Study on dynamic characteristics of flexible feed system by mechanical parameters

Fei Luo 1,a, Hongsheng Chen 1,b, Nan Wei 1,2,c

1Taishan University, College of Mechanical And Architectural Engineering, Tai An, Shan Dong, China
2BEIJING UNEIVERSITY OF TECHNOLOGY, BeiJing, China
a-e-mail: 2017058@tsu.edu.cn b-e-mail: weinan0008@163.com
c*corresponding author: e-mail: chs8921@163.com

Abstract: The dynamic characteristics of CNC feed system are determined by the dynamic characteristics of mechanical drive and control parameters. The dynamic characteristics of transmission link are closely related to the mechanical characteristic parameters. The designer must find the matching control parameters by analyzing the law of mechanical characteristic parameters and dynamic characteristics. In this paper, the relationship between inertia ratio, resonant frequency and velocity loop control gain is analyzed by using the established three-inertia system model, and the parameters are input into the system model for simulation. It provides a method for the designers of CNC machine tools to adjust the internal control parameters, which has important theoretical and practical value.

1. Introduction

The performance of CNC machine tools depends on the performance of each component of the machine tool and its coupling degree, including the machining accuracy of mechanical structure, CNC system, servo drive system, speed and position feedback system. The dynamic characteristics of the mechanical transmission link of the feed system and the PI parameter configuration of the control link jointly determine the dynamic characteristics of the feed system, but the mechanical characteristics parameters (inertia ratio, frequency, etc.) have an important correlation with the control parameters. Therefore, it is of great significance to study the law between mechanical characteristic parameters and dynamic characteristics for analyzing dynamic characteristics and finding matching control parameters.

The research shows that the weak stiffness of the transmission system is the main factor that causes the vibration of the feed system and affects the machining error of the system. The weak link of the mechanical transmission system causes different resonant frequencies, and the high-order frequencies are filtered out by the filter. Therefore, the low order natural frequency is the main factor affecting the vibration of the system. Because the static stiffness of the machine tool determines the stiffness of the joint, the damping of the machine tool comes from the joint, so 60% of the vibration of the feed system comes from the joint. Literature established a finite element model and studied dynamic characteristic parameters of feed system joints according to Hertz contact theory to analyze the effect of feed system mass, position and stiffness on the dynamic performance of the system. In Literature, a double inertia system was established by using the lumped parameter method, and the influence law of the resonance characteristics of the mechanical transmission system on the control parameter setting and the dynamic characteristics of the system was analyzed, and the influence law of the change of mechanical load,
stiffness and damping on the dynamic characteristics of the feed system was also analyzed. The paper derived the motion equation of precision lathe feed system, and studied the reason and mechanism of dynamic response of the feed system under low-frequency servo excitation. The results show that there is a harmonic component in the servo torque which is lower than the natural frequency of the first section 66Hz, and the frequency component increases with the increase of speed.

Aiming at the above problems, the dynamic characteristics of the system are simulated and simulated by using the speed loop control parameters which have been set, and the law between mechanical characteristic parameters and dynamic characteristics is found.

2. Establish mathematical models

The ball screw feed structure consists of two parts: mechanical transmission link and servo control system. Its transmission mechanism is shown in Fig 1, which is mainly composed of servo motor, coupling, lead screw, lead screw nut and working table. The transmission process is driven by a motor to connect the lead screw through the coupling, and then the rotation of the lead screw is transformed into the movement of the worktable through the nut assembly.

![Figure 1 Schematic diagram of feed system](image)

A schematic diagram of the three-inertia model transformed according to Fig.1 is shown in Figure 2:

![Figure 2 Schematic diagram of three inertia model](image)

According to the schematic diagram of the double inertia structure in Fig.2, the kinetic energy of the three inertias can be expressed as:

\[ T_m = J_m \ddot{\theta}_1 + c_1(\dot{\theta}_1 - \dot{\theta}_2) + k_3(\theta_1 - \theta_2) \]  \hspace{1cm} (1)

\[ c_1(\dot{\theta}_1 - \dot{\theta}_2) + k_1(\theta_1 - \theta_2) = J_1 \ddot{\theta}_2 + c_2(\theta_2 - \theta_3) + k_2(\theta_2 - \theta_3) \]  \hspace{1cm} (2)

\[ J_1 \ddot{\theta}_3 + c_2(\dot{\theta}_2 - \dot{\theta}_3) + k_2(\theta_3 - \theta_2) = 0 \]  \hspace{1cm} (3)

