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Static and Dynamic Characteristic Simulation of Feed System Driven by Linear Motor in High Speed Computer Numerical Control Lathe

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Abstract

In order to design the feed system of high speed Computer Numerical Control (CNC) lathe, the static and dynamic characteristics of feed system driven by linear motor in high speed CNC lathe were analyzed. The slide board was taking as the main moving part of the feed system, and the guide rail was the main support component of the linear motor feed system. The mechanical structure static stiffness of feed system is researched through the slide board statics analysis. The simulation results show that the maximum deformation of the slide board occurs in the middle of the slide board where the linear motor is placed. The linear motor feed system control model was established based on analysis of high-speed linear feed system control principle, and the linear motor feed system transfer function was established, and servo dynamic stiffness factors were analyzed. The control parameters of the servo system and actuating mechanism parameters of feed system on the effect of the linear motor servo dynamic stiffness were analyzed using MATLAB software. The simulation results show that the position loop proportional gain, speed loop proportional gain and speed loop integral response time are the biggest influence factors on servo dynamic stiffness. The displacement response is reduced under the cutting interference force step inputting, the servo dynamic stiffness is increased, the number of system oscillation is also reduced, and the system tends to be stable.

***Keywords**: Linear motor feed system; High speed Computer Numerical Control (CNC) lathe; Static characteristics simulation; Dynamic characteristics simulation*

1. Introduction

High speed CNC lathe feed system not only has the advantages of high speed, high feed acceleration and deceleration, but also has the requirements of high response, high precision and high stability [1]. Using the linear motor driving feed method can minimize inertia of the feed drive system and the quality of moving components, and can improve the motor drive force, realize linear feed of the worktable without intermediate transmission device, and can meet the rapid feed requirements of high-speed CNC lathe, improve the dynamic response, the positioning accuracy and stability [2].

The stiffness and positioning accuracy of feed system greatly affect the machining accuracy of machine tool, There are many relevant literatures on the subject. Reference [3] described a method for stabilizing feed drive systems by introducing virtual friction characteristics having higher vibration damping with a friction compensator. The friction compensator corrects the decrease in stability of control systems. And the control design method increases the stability of control systems and enables servo gains leading to desirable overshoot-free responses by specifying the natural frequency of the position control system. Reference [4] proposed a systematic design methodology for the mechatronic system composed of mechanical and control subsystems to design high-speed and high-precision feed drive systems. In addition to the strict modeling of subsystems, an accurate identification process of the mechanical subsystem has been conducted. Parametric studies and circular motion experiments on the x-y table are performed in order to investigate interactions between

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mechanical and controlsubsystems, as well as the influence of the interactions on system performance. From the circular motion experiments, it is confirmed that limitations of system performance depend on characteristics of both mechan-ical and control subsystems. Reference [5] proposed a synchronous control scheme for a linear servo system applied to the vertical axis drive of a die-sinking electric discharge machine (EDM) tool. The investigated vertical axis drive is constructed with dual parallel linear motors, which are arranged to jointly drive the feed axis for improvement of the overall thrust and structural stiffness. The effective control scheme named the ‘‘position/thrust hybrid synchronous control’’ is applied to the EDM to achieve high-speed, accurate machining, and the experimental results show that the synchronization error between the two parallel motors and the positioning accuracy are both satisfactory when operated under high-speed conditions.

The feed system of high speed CNC Lathe consists of servo driving, servo components, mechanical transmission device and executive component. The static and dynamic characteristics of feed system driven by linear motor in high speed CNC lathe greatly affect the machining accuracy of machine tool. The slide board is the main moving part of the feed system, and the guide rail is the main support component of the linear motor feed system. The mechanical structure static stiffness of feed system is researched through the slide board statics analysis. MATLAB software has excellent calculation function and visual modeling and multiple control toolbox [6, 7], so the control parameters of the servo system and actuating mechanism parameters of feed system on the effect of the linear motor servo dynamic stiffness were analyzed using MATLAB software.

2. Composition of Linear Motor Feed System in High Speed CNC Lathe

High-speed CNC lathes have the fundamental characteristics of the high-speed spindle rotary motion and high-speed axial feed movement, which is different from the common lathes [1, 8].The linear motor direct-drive feeding system was adopted to obtain higher feed deceleration and acceleration, reduce the inertia of the feed drive system, decrease the mass of the moving parts and improve the feed driving force of the motor. The components of the feed system driven by linear motor are shown in Figure 1. The linear motor primary and secondary are directly installed in the feed unit of working table and bed to achieve the linear feed, without the intermediate transmission converting devices, that is called "zero gap transmission", avoiding the low rigid, large inertia, low transmission efficiency, incompact structure and nonlinear shortcomings of the traditional rotary motor and ball screw driving method [2, 9]. The Alternating Current (AC) permanent magnet synchronous linear motor is used to meet the high-thrust of feed components in High-speed CNC lathe. Taking the High-speed CNC lathe HTC2550hs for example, L2U Series AC permanent magnet synchronous linear motors are used in X and Z feed system, which have smaller moving mass, lower power loss, and greater thrust. The primary is installed between two sets of the symmetrical arrangement secondaries, so the attraction between the primary and secondary of linear decreases almost to zero.

