Trajectory Tracking Control Method for High-Speed and High-Acceleration Machine Tool

Jianfu Cao1,2  Jialiang Zhang1

1. State Key Laboratory for Manufacturing System Engineering, Xi’an Jiaotong University, Xi’an 710049, China
   E-mail: cjf@xjtu.edu.cn
2. Xi’an Jiaotong University Suzhou Academy, Suzhou 215123, China

Abstract: For the trajectory tracking control problem of high-speed and high-acceleration machine tool, an adaptive feedforward control method with frictional compensation is proposed. The mathematical model of high-speed machine tool drive system is established, and the influence on tracking dynamic characteristic of nonlinear factor is analyzed. In order to enhance tracking characteristic of feed system, the traditional feedforward method is improved by introducing velocity-acceleration feedforward control, condition integral and anti-saturation links, and the acceleration feedforward parameter is adjusted online by target acceleration and position output deviation. To eliminate the influence of nonlinear friction of drive system, a friction compensator is constructed based on online identification method. Simulation experiments are made using the proposed trajectory tracking method, and the method is applied to a two-axis high-speed motion control platform. The actual data show that the proposed method has small tracking error and fast response speed, which can meet the control requirement of the feed system of high-speed and high-acceleration machine tool.

Key Words: High-Speed Machining, Nonlinear System, Feedforward Control, Trajectory Tracking

1 INTRODUCTION

High-speed and high-acceleration machining is a development direction of manufacturing technology. At present, the feed speed has reached more than 40m/min, the acceleration has reached more than 1g, and the spindle speed has reached tens of thousands rotations of high speed machine tool. With the development of Chinese manufacturing industry, the urgent requirement has been proposed for the trajectory tracking control of high speed and High-acceleration machining in aerospace, vehicle, ship, new energy industry and so on. However, the equipments used in these industries depending on importation near upon 100%, and are subjected to embargo in defense industry. In recent years, the great progress of domestic machine tool control technology has been made, but the great disparity in control technology of High-speed and high-acceleration computer numerical control (CNC) machine compared with abroad has been existed.

CNC machine in the case of high speed and high acceleration, with the increase of velocity and acceleration, mass distribution of mechanical system will shift, axial stiffness of screw nut pairs and bearing exist mutation point, servo output force frequency characteristic also change due to the influence of nonlinear inductance, and the influence of electromechanical coupling on motion accuracy is more obvious[1]. In addition, in order to play the role of shock absorption and protection, the elastic couplings with variable stiffness and variable damping characteristics are often used. These reasons make the nonlinear characteristics of the system greatly enhanced, and bring new requirements for the control system of CNC machine tools.

In order to improve the trajectory tracking performance of NC machine tool, people proposed feed-forward control and many other improved control method[2-5]. In order to reduce the influence of delay in NC machine tool drive system, a direct velocity-acceleration feedforward control method is presented, the velocity-acceleration feedforward controller is constructed directly according to the position command signal[6]. To further improve the tracking performance of NC machine tool, a compounding feedforward control method is proposed by combining velocity-acceleration feedforward control method with friction feedforward compensation control method[7]. In order to improve the dynamic response characteristics of the high-speed machine tool, a kind of control method with reference model based on feedforward control is presented, and the reference model is constructed by backward compensation filter[8]. In [9], a fuzzy self-tuning PID controller with feedforward is proposed for the trajectory tracking problem of high speed and high precision CNC machine tool. In [10], a control method combined feedback controller with feedforward controller is proposed for the position control problems of NC machine, the feedback controller is designed according to linear quadratic regulator design method system model, and the nonlinear friction is compensated by using feedforward compensator. The feedforward controller parameters are fixed in above methods. High-speed and high-acceleration CNC machine tools in the operation process, the velocity and acceleration are large and change frequently, systems have significant nonlinear characteristics, and in the course of operation system parameters will change too, so these methods are difficult to meet the requirements of actual control system.
The trajectory tracking control problem of high-speed and high-acceleration machine tool is studies in this paper. In order to reduce the influence of nonlinear characteristics on control performance, a new adaptive feedforward control method is proposed. The drive system model of high-speed machine tool is established, and the influence of nonlinear factor on tracking dynamic characteristic is analyzed. Based on the traditional feedforward algorithm, the acceleration feedforward coefficient is adjusted adaptively, and the nonlinear friction compensator is constructed by using online identification method. The proposed tracking algorithm is carried on the simulation experiment, and is applied in two-axis high speed motion control platform.

