Analysis of creeping mechanism and eliminating measures of creeping phenomenon of machine feeding system

Chuanliang Yu, Ruijun Liang*, Wei Li and Dan Song
School of Mechanical and electrical College, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
*Corresponding author’s e-mail: lruijun@nuaa.edu.cn

Abstract. When the machine tool feeding system is running at low speed, the creeping phenomenon of the system will occur, which seriously affects the machining accuracy of the machine tool and the surface quality of the parts. In this paper, the mechanism behind the creeping phenomenon generated by the machine tool is theoretically analyzed. The dynamics and mathematical model are established, and the critical equation for generating the creeping phenomenon is solved based on the dynamics and mathematical model which we established. The influence of various factors on the creeping phenomenon is obtained by the equation analysis. Some measures to eliminate creeping phenomenon are presented.

1. Introduction

The machine tool feeding system is an important part of the machine tool, and its accuracy has an important influence on the machining accuracy of the machine tool[1]. When the feeding system moves under the condition of low speed and heavy load, the phenomenon of the feeding system’s periodic walking and stopping, fast and slow motion will occur. This phenomenon is called the creeping phenomenon, also known as stick-slip motion. The creeping phenomenon of the machine feeding system is a form of self-excited vibration of the machine tool[2,3,4]. The error generated by the machine belongs to the dynamic error of the machine feeding system, which leads to the unevenness of the movement of the table, reduces the surface quality of the machined workpiece and the machining accuracy of the machine tool, meantime causes wear on the parts and tools of the feeding system and reduces the service life of the machine[5,6]. Therefore, studying the creeping phenomenon of the machine feeding system and its production mechanism and influencing factors have a great practical significance for reducing the influence of creeping phenomenon on the machine feeding system and improving the machining accuracy of the machine tool[7]. This paper mainly establishes the mechanical and mathematical models of the machine feeding system, analyzes the influencing factors of the creeping system, and proposes several measures that can use to eliminate the creeping phenomenon.
2. Characteristic analysis of Machine tool feeding system

2.1 Machine tool feeding system dynamics model

![Mechanical model of the creeping phenomenon of the feeding system.](image)

The machine feeding system can be simplified to the mechanical model shown in figure 1. The movement of the servo motor driving table is simplified as the drive member \( A \) drives the driven member \( B \) to move at a constant speed \( v \). The displacement of the driven member \( B \) is \( x \). The dynamics characteristic of the entire feeding system are simplified into an equivalent spring which stiffness is \( K \) and a damper which damping value is \( C \). The general friction force between the sports pair is defined as \( f \). When the driving body starts to move right at a constant speed, due to the frictional resistance \( f \), the driving member does not move for a short time after the start of the movement, meantime the spring is compressed. The driving body moves \( \Delta x \) away from the spring and stores potential energy. When the elastic force \( k \Delta x \) exceeds the static friction force \( f_s \), the driven body starts to move. After the driven body moves, the general friction force is not the static frictional force \( f_s \) but the dynamic frictional force \( f_d \). As is known from the frictional force characteristics, we know that \( f_d < f_s \), so we can get that \( k \Delta x > f_d \). Then the potential energy stored in the spring is starting to release, and the driven body obtains an acceleration to jump. When the compression amount of the spring is reduced to make the spring force equals to the dynamic friction force, the driven body is balanced, and the motion should be performed at a constant speed. However, due to the existence of inertial force, the driven body continues to jump forward, and the compression of the spring is further reduced, so that the elastic force starts to be smaller than the frictional resistance, so that the driven body is decelerated; if the inertia is too large, the elastic force will be too small to maintain its motion, so that the driven body is stopped. Then, the above process is repeated to form a creeping phenomenon of the driven body. If the driving speed is at a high level, the frictional force works without the falling characteristic, and the creeping phenomenon naturally does not occur.

2.2 Mathematical model of machine tool feed system

For the force analysis of the driven member in figure 1, the equation of motion can be expressed as:

\[
M\ddot{x} + C(\dot{x} - v) + K(x - vt) = -f
\]  

(1)

Where \( M \) - the quality of the driven parts, \( t \) - the movement time of the driving parts.

2.2.1. The feeding system does not occur creeping phenomenon. If the creeping phenomenon does not occur, the driven member moves stably, that is

\[
\begin{align*}
\dot{x} &= \dot{x}_w = v \\
\ddot{x} &= \ddot{x}_w = 0 \\
f &= f_s
\end{align*}
\]  

(2)

Where \( \dot{x}_w \) - the speed at which the driven member is in a stable motion, \( \ddot{x}_w \) - the acceleration when the driven member is in a stable motion, \( f_s \) - friction when the driven member is in stable motion.
Substituting equation (2) into equation (1) and simplifying it:

\[ f_w = K(vt - x_u) \]  (3)

At this time, the elastic force \( K(vt - x_u) \) and the stable friction force \( f_w \) are balanced, and the amount of expansion and contraction of the equivalent spring \( vt - x_u \) is a constant value.