The feed system of high speed CNC Lathe consists of servo driving, servo components, mechanical transmission device and executive component, which using the linear motor direct drive the sliding plate feed movement, abolishing the ball screw, gear and other mechanical transmission devices of feed system in traditional machine tool. The static and dynamic characteristics of feed system driven by linear motor in high speed CNC lathe were analyzed, because the stiffness and positioning accuracy of feed system greatly affect the machining accuracy of machine tool.

3. Static Characteristics Analysis of Feed System Driven by Linear Motor in High Speed CNC Lathe

The stiffness of the feed system refers to the ability to resist deformation under load, which divides into the mechanical structure stiffness and servo stiffness. And the mechanical structure stiffness is the required loads under mechanical components unit deformation in feed system [2,10]. Servo stiffness is divided into servo static stiffness and servo dynamic stiffness, and the servo static stiffness refers to the ability to resist the position deviation of feed drive system under the constant loads; the servo dynamic stiffness refers to the ability to resist the position deviation of feed drive system under the alternating loads [2,10].

The slide board is the main moving part of the feed system, and the guide rail is the main support component of the linear motor feed system. The mechanical structure static stiffness of feed system is researched through the slide board statics analysis.

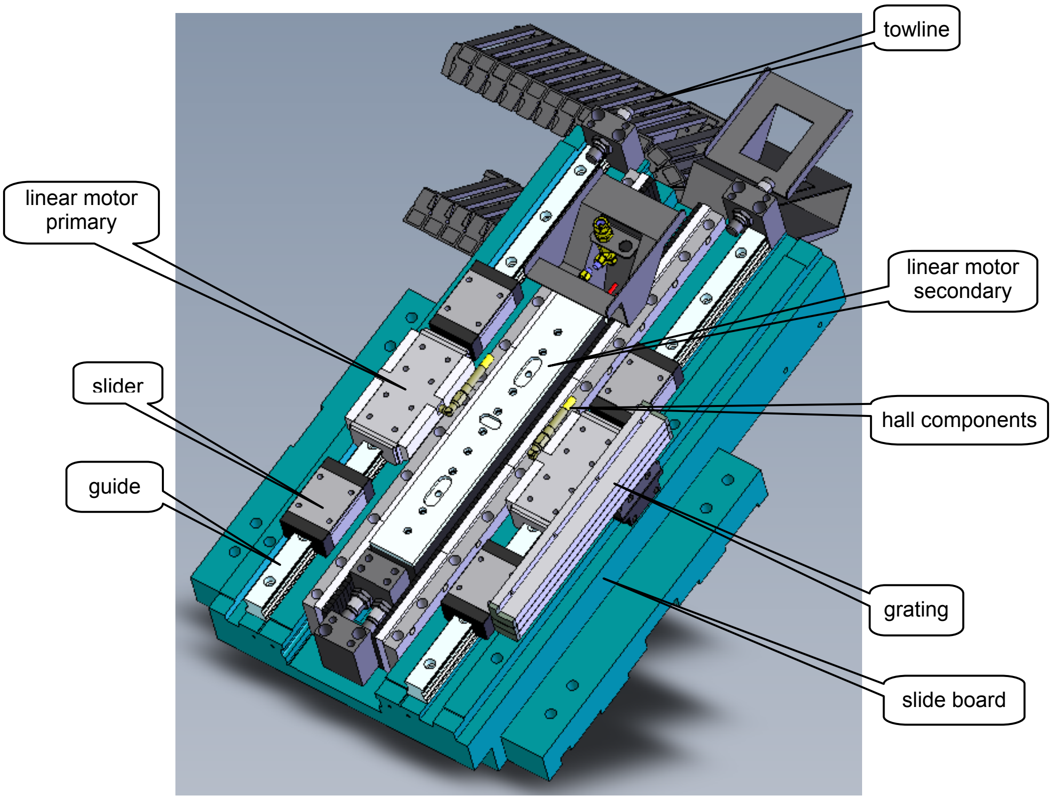

Figure 1. Components of the feed system driven by Linear motor

3.1. Statics and Kinematics Analysis of the Slide Board

L2U Series AC permanent magnet synchronous linear motors were used in X and Z feed system of high-speed CNC lathe HTC2550hs, and the guide rails in X axis were mounted at 45°oblique slide board, the maximum load of moving parts in X axis is 260kg, the rolling linear guideways were adopted and the friction coefficient of linear guide rail is 0.01, the slide board static force is shown in Figure 2, the slide board sustain the linear motor thrust F_c and the guide rail friction F_f .