2 HIGH-SPEED MACHINE TOOL DRIVE SYSTEM MODELING AND NONLINEAR CHARACTERISTIC ANALYZING

The servo motors in high-speed machine tool drive system mainly are permanent magnet synchronous motor(PMSM) and AC asynchronous motor. In addition, in order to play the role of shock absorption and protection, the elastic couplings are used in drive system, and it is a nonlinear damp system. Other components of drive system such as screw, gear reducer, detecting element, strictly speaking is nonlinear components. The mechanical drive links and the worktable also exists nonlinear factors such as friction and gap. Due to above reasons, the drive system of high speed machine tool has obvious nonlinearity. Fig.1 is a structure diagram of high-speed machine tool drive system, it consists of position controller, driver, motor, elastic coupling, ball screw, worktable and other parts, where \( r \) is input position, \( V_r \) is position controller output, \( \omega_i \) is motor angular velocity, \( \theta_i \) is motor rotor angle, \( y \) is real output position, \( f \) is nonlinear friction.

![Fig.1 Structure diagram of high-speed machine tool drive system](image)

The high performance permanent magnetic materials are used to provide rotor excitation magnetic field for three phase permanent magnet synchronous motor, so the motor has the advantages of high power density, small volume, high efficiency and convenient maintenance and so on. Three phase permanent magnet synchronous motor is a typical kind of nonlinear multivariable coupling dynamic system, and it is sensitive to external disturbance and system parameters change. Without considering the saturation effect of the magnetic circuit and ignoring hysteresis and eddy current loss, the voltage equation of permanent magnet synchronous motor under \( dq \) rotating coordinate system is given by

\[
\begin{align*}
U_d &= RL_d \dot{I}_d + L_q \dot{I}_q - p\omega q L_q I_q(t) \\
U_q &= p\omega q L_d I_d + RL_q \dot{I}_q + L_q \dot{I}_q + p\omega q \psi_f \\
T_m &= \frac{3}{2} p[\psi_f L_q(t) + (L_d - L_q) I_d(t) L_q(t)] \\
J \ddot{\theta}(t) + B \dot{\theta}(t) &= T_m(t) - T_f(t)
\end{align*}
\]

where \( U_d(t) \) is the direct-axis voltage, \( U_q(t) \) is the quadrature-axis voltage, \( I_d(t) \) is the direct-axis current, \( I_q(t) \) is the quadrature-axis current, \( R \) is the stator winding resistance, \( L_d \) is the direct-axis inductor, \( L_q \) is the quadrature-axis inductor, \( p \) is the pole-pairs number, \( \psi_f \) is the magnetic linkage of rotor.

The relation between the motor angular displacement \( \theta_i(t) \) and output torque \( T_m(t) \) can be obtained by the motor motion equation

\[
J \ddot{\theta}_i(t) + B \dot{\theta}_i(t) = T_m(t) - T_f(t)
\]

where \( J_1 \) is rotational inertia of motor, \( B_1 \) is viscous damping coefficient, \( T_i(t) \) is load torque.

From equation (1) and equation (2), the input-output equation of permanent magnet synchronous motor is given be

\[
\begin{align*}
U_d &= RL_d \dot{I}_d + L_q \dot{I}_q - p\omega q L_q I_q(t) \\
U_q &= p\omega q L_d I_d + RL_q \dot{I}_q + L_q \dot{I}_q + p\omega q \psi_f \\
T_m &= \frac{3}{2} p[\psi_f L_q(t) + (L_d - L_q) I_d(t) L_q(t)] \\
J \ddot{\theta}_i(t) + B \dot{\theta}_i(t) &= T_m(t) - T_f(t)
\end{align*}
\]

The drive system of high speed machine tool is composed by elastic coupling, ball screw, worktable and other components. The friction exists in the contact parts with relative motion, and has obvious nonlinearity. The nonlinear behaviors of friction mainly come from the difference between static friction and dynamic friction as well as Striebeck effect. We use Striebeck friction model to describe drive system friction force \( f \) that can be obtained

\[
f = \left[ F_c + (F_s - F_v) e^{-\frac{\nu_s}{v^*}} \right] \text{sgn}(v) + k
\]

where \( F_c \) is the coulomb friction, \( F_s \) is the static friction, \( \nu_s \) is the Striebeck velocity, \( \delta \) is the empirical constant, \( k \) is the viscous friction coefficient, \( v \) is the feed speed.

