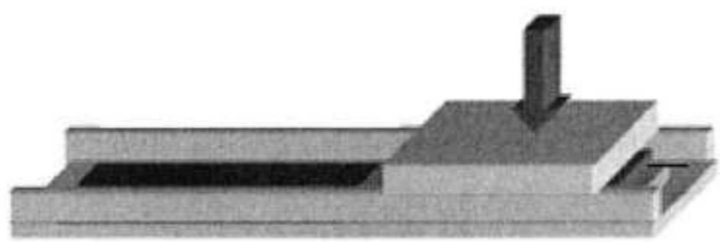

Fig 1: Schematic diagram of normal magnetic suction

When permanent magnet linear synchronous motor (PMLSM) is applied to machine tools, the normal force generated by PMLSM can be divided into two categories: one is the normal force between the permanent magnet and the primary motor, the other is the normal force between the permanent magnet and the machine tool bed. The first kind of normal force can be divided into the normal force between the permanent magnet and the traveling magnetic field of the motor and the normal force of the permanent magnet on the primary core.

2.2 Finite element simulation analysis of feed system structure deformation caused by normal force

Structural analysis is one of the most common application fields of finite element method, in which static analysis is used to solve the displacement and stress of structure under static load. This paper takes linear motor feed system as the research object, and uses ANSYS structure analysis module to study the influence of normal force between the first and the stages on the structural deformation of the feed system. The finite element analysis flow of the feed system is shown in Figure 2.

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The linear motor feeding system studied in this paper adopts the structure of long primary and short secondary, and the one-way stroke of the worktable is 100 mm. The secondary is fixed on the base, and the primary is connected with the worktable for high-speed reciprocating motion. The grating ruler is fixed on the side of the worktable and moves with the worktable, and its reading head is fixed on the base to realize feedback. Because of the complex structure of linear feed system, it is composed of many parts. Compared with the professional 3D drawing software, the geometric modeling function of ANSYS is relatively weak, and SolidWorks is an efficient 3D mechanical design work, with strong solid modeling function, and the model generated by SolidWorks can realize data sharing and exchange with ANSYS software. Therefore, firstly, the model is built in SolidWorks, and then the model is imported into ANSYS software for finite element analysis.

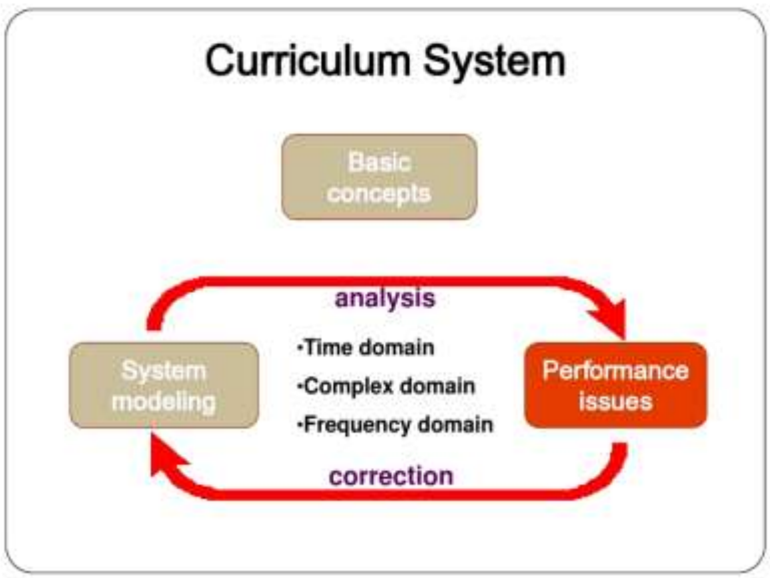


Fig 2: Finite element analysis process of linear motor feed system

2.3 Experimental device for positioning accuracy and repeated positioning accuracy of feed system

Dual-spectrum laser interferometer is a measuring device used in international machine tool standards to check and accept the positioning accuracy of CNC machine tools. Its basic principle is interference technology. Interferometric technique is a measuring method with distance accuracy equal to or higher than lppm. This technique is based on the fact that the beam is a wave, and its wavelength is precisely known. The wavelength range of visible light varies from 0.45 μm to 0.70 μm, while the wavelength of experimental laser interferometer is 0.633μm, and its long-term wavelength stability (in vacuum) is higher than 0.05ppm. The

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principle of measurement technology is to combine two coherent light waveforms to be coherent (or cause mutual interference), and the synthesized result is the phase difference between the two waveforms, which can be used to determine the change of optical path difference between two light waves. The structure of fractional order sliding mode controller is shown in Figure 3..