In Figure 2, G_X is the load gravity along X direction, and $G_X = G\cdot\sin 45^\circ = 260\times 9.8\times\sqrt{2}/2 = 1802\,\mathrm{N}$; G_Y is the load gravity along Y direction, and $G_Y = G\cdot\cos 45^\circ = 260\times 9.8\times\sqrt{2}/2 = 1802\,\mathrm{N}$. F_f is the friction between the linear guide rail and the slide board,and $F_f = \mu G_Y = 0.01\times 1802 = 18.02\,\mathrm{N}$, so the required motor thrust is $F_c = G_X - F_f = 1802 - 18.02 = 1783.98\,\mathrm{N}$.

The slide board forward X+ acceleration force analysis diagram is shown in Figure 3, the rapid moving speed is 60m/min, and the acceleration time is $t = 1s$, so the acceleration is $a = 1m/s^2$, the required motor thrust under the maximum cutting force is $F_c = G_X + F_f + F_{X\max} + ma = 1802 + 18.02 + 1600 + 260\times 1 = 3680.02\,\mathrm{N}$.

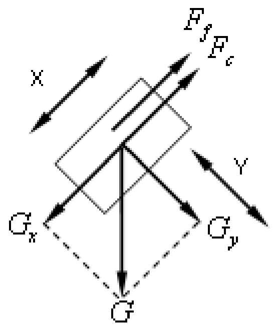

Figure 2. Static force analysis diagram of the slide board

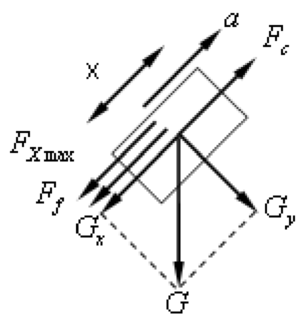

Figure 3. Forward X+ acceleration force analysis diagram of the slide board

The slide board forward X- acceleration force analysis diagram is shown in Figure 4, the required motor thrust under the maximum cutting force is $F_c = ma - G_X + F_f + F_{X\max}$ $= 260 \times 1 - 1802 + 18.02 + 1600 = 76.02\,\mathrm{N}$.

3.2. Static Stiffness Finite Element Analysis of the Slide Board

The slide board is subjected to the motor thrust in the machine tool start, acceleration, braking and operation process, if the stiffness of the slide board is insufficient, the feed system will be oscillated and deformed, so the stiffness of the slide board directly influences the precision of the machine tool and the stability of the machine tool control system. Here, the static characteristic of the slide board is analyzed using ANSYS12.0 finite element software. The three-dimension solid model of the slide board is established using SOLIDWORKS, as shown in Figure 5, and it is imported to ANSYS12.0, the model of the slide board is box structure and has the grooves, dabbers and other structural elements, so the automatic mesh generation approach is adopted and divided into the tetrahedral element, the finite element model of the slide board is shown in Figure 6. In order to eliminate the rigid displacement of the slide board, the constraints between the slide board and the slider in guide were set as the Fixed Support, the constraints of the slide board in X direction are set as the Frictionless Support. And the slide board is subjected to the motor thrust, slide board weight and load pressure. The static structural total deformation of the slide board is calculated as shown in Figure 7.

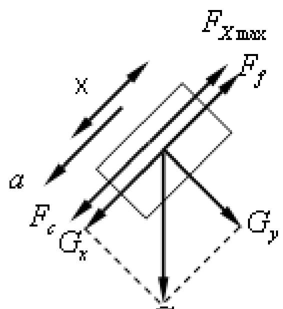

Figure 4. Forward X- acceleration force analysis diagram of the slide board

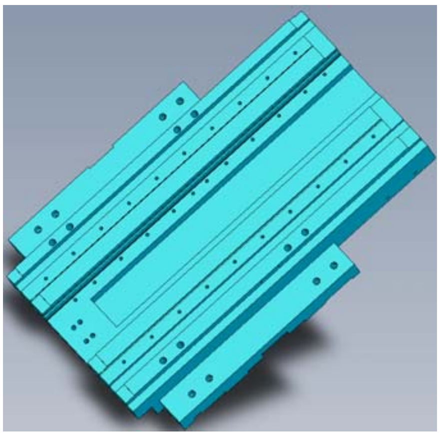

Figure 5. Three-dimensional solid model of the slide board

Figure 7 shows that the maximum deformation of the slide board occurs in the middle of the slide board, placed the linear motor, and the maximum deformation in perpendicular direction is 8.4838×10^{-8} m ,so the minimum static stiffness is $K_{\min}=\frac{1802\text{N}}{8.4838\times10^{-8}\ \text{m}}=21240.48\ \text{N}/\mu\text{m}$.