The mechanical drive system can be as a two inertia system, and the motion equation is given by

\[
J_2 \ddot{\theta}_i(t) + B_2 \left( \dot{\theta}_i(t) - \dot{\theta}_r(t) \right) + k_f f(v) = T_r(t)
\]

where \( \dot{\theta}_i(t) \) is the motor angle displacement, \( \dot{\theta}_r(t) = \psi(t)/L_0 \) is the equivalent angular displacement of worktable, \( L_0 \) is the pitch coefficient, \( J_2 \) is the sum of rotary inertia of coupling, ball screw and worktable, \( B_2 \) is the damping of drive system, \( k_f \) is the friction torque coefficient,
function \( f(v) \) is the system friction, \( v \) is the feed speed, \( T_{f}(t) = K_{c}[\dot{\theta}(t) - \dot{\theta}(t)] \), \( K_{c} \) is the stiffness of drive system.

According to the nonlinear friction model that described in equation (4), it can be seen that the maximum static friction is zero speed and the negative damping phenomenon in low speed will impact the system control accuracy. The coulomb friction is reflected as the static torque of rotating shaft opposite to the motion direction, and it increases the steady state tracking error of feed system. The model describes the continuity between the maximum static friction force and the continuous friction. The friction force will appear nonlinear mutation when the speed pass zero. The Striebeck velocity determines the interval of friction existing negative slope. Due to the negative slope characteristics of friction under low speed, the feed speed is lower and will cause the worktable movement is not smooth. Especially, when feed speed is less than Striebeck speed, it will cause crawling phenomenon.

From equation (3), it can be seen that the motor angular velocity and current exists coupling, motor angular velocity and voltage has nonlinear relation, and motor output torque and current has nonlinear relation, so PMSM is a multivariable nonlinear coupling system. In the control of AC servo system, vector control mode is usually used. It through the field-oriented to weaken nonlinear characteristics and coupling characteristic of the PMSM, but the nonlinearity and coupling can not be completely eliminated.

Due to the influence of various nonlinear characteristics on CNC drive system, the position controller designed by traditional PID control algorithm can not meet the performance requirement of the high speed and high precision CNC drive system. Fig.2 is the tracking error curve under high speed and high acceleration condition when position input is sinusoidal signal, the maximum speed is 42m/min and maximum acceleration is 20m/s². From Fig.2, it can be seen that the tracking performance is poor, which the initial tracking error is more than 50 \( \mu \)m and appear oscillation, and the dynamic tracking error achieves 30 \( \mu \)m. Fig.3 is the tracking error curve under low speed and low acceleration condition when position input is sinusoidal signal, the maximum speed is 1.2m/min and the maximum acceleration is 0.9m/s². From Fig.3, it can be seen that the error curve in the peaks and troughs are not smooth due to the influence of nonlinear friction, the oscillation are appeared and more error are caused.

Fig.2 The tracking error curve under high speed and high acceleration condition

Fig.3 The tracking error curve under low speed and low acceleration condition

3 HIGH-SPEED POSITION TRACKING ALGORITHM BASED ON ADAPTIVE FEEDFORWARD CONTROL

The drive system of high speed machine tool is a nonlinear system. In order to improve the responsiveness and anti-interference ability of the feed system, the traditional PID control algorithm can be improved by velocity-acceleration feedforward method. Because the drive system of NC machine tool has nonlinear characteristic and the parameters are changed, so the traditional feedforward method with fixed parameter is difficult to meet the system requirements. In order to improve tracking performance, an adaptive feedforward control algorithm is used in this paper, which the acceleration feedforward parameter is adjusted by using the target acceleration and the deviation of position output. In addition, in order to eliminate the influence of nonlinear friction of drive system, the friction is compensated based on the online identification method. The basic structure of adaptive feedforward control of CNC machine tool drive system is shown in Fig.4, where \( r(t) \) is position input, \( V'(t) \) is driver input, \( \omega_i(t) \) is motor speed, \( I(t) \) is motor current, \( f \) is friction, \( y(t) \) is actual position.

3.1 Adaptive Feedforward Control

After feed forward control is added, the steady value of output velocity \( V' \) is

\[
V'_s \approx K_p e(t) + K_{off} \frac{dr(t)}{dt}
\]  

(6)

From equation (6), it can be seen that the change trend of machining trajectory is added to controller output by velocity feed forward. So actual output can rapidly track trajectory and tracking error is small. The expectation
acceleration is proportionally added to output velocity by acceleration feedforward so that dynamic process of start-up or deceleration can be speeded up. Therefore, the rapid responsiveness is enhanced when double feed forward control of velocity feed forward and acceleration feed forward are added.

In order to avoid system prematurely appear integral saturation, decrease overshoot and adjusting time, and ensure low-speed and high-speed characteristics, the condition integral is added. Owing to condition integral, integral part of PID controller has effect only when error is small. The integral coefficient \( \beta \) is defined as

\[
\beta = \begin{cases} 
1 & |e(t)| \leq \varepsilon \\
0 & |e(t)| > \varepsilon
\end{cases}
\]  

(7)

where \( \varepsilon \) is error threshold.