Take the Laplace transform of the above equation, and the transfer function of the feed system is:

\[ G_1(s) = \frac{\theta_1(s)}{T_m} = \frac{J_2J_3s^4 + (J_1J_3s^3 + (J_1J_2s^2 + J_1s^4 + J_3)s^3 + J_3)s^2 + (J_1s^2 + J_2s + J_3) + J_3k_1 + J_1J_3k_2 + J_3k_3 + J_1k_3s + J_2k_3s^2) + (c_1k_2 + c_2k_1) + k_3k_2}{J_1J_2J_3s^6 + (J_1J_2s^5 + J_1J_3s^4 + J_1k_2s^3 + J_3k_1s^2 + J_1k_3s + J_2k_3s) + J_3k_1s^4 + J_1k_2s^3 + J_1k_3s^2 + J_2k_3s + J_3k_2s} \]

(4)

3. Relation between setting parameters and inertia ratio

In this paper, PID control is used to tune the closed-loop control parameters of the feed system. The commonly used method is the "third-order best" tuning method for dual inertia. References have adjusted the dual inertia control gain parameters, mechanical The relationship between resonance frequency and inertia ratio is simulated. The model established in this paper is three inertia, so a closed-loop root locus method is used to optimize system control parameters. The relationship between speed loop control parameters and speed feedback gain, current loop gain and torsion coefficient is as follows:
\[ K_\text{opt} = k_{\text{opt}} \cdot \theta \cdot K_\text{a} / K_\text{eff} \]  

(5)

\(K_{\text{opt}}\) is the optimal parameter with the minimum damping angle. \(\theta\) is the total inertia \((\theta=J_m+J_s+J_l)\). According to the formula of inertia ratio and the description of resonant frequency in literature\(^1,9\), it is determined that the calculation of inertia ratio is the ratio between each inertia and the total inertia. In Fig.2, \(J_m\) represents the input inertia and \(\theta\) is the total inertia. Therefore, it can be determined that the formula (6) for calculating the two inertia ratios \(\lambda_1/\lambda_2\) in the three inertia quantities is:

\[ \lambda_1 = \frac{J_m}{\theta}, \quad \lambda_2 = \frac{J_l}{\theta} \]  

(6)

Resonant frequency formula (7):

\[ \omega_0 = \sqrt{\frac{K \cdot J_m}{J_m + J_l}} \]  

(7)

According to Equation (7) and Reference 13, the numerical relationship between the three-inertia related gain parameters, low-order resonant frequency and inertia ratio is shown in Equation (8):

\[ k_{\text{opt}} \approx \omega_{01} \cdot \lambda_1^{0.8} + \omega_{02} \cdot \lambda_2^{2.6} \]  

(8)

Considering the speed feedback gain, current loop gain and torque coefficient, the proportional gain of the speed loop can be expressed in Formula (9):

\[ K_v = (\omega_{01} \cdot \lambda_1^{0.8} + \omega_{02} \cdot \lambda_2^{2.6}) \cdot \theta \cdot K_\text{a} / K_\text{eff} \]  

(9)

In the mechanical part of the flexible system, the integral lag of inertia, the elastic deformation of the elastic link, and the oscillation of the three inertias all cause the oscillation of the control system, so the increase of the closed-loop control gain should be limited. Because the inertia ratio can comprehensively reflect the factors above the mechanical part of the system, it is necessary to study the relationship between the inertia ratio and the control gain in order to investigate the influence of multiple factors on the mechanical part of the system. According to the formula of 8, can determine the different inertia ratio of the optimal control gain (\(\omega_{01} = 42.2\) Hz, \(\omega_{02} = 92.2\) Hz), such as table 1 and table 2:

| Inertia ratios | \(\lambda_1/\lambda_2\) | 1 | 2 | 3 | 4 | 5 |
|---------------|------------------------|---|---|---|---|---|
| \(K_{\text{opt}}\) | 13.714 | 22.41 | 37.58 | 64.01 | 110.0 |
| \(K_p\) | 1.08 | 1.76 | 2.95 | 5.032 | 8.64 |

Table 1 Optimal gain for different inertia ratios (The first moment of inertia)

| Inertia ratios | \(\lambda_1/\lambda_2\) | 1 | 2 | 3 | 4 | 5 |
|---------------|------------------------|---|---|---|---|---|
| \(K_{\text{opt}}\) | 20.79 | 22.41 | 32.18 | 91.398 | 45.17 |
| \(K_p\) | 1.6 | 1.76 | 2.53 | 7.18 | 35.46 |

Table 2 Optimal gain for different inertia ratios (The second moment of inertia)

According to Formula (8), the control parameters of the flexible feed system can be roughly calculated, and the optimal control gain is determined by the resonant frequency. In this paper, only low frequencies are simulated as fixed values respectively \(\lambda_1=0.405/\lambda_2=0.226\), as shown in Table 3:

| Resonant frequency (Hz) \(\omega_{01}/\omega_{02}\) | 1 | 2 | 3 | 4 | 5 |
|---------------------------------------------|---|---|---|---|---|
| \(K_{\text{opt}}\) | 32.4/92.5 | 42.4/92.5 | 52.4/92.5 | 62.4/92.5 | 72.4/92.5 |
| \(K_p\) | 18.68 | 23.53 | 28.38 | 32.24 | 38.09 |