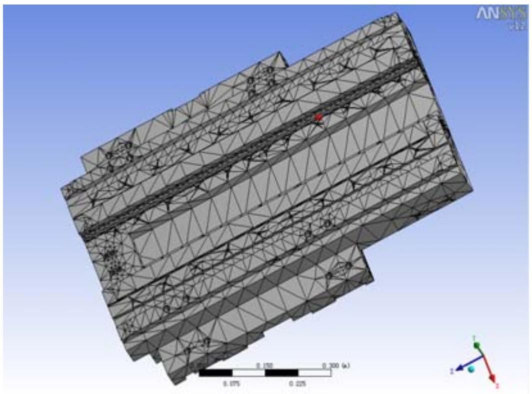

Figure 6. Finite element model of the slide board

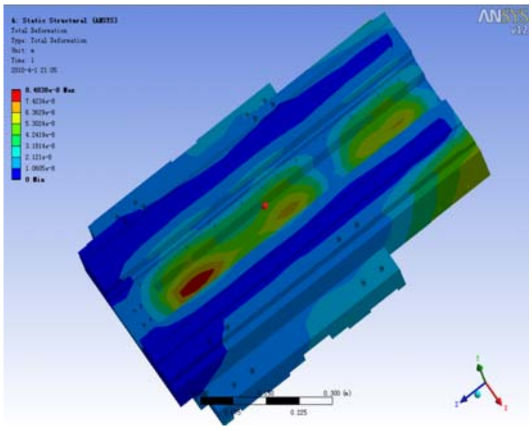

Figure 7. Static structural total deformation of the slide board

4. Dynamic Characteristics Analysis of Feed System Driven by Linear Motor in High Speed CNC Lathe

High speed CNC lathe feed system not only has the advantages of high speed, high feed acceleration and deceleration, but also computer numerical control servo system has the requirements of high response, high precision and high stability[1,2]. The dynamic stiffness was used to measure the external force interfere with the feed system,Due to the high speed CNC lathe feed system driven by linear motor is zero transmission, combined the driving component and the executive component, there is no mechanical transmission links. And the dynamic stiffness of the linear motor feed system depends mainly on the servo dynamic stiffness of the driving devices.

4.1. Position Control Principle of AC Permanent Magnet Synchronous Liner Motor

The feed system driven by the Alternating Current (AC) permanent magnet synchronous linear motor was used to meet the high-thrust in High-speed CNC lathe. AC permanent magnet synchronous linear motor feed system is suitable for high speed and ultra-high speed, high acceleration, long stroke, high precision, medium-sized thrust of feed drive in high speed machining center and other types of high speed and extra-high speed machine tools[11]. It has many advantages such as high feed speed and acceleration, long working stroke, high system stiffness, good dynamic performance, high tracing and positioning accuracy, the smooth movement, low noise and large thrust etc.[12,13]. And electromagnetic force control is realized through the simple magnetic field orientation control, the block diagram of AC permanent magnet synchronous linear motor position control is shown in Figure 8. The detection units provide information for the linear motor controlling rotor magnetic pole position, and also accurately detect the actual displacement of the machine tool motion components in order to realize the closed-loop feedback control of the machine tool movement.

4.2. The Mathematical Model Establishment of Linear Motor Control System

AC permanent magnet synchronous linear motor feed drive system is used in high-speed CNC lathe HTC2550hs feed system; it consists of linear motor and drive control system, and the control object is the mechanical actuator. The dynamical equation of feed system is expressed as Equ.1.