For the saturation appeared in execution unit, upper limit and lower limit are set on output so that regulator output can stop accumulation after motor rotational speed saturation. So saturation can be inhibited and high-speed-characteristic of dynamic state can be improved. There are interference signal in the position detection channel of system, so weighted average filter is used for anti-interference processing.

Adaptive feedforward control method use the output errors of the first \( l \) servo periods to online modify the acceleration feedforward coefficient of the \( l \)th servo period, \( K_{\text{aff}}(l) = K_{\text{aff}}(l-1) + \Delta K_{\text{aff}}(l) \), where \( \Delta K_{\text{aff}}(l) \) is the compensation of the acceleration feedforward coefficient of the \( l \)th servo period. The feedforward coefficient must satisfy the equation \( F(\Delta K_{\text{aff}}(l), l) = \min_{\Delta K_{\text{aff}}(l)} \sum_{i=1}^{l} \eta^2(i) \), where \( \eta(i) = e(i) - \Delta K_{\text{aff}}(l) a(i) \), \( a(i) \) is acceleration.

The least square algorithm is used to solve the equation, and \( \Delta K_{\text{aff}}(l) \) is obtained by

\[
\Delta K_{\text{aff}}(l) = [\Phi^T(l) \Phi(l)]^{-1} \Phi^T(l) E(l) 
\]  

(8)

where \( \Phi(l) = [a(l), \cdots, a(l)]^T \), \( E(l) = [e(1), \cdots, e(l)] \).

The adaptive calculation method of acceleration feedforward coefficient can be got by making transform for equation (8), the specific formula is

\[
\begin{align*}
K_{\text{aff}}(l) &= K_{\text{aff}}(l-1) + \Delta K_{\text{aff}}(l) \\
\Delta K_{\text{aff}}(l) &= \Delta K_{\text{aff}}(l) + [Q(l)] \eta(l) \\
\text{where } &\eta(l) = e(l) - \Delta K_{\text{aff}}(l) a(l), \quad Q(l) = P(l) a(l), \\
P(l) &= \frac{1}{1+\alpha^2(l)}, \quad \alpha(l) = \frac{f(l-1)}{P(l-1)} \\
\end{align*}
\]  

(9)

where \( \eta(l) = e(l) - \Delta K_{\text{aff}}(l) a(l) \), \( Q(l) = P(l) a(l) \), \( P(l) = \frac{1}{1+\alpha^2(l)} \), \( \alpha(l) = \frac{f(l-1)}{P(l-1)} \).

The acceleration feedforward coefficient can be adjusted on line by the use of equation (9), but the calculated acceleration feedforward coefficient of the \( l \)th servo period contains position information of the first \( l \) The sampling point. In order to more accurately reflect the dynamic characteristics of the current location, by introducing forgetting factor \( \rho \), the target function is transform to \( F(\Delta K_{\text{aff}}, l) = \min_{\Delta K_{\text{aff}}} \sum_{i=1}^{l} \rho^{l-i} \eta^2(i) \), then adaptive formula with forgetting factor of acceleration feedforward coefficient is

\[
\begin{align*}
K_{\text{aff}}(l) &= K_{\text{aff}}(l-1) + \Delta K_{\text{aff}}(l) \\
\Delta K_{\text{aff}}(l) &= \Delta K_{\text{aff}}(l-1) + \frac{1}{\rho} [Q(l-1) a(l)] \eta(l) \\
\text{where } &P(l) = (1/\rho) [1-\rho^2] [Q(l-1) a(l)] P(l-1), \\
Q(l) &= [P(l-1) a(l)] [\rho + \alpha^2(l) P(l-1)], \\
\eta(l) &= e(l) - \Delta K_{\text{aff}}(l-1) a(l) \\
\end{align*}
\]  

(10)

Given the initial values of \( \Delta K_{\text{aff}}, K_{\text{aff}} \) and forgetting factor \( \rho \), the specific steps of calculating the acceleration feedforward coefficient are

1. Sample the \( l \)th \( (l \geq 1) \) group data, then calculate \( \eta(l) = e(l) - \Delta K_{\text{aff}}(l-1) a(l) \);
2. Calculate \( Q(l) \) and \( P(l) \) respectively;
3. Use equation (10) to calculate the compensation \( \Delta K_{\text{aff}}(l) \) of the acceleration feedforward coefficient of the \( l \)th servo period;
4. Use equation (10) to calculate the acceleration feedforward coefficient \( K_{\text{aff}}(l) \) of the \( l \)th servo period;
5. Feed whether termination, if termination, end calculation, Otherwise, let \( l = l + 1 \), turn to step 1.