2.2.2. The feeding system produces creeping phenomenon. When the feeding system is creeping, the amount of expansion and contraction of the spring changes with time, and the movement of the driven member is unstable at this time. Assume the amount of deviation \( \Delta_x \) of the instantaneous displacement \( x \) from the steady state value \( x_u \) of the driven member, then

\[
\begin{align*}
    x &= x_u + \Delta_x, \\
    \dot{x} &= \dot{x}_u + \dot{\Delta}_x = v + \dot{\Delta}_v, \\
    \ddot{x} &= \ddot{x}_u + \ddot{\Delta}_x, \\
    f &= f_w + \Delta_f
\end{align*}
\]  (4)

where \( \Delta_f \) - The amount of changing in friction

When the speed of movement is a low level, \( \Delta_f \) and \( \dot{\Delta}_v \) can be considered to be proportional, let

\[ \Delta_f = C_1 \dot{\Delta}_v \]  (5)

Simplifying the simultaneous equation (1) and (4), we can get

\[ M(\ddot{x}_u + \ddot{\Delta}_v) + C(\dot{x}_u + \dot{\Delta}_v - v) + K(x_u + \Delta_x - vt) = -f_w - \Delta_f \]  (6)

Simplifying the simultaneous equation (2), (3), (5) and (6), we can get

\[ M\ddot{\Delta}_x + (C + C_1) \dot{\Delta}_x + K\Delta_x = 0 \]  (7)

When the driven member is unstable, solve the equation (7) and we can get

\[ \Delta_x = e^{-\zeta\omega_d t} (Ae^{\omega_d t_1} + Be^{\omega_d t_2}) \]  (8)

where \( \zeta = \frac{C + C_1}{2\sqrt{KM}} \) - the damping coefficient of the system, \( \omega_d = \frac{K}{\sqrt{M}} \) (when the damping is small), \( \omega_d \) - the natural frequency of the system damping,

\( \omega_d = \omega_n \approx \frac{K}{M} \) - the time when the driven member moves, \( \omega_n \) - the natural frequency of the system damping,

Assume the interval between the start of the movement of the driving member and the start of the movement of the driven member is \( t_0 \), and the subjected force of driving member during this period is the static friction force \( f_s \), at which time the driven member is in an equilibrium state before the movement, that is \( t = t_0, x = \ddot{x} = \dot{x} = 0 \). By the equation (1) we can get

\[ f_s = Cv + Kvt_0 \]  (9)

At the moment when the driven member starts to move, the general friction force is not the static frictional force \( f_s \), but the dynamic frictional force \( f_d \), and the driven member obtains an acceleration.

The initial conditions at this time are

\[
\begin{align*}
    t &= t - t_0 = 0, \\
    x &= \dot{x}_u + \dot{\Delta}_x = 0, \\
    \dot{x} &= \ddot{x}_u + \ddot{\Delta}_x = 0, \\
    \ddot{x} &= \dddot{x}_u + \dddot{\Delta}_x = \dddot{\Delta}_x
\end{align*}
\]  (10)

Simplifying the simultaneous equation (1), (9) and (10), we can get:

\[ \dddot{\Delta}_x = \frac{f_s - f_d}{M} = \frac{\Delta_f}{M} \]  (11)

\( \Delta_f \) - The difference between static friction and dynamic friction.
Substituting equations (10) and (11) into the first-order and second-order derivatives of equation (8), and omitting the high-order terms $\varepsilon^2 (\ll 1)$, we can obtain:

$$
A = \frac{v}{\omega_n} (-D \varepsilon - 1)
$$

$$
B = \frac{v}{\omega_n} (2 \varepsilon - D)
$$

$$
D = \frac{\Delta_f}{v \sqrt{KM}}
$$

Substituting equation (12) into equation (8), the vibration displacement of the driven member can be obtained as:

$$
\Delta_v = \frac{v}{\omega_n} e^{-\omega_n t} [(-D \varepsilon - 1) \sin \omega_n t - (2 \varepsilon - D) \cos \omega_n t]
$$