$$m\frac{dx^2}{dt^2}+c\frac{dx}{dt}=F \tag{1}$$

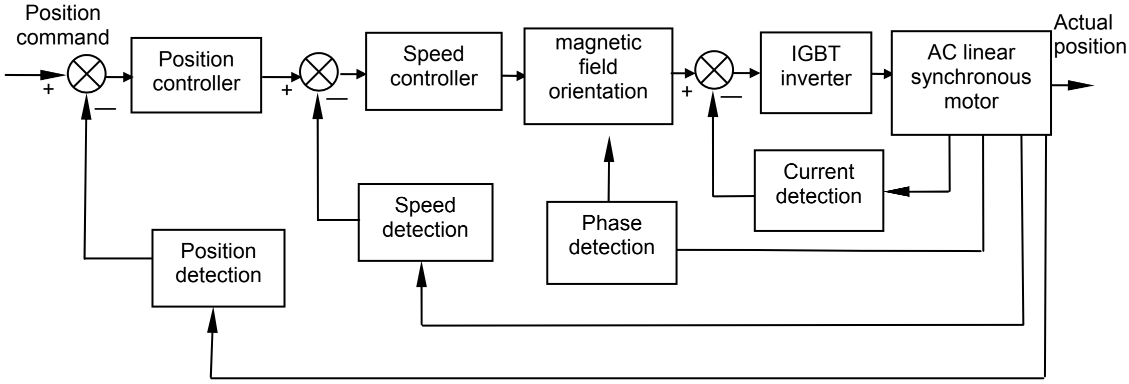

Figure 8. Block diagram of AC permanent magnet synchronous linear motor position control

Equ.2 is obtained using Laplace transform:

$$ms^2X(s)+csX(s)=F(s) \tag{2}$$

Then the transfer function of mechanical actuator in linear motor feed system is obtained as illustrated in Equ.3.

$$G(s)=\frac{X(s)}{F(s)}=\frac{1}{ms^2+cs}=\frac{1}{s(ms+c)} \tag{3}$$

The transfer function is the product of inertia unit and integral unit, the system characteristic parameters are mainly moving part mass and guide damping, the main factors affecting feed system servo stiffness are the working table mass, loading mass and guide damping.

The double closed loop control mode is adopted in linear motor feed system control structure, and the outer loop is taken as position regulation using proportion correction unit to increase the system gain and response speed, the inner loop is taken as speed regulation using proportion integral correction unit to increase the system low frequency gain and reduce the steady-state error. The speed filter unit can filter out the high frequency interference signal to increase the speed stability. The Transfer function diagram of linear motor feed drive system is shown in Figure 9.

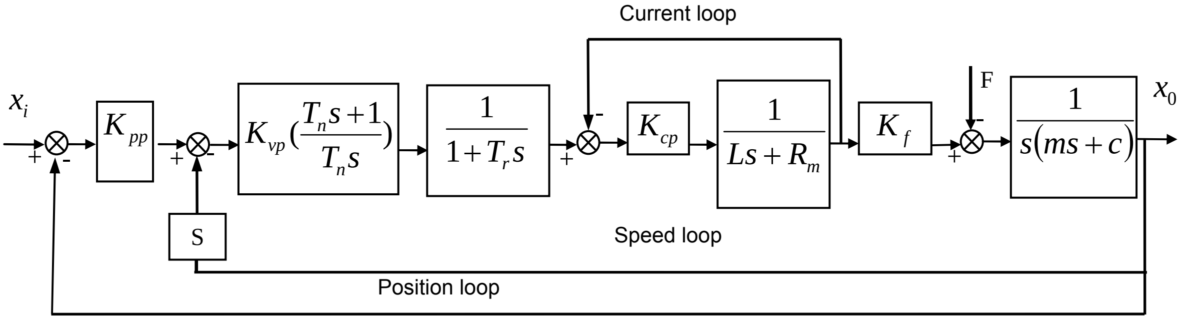

Figure 9. Transfer function diagram of linear motor feed drive system

Where x_i is the inputting reference displacement signal, K_{pp} is the position loop proportional gain, K_{vp} is the speed loop proportional gain, T_n is the speed loop integral response time constant , T_r is the speed loop filtering time constant, K_{cp} is the current loop gain, L is the motor armature inductance, R_m is the motor resistance, K_f is the force constant, m is the mass of the mechanical execution parts, c is the guide rail damping coefficient, and x_o is the output of actual position.

The simplified transfer function diagram of linear motor feed drive system is shown in Figure 10, combining the middle loop transfer function.

Where $$G_1(s) = K_f K_{vp}\left(\frac{T_n s+1}{T_n s}\right)\frac{1}{1+T_r s}\frac{K_{cp}}{R_a + Ls + K_{cp}} \tag{4}$$

Then, the servo dynamic stiffness of linear motor feed system is the ratio of loading disturbance force F and the maximum response displacement of the system Δx , that is illustrated in Equ. 5.

$$K_{sd} = \frac{F}{\Delta x} = \frac{F}{x_0 - x_i} \tag{5}$$

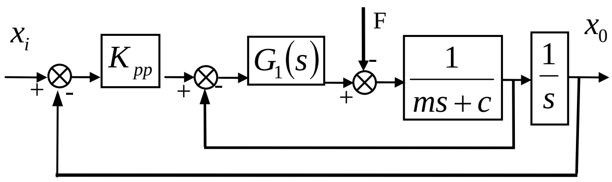

Figure 10. Simplified transfer function diagram of linear motor feed drive system