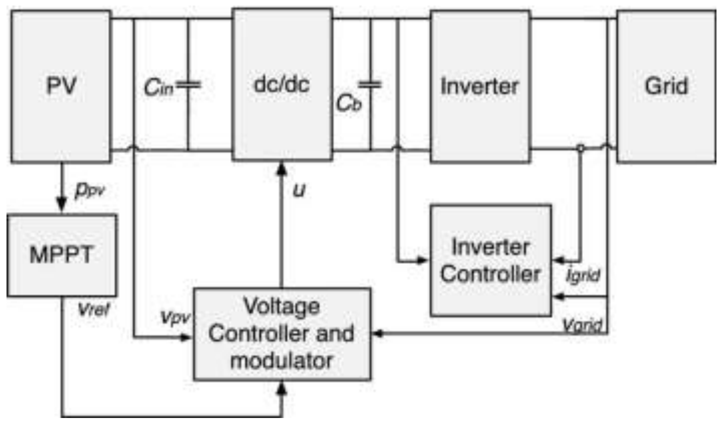


Fig 3: The structure of fractional order sliding mode controller

Therefore, with the change of the optical path difference of two beams, the phase difference of the two coherent waveforms will change accordingly. Then the intensity of the light wave superimposed after interference (which can be reflected by amplitude) will show the periodic change law accordingly, which is the basic principle of interference measurement. The laser interferometer produces a stable coherent laser beam, which is divided into two beams. After the two beams are reflected back, an interference beam is formed through the spectroscope. The intensity change of the beam is the basis of the laser interferometer detection data. Specifically, if the optical path difference of the two beams is constant, the signal strength obtained by the detector is stable, and it is stable at a certain value between the strongest signal of the long interference and the weakest signal of the interference cancellation. If the optical path difference of the two beams changes, the interference light will change continuously between the long interference and the cancellation interference. When the optical path difference of the two beams is one wavelength, the signal intensity of the detector will change, and the change (interference fringes) will be recorded, so the change of the optical path difference can be calculated.

## III. RESEARCH ON THERMAL CHARACTERISTICS OF PERMANENT MAGNET LINEAR SYNCHRONOUS MOTOR FEED SYSTEM

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3.1 Heating analysis of permanent magnet linear synchronous motor feed system

Permanent magnet linear synchronous motor (PMLSM) can convert electric energy into mechanical energy of linear motion. Because the energy efficiency can not reach 100%, it will inevitably produce a lot of energy loss. In the end, most of these losses are converted into heat, which increases the temperature of each part of the feed system. The loss of linear motor is divided into winding loss, core loss and stray loss. When the permanent magnet linear synchronous motor is running, because of the copper loss and iron loss, the coil will heat, and its temperature will exceed 100℃. Because of its simple structure, the heat dissipation effect of the permanent magnet linear synchronous motor is relatively good. However, when it is applied to CNC machine tools, it is usually installed inside the machine tools, resulting in heat dissipation difficulties. A lot of heat is generated between the linear guide rail and the sliding block which support the motion of the linear motor mover because of the friction.

Permanent magnet synchronous motor (PMSM) can convert electric energy into mechanical energy in linear motion. Because the efficiency of energy conversion cannot reach 100%, it will inevitably produce a lot of energy losses, and most of these losses will eventually be converted into heat, which will increase the temperature of each part of the feed system. The main mechanical structure of permanent magnet linear synchronous motor mainly includes the following four parts: winding coil, silicon steel lamination (core), magnetic steel and soft iron base plate. Among them, silicon steel and winding are the primary motor, and magnetic plate and soft iron base plate are the secondary motor. From this we know that there are three main parts of motor loss: (1) core loss, which mainly includes basic iron loss and additional iron loss; (2) Winding loss mainly refers to the copper loss of the primary winding; (3) Stray losses mainly include mechanical losses such as friction losses and some additional losses.

(1) Core loss

The basic iron loss is generated by the main magnetic field alternating in the core, including the hysteresis loss and eddy current loss in the core. The core has hysteresis eddy current effect, the loss caused by hysteresis effect is hysteresis loss, and the loss caused by induced current in conductor by alternating magnetic field is eddy current loss. Both of them occur in the core at the same time, so it is not necessary to calculate them separately.

(2) Winding loss

Winding loss refers to the loss of current in conductor, which includes basic copper loss and additional loss. The basic copper loss is caused by the existence of winding resistance, which is the main heat source of permanent magnet linear synchronous motor.