3. Factors influencing the creeping phenomenon

Deriving equation (14) and omitting the high-order term $\varepsilon^2 (\ll 1)$, the corresponding self-excited vibration velocity is obtained as follows:

$$
\Delta_v \approx e^{-\omega_n t} [(D - \varepsilon) \sin \omega_n t - \cos \omega_n t]
$$

According to equation (15), if

$$
e^{-\omega_n t} [(D - \varepsilon) \sin \omega_n t - \cos \omega_n t] < 1
$$

Then the vibration speed of the driven member will gradually decay to zero. Obviously, we can obtain some conditions that the driven member does not creep from the equation (16), let

$$
e^{-\omega_n t} [(D - \varepsilon) \sin \omega_n t - \cos \omega_n t] = 1
$$

Equation (17) is difficult to solve. For the convenience of calculation, let $D_0 \approx 4\pi \varepsilon$. Substituting into equation (13), the critical speed $v_0$ at which the driven member does not creep is:

$$
v_0 = \frac{\Delta_f}{D_0 \sqrt{KM}} = \frac{\Delta_f}{\sqrt{2\pi(C + C_1)\sqrt{KM}}}
$$

It can be seen from equation (18) that the factors affecting the creeping phenomenon include the difference between the static and dynamic friction $\Delta_f$ of the feed system, the dynamic characteristics of the feeding system (stiffness $K$ and damping value $(C + C_1)$), the load mass $M$ and the running speed $v$ of the table.

4. Measures to eliminate the creeping phenomenon of the machine feeding system

(1) Reduce the difference between static and dynamic friction coefficients. The following two measures are usually taken: One is that rolling friction can be used instead of sliding friction. There is virtually no difference in the coefficients between static and dynamic friction, and the coefficient of dynamic friction does not change with speed [8].

(2) Change the characteristics of the dynamic friction coefficient as a function of speed. To avoid creep, the speed of movement must be greater than the critical speed. In this case, the moving member will change at a uniform speed according to the driving speed after a period of transition, and no creeping phenomenon occur.

(3) Improve the rigidity of the transmission mechanism. It is very beneficial to eliminate creeping phenomenon by improving the transmission stiffness of the drive chain. The cause of creeping is often the bearing, screw nut pair and screw itself pretension or pretension is not ideal, there is a gap in the transmission chain, or the transmission chain is too long, drive shaft diameter is small, support part stiffness or support seat stiffness is not enough.

(4) Increase the damping ratio. In addition to introducing damping into the system and changing the dynamic characteristics of the system, the most effective way is to change the coefficient of friction by improving lubrication or changing materials.
5. Conclusion
The creeping phenomenon of the machine feeding system is a kind of fault of the machine tool, and the consequences are quite serious, which will directly affect the machining accuracy of the machine tool. The causes of CNC machine tool creeping are mechanical, hydraulic, electrical and so on. Only by rationally analyzing the principle and accumulating experience in practice, can we find the best solution to eliminate the creeping of machine tools, thus improving the machining accuracy and reliability of CNC machine tools.

Acknowledgement
The author(s) disclosed receipt of the following financial support for the research and/or authorship of this article: This work was supported by the National Natural Science Foundation of China (No. 51575272).

References
[1] Tang, X., Chai, X., Tang, L., Shao, Z. (2014) Accuracy synthesis of a multi-level hybrid positioning mechanism for the feed support system in fast. Robotics and Computer-Integrated Manufacturing, 30:565-575.
[2] Leine, R. I., Campen, D. H. V., Kraker, A. D., Steen, L. V. D. (1998) Stick-slip vibrations induced by alternate friction models. Nonlinear Dynamics, 16: 41-54.
[3] Capone, G., D'Agostino, V., Valle, S. D., Guida, D. (1993) Influence of the variation between static and kinetic friction on stick-slip instability. Wear, 161: 121-126.
[4] Wang, D., Xu, C. (2014) A tangential stick-slip friction model for rough interface. Chinese Journal of Mechanical Engineering, 50: 129-134.
[5] Wang, S. M., Yu, H. J., Liao, H. W. (2006) A new high-efficiency error compensation system for CNC multi-axis machine tools. International Journal of Advanced Manufacturing Technology, 28: 518-526.
[6] Yu, Y., Liu, Ping. (2012) Evaluation of cutting error in five-axis free-form surface milling for table-tilting type machine. Advanced Materials Research, 472-475: 2125-2128.
[7] Wagner, Erika. (2016) A new method of diminishing errors of form generated by the imprecision of CNC machines. Procedia Technology, 22:13-19.
[8] Yeh, S. S., Sun, Jin Tsu. (2010) Measurement and analysis of static friction for feed drives of CNC machine tools. Applied Mechanics & Materials, 36:86-95.