If $x_i = 0$, then $K_{sd} = \frac{F}{\Delta x} = \frac{F}{x_0}$. And the transfer function of the position outputting caused by disturbing force F can be expressed as Equ. 6.

$$G_2(s) = \frac{X_0(s)}{F(s)} = \frac{\frac{1}{ms+c}\cdot\frac{1}{s}}{1+\frac{1}{ms+c}\cdot\frac{1}{s}\cdot\left(K_{pp}+s\right)\cdot G_1(s)} = \frac{1}{(ms+c)s+\left(K_{pp}+s\right)\cdot G_1(s)} \tag{6}$$

So, the complex function of dynamic servo stiffness is expressed as Equ.7.

$$K_{sd}(s) = \frac{F(s)}{X_0(s)} = (ms+c)s+\left(K_{pp}+s\right)\cdot G_1(s) = (ms+c)s+\left(K_{pp}+s\right)K_f K_{vp}\left(\frac{T_n s+1}{T_n s}\right)\frac{1}{1+T_r s}\frac{K_{cp}}{R_a+Ls+K_{cp}}$$
$$= \frac{a_5 s^5 + a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s^1 + a_0}{s(T_r s+1)(Ls+R_a+K_{cp})} = \frac{a_5 s^5 + a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s^1 + a_0}{b_3 s^3 + b_2 s^2 + b_1 s^1 + b_0} \tag{7}$$

Where $a_0 = AK_{pp}$; $a_1 = A(T_n K_{pp}+1)$; $a_5 = mLT_r$;
$a_4 = Lm + R_a m T_r + K_{cp} T_r m + cLT_r$; $a_3 = Lc + R_a c T_r + K_{cp} T_r c + mR_a + mK_{cp}$;

$A=\frac{K_f K_{vp} K_{cp}}{T_n}$; $a_2 = AT_n + cR_a + cK_{cp}$; $b_3 = LT_r$; $b_2 = L + T_r(R_a + K_{cp})$; $b_1 = R_a + K_{cp}$;

$b_0 = 0$.

4.3. Influence Control Parameters on Servo Dynamic Stiffness

The transfer function of the linear motor feeding system and the complex function of the servo dynamic stiffness indicate that the system is a high order mathematical model. The main parameters affecting the servo dynamic stiffness of linear motor feed system are the mass of the mechanical execution parts, guide damping coefficients, position loop proportional gain, speed loop proportional gain, speed loop integral response time constant, speed loop filtering time constant, and current loop gain [2,14]. Basic technical parameters and control parameters of linear motor L2U-400×75WL of X feed system are presented in Table 1.

The mass of the working table and loading have an influence on servo system, because there is not any deceleration transmission mechanism between loading and driving parts in linear feed system. Under the initial conditions, the displacement response is shown in Figure11 with the moving part mass of 160kg, 260kg and 400kg respectively when the cutting interference force1600N step inputting. It indicates that the system respond speed is faster and the servo dynamic stiffness is higher if the moving part mass is smaller. And the servo dynamic stiffness of feed system reduces and the number of oscillation increases with the increasing of moving part mass, the adjusting time also increases, and the system tends to overshoot and influence the machining accuracy highly.

Table 1. Control parameters and technical parameters of linear motor servo system

Parameters	Value
K_{pp} (m/min)/mm	1.5
K_{vp} (mA/(m/min)	5000
T_n (ms)	7
T_r (μs)	500
K_{cp} (V/A)	16
L (mH)	19.35
R_m (Ω)	2.39
K_f (N/A)	151.9
m (kg)	260
c (N•s/m)	50

The rolling guide rail is adopted to ensure low-speed performance in high speed linear motor feeding system. The displacement response is shown in Figure 12 with damping coefficient of 5 Ns/m, 50 Ns/m and 90 Ns/m respectively when the cutting interference force1600N step inputting. It indicates that the damping coefficient has almost no effect on servo dynamic stiffness. Because only three terms a_4, a_3 and a_2 have damping coefficient in the transfer function and it has little effect on these three terms.

The displacement response is shown in Figure 13 with the position loop proportional gain of 0.5 m/min/mm, 1.5 m/min/mm and 2.5 m/min/mm respectively when the cutting interference force1600N step inputting. It indicates that the system response speed increases, servo dynamic stiffness increases and the number of oscillation also increase with the magnifying of position loop proportional gain. The system tends to be unstable when K_{pp} is too large. Steady-state error and position tracking error can be reduced and control accuracy can be increased by increasing K_{pp} under the system is stable, but the steady-state error cannot be eliminated completely. The position loop proportional gain is an important parameter in AC servo system; it is adjusted according to loading and required positioning accuracy.