3.2 Friction Compensation Based on Online Identification

In order to eliminate the influence of nonlinear friction on the drive system, the friction parameter can be obtained based on online identification according to feed speed and torque data of worktable, then the compensation quantities are sent to driver through compensator.

The exponential term in equation (4) is launched accordance with the Taylor formula, then we can obtained

\[
f = (a + bv + cv^2 + dv^3 + ev^4 + fv^5 + gv^6) \text{sgn}(v) \]  

(11)

where \( a = F_s, \quad b = k(F_s - F_s)/v_s, \quad b = (F_s - F_s)/(2v_s^2), \quad c = (F_s - F_s)/(2v_s^3), \quad d = (F_s - F_s)/(6v_s^4), \quad e = (F_s - F_s)/(24v_s^5), \quad f = (F_s - F_s)/(120v_s^6), \quad g = (F_s - F_s)/(720v_s^6). \)

The friction is expressed as the linear expression of every power of velocity \( v \) in equation (11). Let \( \theta = [a, b, c, d, e, f, g]^T, \quad Z = [\text{sgn}(v + \text{sgn}(v)v + \cdots + v^6 \text{sgn}(v)]^T, \) then equation (11) can be written as \( f = Z^T \theta \). We use recursive least square algorithm to solve the equation, then the parameter vector \( \theta \) can be obtained, and the nonlinear friction parameters can be further obtained according to \( \theta \).
4 EXPERIMENTAL RESEARCH ON HIGH SPEED MOTION CONTROL PLATFORM

4.1 Friction Compensation Based on Online Identification

For the proposed adaptive feedforward control algorithm, some simulation experiments are made, and the input signal is sine signal. Fig.5 and Fig.6 respectively are the feed speed curve and acceleration curve of drive system under high speed and high acceleration state. From Fig.5 and Fig.6, it can be seen that the feed speed range is $0 \sim 42 \text{m/s}$, the acceleration range is $0 \sim 20 \text{m/s}^2$, and the tracking curves of velocity and acceleration are smooth. When using traditional PID algorithm, because of the influence of nonlinear characteristics, the dynamic error of the drive system is large and reaches $31.5 \mu \text{m}$. It is difficult to meet the high precision requirement of CNC machine tool. When using the traditional feedforward algorithm, the tracking performance is improved and the dynamic error is $23.8 \mu \text{m}$, but the dynamic error is still large. When using the proposed adaptive feedforward algorithm, because the acceleration feedforward coefficient is adjusted in real-time according to dynamic characteristics of trajectory curves and the friction is compensated by the online identification method, so the influence of nonlinear friction is eliminated and the tracking error is decreased obviously. The dynamic error is $0.3 \mu \text{m}$ and the tracking performance is improved significantly.

4.2 Application in High-Speed Motion Platform

The proposed adaptive feedforward control algorithm is applied to a two-axis high speed motion control platform. The motion control platform mainly consists of closed loop motion control board, Panasonic driver and incremental encoder etc. The closed loop motion control board uses DSP+FPGA as core processing unit. The incremental encoder detects the motor running position and sends to the FPGA, so a position feedback loop is formed. The peripheral switch input and output are connected to DSP through IO bus, and some operating for system can be made or status information of system running can be displayed. At the same time, to complete the communication of the upper computer and lower computer, high speed communication interface is used to connect DSP and upper computer.

In order to validate the tracking performance of proposed control algorithm, the sine signal and step signal are tracked respectively. Fig.7 is the tracking curve of sine signal, it can be seen that the input position curve and the output position curve are basically in coincidence, and the tracking error is very small that closed to 0. Fig.8 is the velocity response curve of step signal and the rotation speed of the motor is 3000r/min. From Fig.8, it can be seen that the velocity response is very fast.

5 CONCLUSION

When CNC machine tool is under high speed and high acceleration motion state, the nonlinear factors of the feed system will seriously affect the tracking performance of the control system. In order to weaken the influence of the nonlinear characteristics and improve the tracking performance, a new adaptive feedforward control method is proposed. The velocity-acceleration feedforward control, condition integral and anti-saturation links are combined, and the acceleration feedforward parameter is adjusted online. In addition, a friction compensator is constructed based on online identification method. For the proposed trajectory tracking method, simulation experiments are made, and the method is applied in a two-axis high-speed motion control platform. Actual data show that the
The proposed method has small tracking error and fast response speed, so it has important practical value.

REFERENCES