(3) Stray loss

Stray loss is also called mechanical loss, including friction loss of linear guide rail, wind friction loss, friction loss between grating ruler and moving ruler, and loss caused by vibration of feeding system. In most cases, these losses are difficult to calculate accurately. Therefore, in general, it is based on the linear motor test data to approximate calculation, or estimate the mechanical loss of the designed linear motor. By optimizing the structure of the feed system, adding lubricating oil and reducing vibration, the mechanical loss of the feed system is very small, and its influence on the heating of the feed system is also very small. In order to simplify the calculation, the mechanical loss of the feed system can be ignored.

From the above analysis, except for copper loss, other losses of linear motor are much smaller than that of rotary motor, which can be ignored in the analysis of total loss. Therefore, the loss of linear motor mainly comes from copper loss, which is the main reason of linear motor heating. For high thrust permanent magnet linear synchronous motor, copper consumption can reach several thousand watts. Under the condition of natural cooling, the motor can not work normally, so water cooling must be used to ensure the stable operation of the motor. At present, many commercial linear motors adopt water cooling technology, which is much more efficient than natural cooling and gas cooling, and can greatly reduce the heating of the motor.

3.2 The basic theory of thermal characteristics analysis of the feed system of PMSM

Thermal convection refers to the heat transfer process caused by the relative displacement between the parts of the fluid caused by the macroscopic movement of the fluid and the mixing of cold and hot fluids. Heat convection can only occur in the fluid, and because the molecules in the fluid are in irregular thermal motion at the same time, when there is a temperature difference in the fluid, heat conduction must occur, so in practice, heat convection and heat conduction are often accompanied. Permanent magnet linear synchronous motor (PMLSM) dissipates heat mainly through heat conduction and heat convection, and radiation heat transfer only accounts for a small part, which can be ignored. The main heat source of the feed system, the winding coil, is located in the interior of the linear motor. In addition, a small amount of heat is produced by the core. Part of the heat generated by the winding and core is transferred to the air gap surface, the front and rear surfaces of the motor, and the left and right surfaces of the motor through heat conduction, and then dissipated to the surrounding air through convection heat transfer. Part of the heat generated by the winding and core is transferred to the upper surface of the motor through heat conduction, and then to the bottom plate of the motor through heat conduction, and finally to the surrounding air from the outer surface of the bottom plate of the motor through convective heat transfer.

Temperature field refers to the temperature distribution of each point in an instantaneous object, which can be generally expressed as a function of space coordinates and time. In

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Cartesian coordinates, it has the following form.

$$t = f\left(x, y, z, \tau\right) \quad (1)$$

If the temperature of each point in the object does not change with time, it is called the steady-state temperature field. If the temperature of each point in the object changes with time, it is called the unsteady temperature field or transient temperature field.

Fourier's law can be expressed as: at any time: the local heat flux at any position in the isotropic continuous medium is numerically proportional to the temperature gradient at that point, and the direction is opposite. The mathematical expression of vector is as follows:

$$q = -\lambda \frac{\partial t}{\partial n} n \quad (2)$$

Where: the negative sign indicates that the heat transfer direction is opposite to the positive direction of the temperature gradient. The proportional coefficient is the thermal conductivity, W / (m · k). Thermal conductivity is a basic macroscopic physical property of all materials, which represents the thermal conductivity of materials. According to the formula, its physical meaning is the value of heat flux generated by the object under the unit temperature gradient.

The thermal conductivity is closely related to the properties of materials. Even for the same material, the thermal conductivity is also related to the structure, density, pressure, humidity and temperature of the material. The thermal conductivity of most materials changes regularly in a large temperature range

$$\lambda = \lambda_0\left(1 + bt\right) \quad (3)$$

Where $\lambda_0$ is the thermal conductivity at 0 ℃;

t is temperature, unit: ℃;

b is a constant, which is determined by experiment.

## IV. RESEARCH ON PERFORMANCE OPTIMIZATION OF HIGH SPEED VERTICAL MACHINING CENTER

Because the structure of the linear motor feed system is similar to that of the linear motor single drive system in the x-axis direction of the high-speed vertical machining center, the finite element model of the linear motor feed system is established in the first two chapters, and the normal force analysis and thermal analysis of the linear motor feed system are completed by using ANSYS. Finally, the thermal structure disaster analysis and design experiment are carried out to verify the correctness of the simulation model, and the validity of the modeling method is explained. It can be used in the linear motor single drive system in the x-axis direction of high-speed vertical machining center, as shown in Figure 4.