The displacement response is shown in Figure 14 with the speed loop proportional gain of 4000 mA/m/min, 5000 mA/m/min and 6000 mA/m/min respectively when the cutting interference force1600N step inputting. It indicates that the maximum output displacement under the step force inputting decreases and servo dynamic stiffness increases with the magnifying of speed loop proportional gain. The speed loop mainly control speed stably and avoid oscillation when positioning.

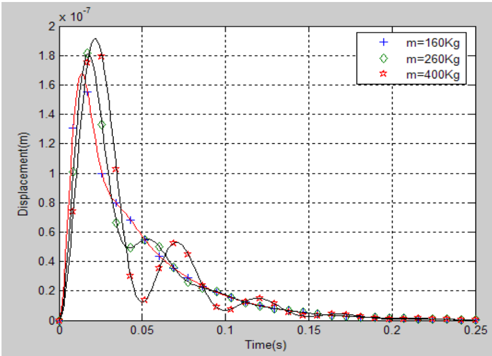

Figure 11. Influence *m* on servo dynamic stiffness

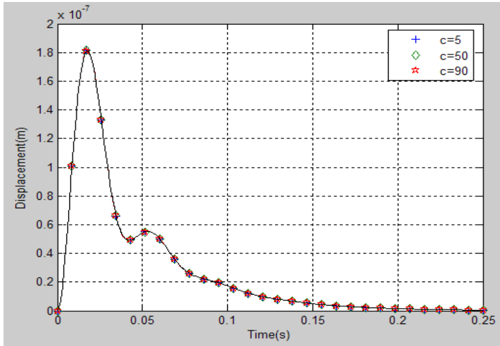

Figure 12. Influence *c* on servo dynamic stiffness

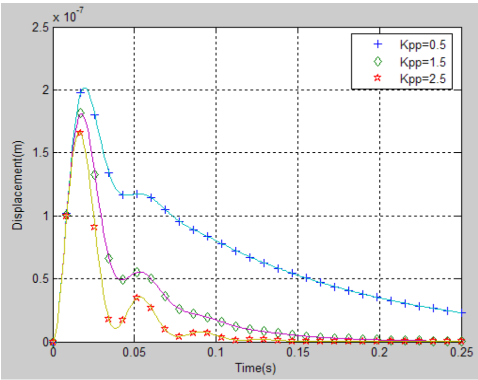

Figure 13. Influence K_{pp} on servo dynamic stiffness

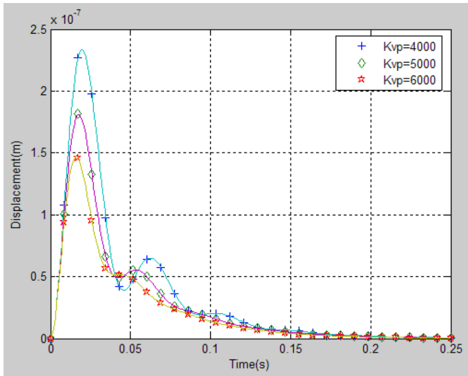

Figure 14. Influence K_{vp} on servo dynamic stiffness

The displacement response is shown in Figure 15 with the speed loop integral response time of 4000 mA/m/min, 5000 mA/m/min and 6000 mA/m/min respectively when the cutting interference force1600N step inputting. It indicates that the servo dynamic stiffness decreases with the increasing of speed loop integral response time. The system performance decreases while T_n is too large; the system is unstable due to too many oscillations while T_n is too small. The servo dynamic stiffness of the system can be increased by reducing T_n when the system is stable. The integral unit mainly reduces the speed fluctuation in loading disturbance, makes sure the system steady state and transient performance, eliminates the steady-state error of the system and improves the system control accuracy.

The filter part is set in speed loop for limiting the speed loop bandwidth, suppressing the interference to the system from high frequency signal, suppressing the quantization effect introduced by A/D, D/A link in servo control system [15,16]. The displacement response is shown in Figure 16 with the speed loop filtering time constant of 100μs, 500μs and 1500μs respectively when the cutting interference force 1600N step inputting. It indicates that the system servo dynamic stiffness decreases, the number of oscillation increases and adjusting time increases with the increasing of speed loop filtering time.