Table 3 Optimal gain for different inertia ratios (Low frequency variable)

4. The influence of mechanical characteristic parameters on the dynamic characteristics of the system

This section will analyzes the influence of inertia ratio and resonant frequency on dynamic characteristics through MATLAB simulation.
4.1 Influence of inertia ratio change on dynamic characteristics of velocity loop

When the mechanical parameters of the mechanical transmission system (load, stiffness, damping, etc.) are fixed, the step response and frequency characteristics of the velocity loop obtained by considering the change of inertia ratio are shown in Fig.3:

![Figure 3 Effects of inertia ratio on velocity loops](image)

In Fig. 3, (a) and (b) are the time-domain and frequency-domain graphs of the changes of partial inertia before Table 1, and (c) and (d) are the time-domain and frequency-domain graphs of the changes of partial inertia after Table 2. As can be seen from the simulation results, when the inertia ratio increases, the speed adjustment time becomes longer. It can be seen that the minimum adjustment time is in the state of $\lambda_1=0.405$ (0.0528s), and the resonant frequency and anti-resonant frequency do not change.

4.2 Influence of frequency change on dynamic characteristics of velocity loop

When the mechanical structure of the system is completed, the parameters of the motor, lead screw and nut pair worktable are fixed values, and the inertia ratio is fixed values. The control parameters of the system can be corrected by their parameters. The simulation graph obtained from Table 3 is shown in Fig 4:

![Figure 4 Effects of different low frequencies on velocity loops](image)

The simulation results show that in the low frequency band, the response time increases with the increase of frequency (0.0527s--0.0649s), but the span range is not large, and the frequency domain...
characteristics change little. Therefore, the method of using frequency parameters to determine control parameters can only be used as a reference, not as the main basis.

5. conclusion
(1) In this paper, the three inertia model of the mechanical part of the feed system is established, and the algorithm formula of the second order frequency and inertia ratio is derived. The relationship between inertia ratio and the time domain and frequency domain characteristics of CNC machine feed system is analyzed. The control gain calculated by the formula can be matched with the system to achieve the optimal response.

(2) Based on the research in this paper, it provides a simple and effective method for NC machine tool designers to calculate the control parameters of the system. The parameters calculated by this method can match the system and correctly describe the dynamic characteristics of the feed system.

Acknowledgments
This paper is one of the phased results of the Youth Fund project of Taishan University "Research on Planning Method Based on Dynamic Characteristic Parameters of Feed System" (QN-01-201902)

References
[1] Oliver Zirn. Machine Tool Analysis Modelling, Simulation and Control of Machine Tool Manipulators [M]. Department of Mechanical & Process Engineering ETH Zürich, 2008.
[2] Liao By, Zhou XM, Yin HZ. Modern Mechanical Dynamics and Its Engineering Applications [M]. Beijing: China Machine Press, 2004.
[3] Gu J.G, Zhang Y.M. Dynamic analysis of a ball screw feed system with time-varying and piecewise-nonlinear stiffness [J]. Journal of Mechanical Engineering Science, 2019, 0(0): 1-16.
[4] ZHU J.M, ZHANG T.C, LI X.R. Dynamic Characteristic Analysis of Ball Screw Feed System Based on Stiffness Characteristic of Mechanical Joints [J]. Journal of Mechanical Engineering, 2015, 51 (17): 72-82.
[5] Li Xuewei. Research on Machining Trajectory Error Prediction and Compensation Method of High-speed CNC Machine Tool [D]. Xi’an Jiaotong University, 2013.
[6] Wang lei. Modeling and Dynamic Response Analysis of Feed System under Low Frequency Servo Excitation [J]. Journal of Mechanical Engineering, 2015, 51(3): 81-86.
[7] Mohamed S. ZAKY. A self-tuning PI controller for the speed control of electrical motordrives [J]. Electric Power Systems Research, 2015, 119: 293-303.
[8] Liu H, Huang Y, ZHAO Wanhua, et al. Comprehensive Analysis and Design of Load Inertial Ratio of NC Machine Tool Feed System under Coupling of Multiple Factors [J]. Journal of Mechanical Engineering, 2014, 50(9): 108-113.
[9] Liu H, Huang Y, Zhao W.H, Lu B.H. Influence Law of Transmission Stiffness Variation on Motion Accuracy Stability of CNC Machine Tool Feed System [J]. Journal of Mechanical Engineering, 2014, 50(23): 128-133.