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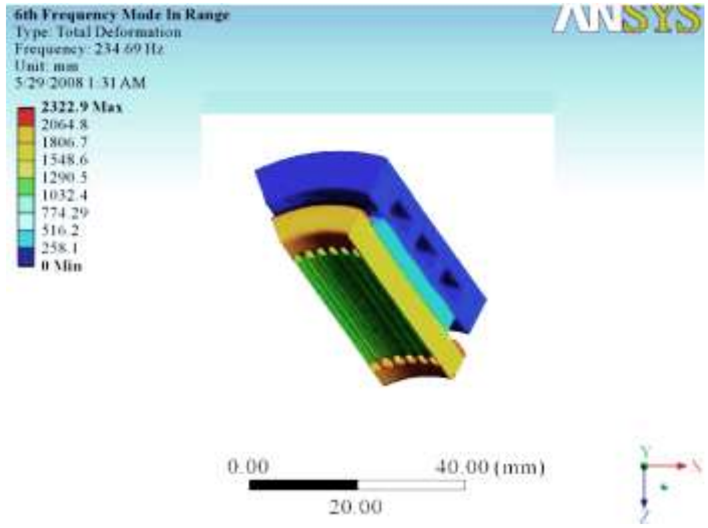


Fig 4: X-axis of high speed vertical machining center

The design of machine tool has developed from the original common function design to the modern advanced machine tool design technology, such as stiffness design, precision design, high-speed design, error compensation technology, life design and reliability design. In order to ensure the rationality of the structural design of the machine tool, the finite element analysis of the vertical machining center is carried out in the previous section of this paper. Therefore, finding out the weak link of the structure and improving it will play a good guiding role in the overall performance optimization and high rigidity design of the machine tool.

From the simulation nephogram of the vertical machining center's structural deformation under the action of thermal load and normal force completed in the previous section, it can be seen that the largest part of the deformation of the vertical machining center's vertical sliding plate occurs in the middle, and the amount of deformation gradually decreases from the middle to both sides. In order to further explore the internal deformation distribution of the vertical machining center, the cross beam and vertical sliding plate are cut open, and the sectional view is obtained. The beam and vertical sliding plate of vertical machining center are thin-walled structures. When the temperature gradient is large due to the heating of linear motor, they are easy to expand and extend when heated, and they will produce bending deformation under normal force.

Because the vertical slide plate is directly connected with the headstock of the high-speed vertical machining center, it directly affects the position of the tool tip, and then affects the machining accuracy of the high-speed vertical machining center. Therefore, the structural deformation of vertical sliding plate is the focus of this paper.

In the analysis, we must consider the strength requirements of the vertical sliding plate. When the stress of the vertical sliding plate exceeds the allowable stress of the vertical sliding plate, the vertical sliding plate is easy to be damaged. When the vertical sliding plate is in the process of loading for a long time, it will produce large bending stress and large deformation. When it exceeds the yield limit of the vertical sliding plate, it will produce deformation instability and strength failure. At the same time, there are a lot of rib plate links in the vertical sliding plate, the structure is complex, there will be stress in the link process, so it is necessary to analyze the equivalent stress of the opposite sliding plate. Therefore, the von Mises stress used in the finite analysis meets the von Mises yield criterion, and the equivalent stress of the opposite slide plate is analyzed.

The vertical slide plate is an important component of the machining center, which supports the spindle box. The white body also feeds through the column, which directly affects the working performance of the whole machine. In this way, the dynamic and static characteristics of the vertical slide plate of the machining center, especially the static stiffness analysis, are analyzed. Static stiffness is a special case of dynamic stiffness, and improving static stiffness is equivalent to improving dynamic stiffness. The static stiffness of the vertical sliding plate is closely related to the deformation of the vertical sliding plate, so the static analysis must be carried out to obtain the total deformation of the vertical sliding plate, reduce the stress concentration and improve the structural stiffness.

To sum up, the structure design of vertical slide plate is the weak link of vertical machining center. In this paper, by changing the structure of vertical slide plate, the stiffness of vertical slide plate is improved, and then the performance of vertical machining center is improved.

## V. CONCLUSION

When linear motor is applied to CNC machine tools, heating and normal magnetic force are the key technical problems. These two factors seriously affect the machining accuracy of the machine tools, resulting in a variety of errors. In this paper, the thermal and structural performance of linear motor drive system are studied by the method of combining finite element simulation and experiment. The structure optimization design of the high-speed vertical machining center driven by linear motor is proposed.

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