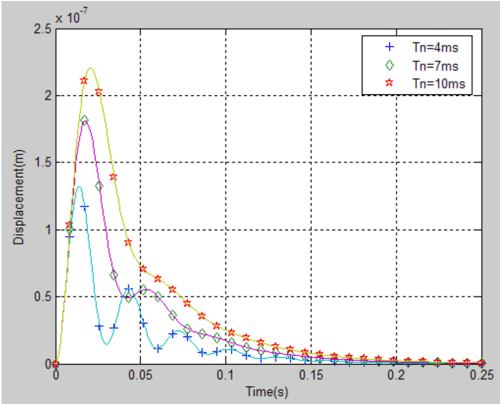

Figure 15. Influence Tn on servo dynamic stiffness

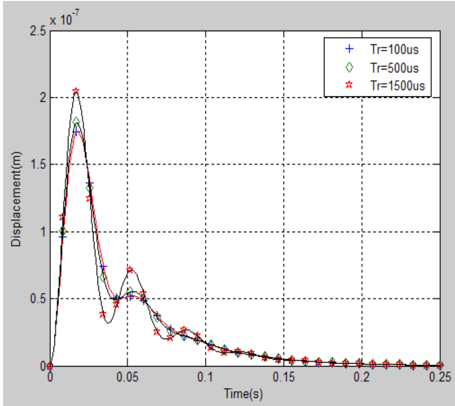

Figure 16. Influence Tr on servo dynamic stiffness

Current feedback part is added in speed loop in order to enhance the anti-interference ability of servo system and control the amplitude and phase of armature current. Proportional gain is adopted to improve the rapidity of dynamic response in current loop, the displacement response is shown in Figure 17 with the current loop proportional gain of 10V/A, 16V/A and 22V/A respectively when the cutting interference force1600N step inputting. It indicates that the servo dynamic stiffness increases with the increasing of current loop proportional gain. If the current loop proportional gain is too large, the drift error of current detecting elements will increase and the speed control accuracy and current control stability will reduce.

Position loop proportional gain, speed loop proportional gain and speed loop integral response time are the biggest influence parameters on servo dynamic stiffness in all the control parameters, so the influence three parameters on servo dynamic stiffness is analyzed, the simulation result is as shown in Figure 18. It indicates that the displacement response under the cutting interference force1600N step inputting decreases, servo dynamic stiffness increases, and the number of system oscillation reduces while the K_{pp}, K_{vp} and T_n increase in small range at the same time; and the system tends to be stable. Therefore, all the parameters should be selected and adjusted reasonably based on object characteristics and loading conditions.

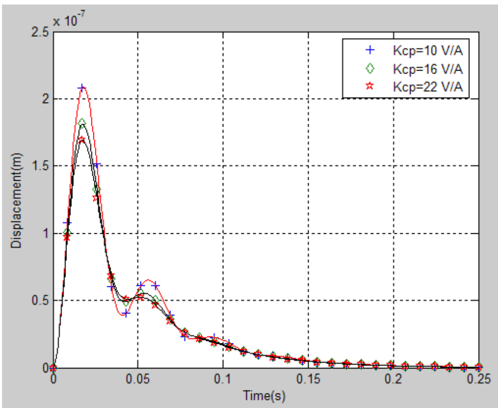

Figure 17. Influence K_{cp} on servo dynamic stiffness

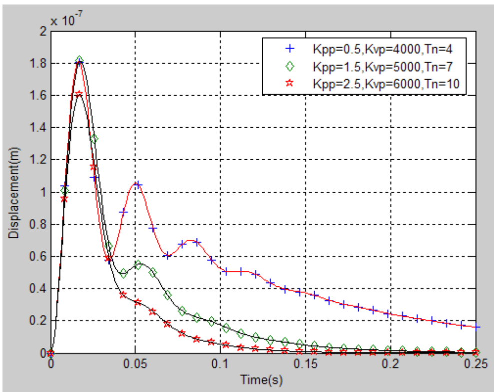

Figure 18. Influence multiple factors on servo dynamic stiffness

5. Conclusion

The static and dynamic characteristics of feed system driven by linear motor in high speed CNC lathe were analyzed. The slide board was taking as the main moving part of the feed system, and the guide rail was the main support component of the linear motor feed system. The mechanical structure static stiffness of feed system is researched through the slide board statics analysis. The simulation results show that the maximum deformation of the slide board occurs in the middle of the slide board where the linear motor is placed. The linear motor feed system control model is established based on analysis of high-speed linear feed system control principle, and the linear motor feed system transfer function is established, and servo dynamic stiffness factors are researched, the control parameters of the servo system and actuating mechanism parameters of feed system on the effect of the linear motor servo dynamic stiffness are analyzed using MATLAB software, which provide the reference for determining the control parameters reasonably. The simulation results show that the position loop proportional gain, speed loop proportional gain and speed loop integral response time are the biggest influence factors on servo dynamic stiffness. The displacement response is reduced under the cutting interference force step inputting, while the position loop proportional gain, speed loop proportional gain and speed loop integral response time are increased, and the servo dynamic stiffness is increased, the number of system oscillation is also reduced, and the system tends to be stable.

Acknowledgements

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