Optimal parameter tuning of feed drive systems to minimize quadrant protrusion errors

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Abstract : This paper describes modeling and identification of nonlinear feed drive systems with stick-slip friction and quadrant protrusion errors, and optimal parameter tuning methods in ball screw driven feed drive systems to compensate for friction. Integrated design of the feed drive system is performed by the genetic algorithm. A circular profiled test simulation is developed to examine the influence of quadrant protrusion error. Experimental setup is constructed by using the encoder board and ¥ ìcomputer. Numerical simulations and experiments are performed to verify the proposed friction models and parameters of the control strategy.

Keywords : CNC machine tools, Feed drive systems, Stick-slip friction, velocity control loop, Contouring accuracy, Genetic algorithm, Quadrant protrusion error, Optimization, Circular profile test.

1. Introduction

The significance of machine tool accuracy is well recognized due to the increasing demand of dimensional accuracy of products. The accuracy enhancement by careful design and manufacturing has been extensively used to solve machine error problems. Various types of errors occurred in CNC machine tools should be minimized to meet the accuracy demand[1].

Errors of feed drive systems of a CNC machine tool are composed of mechanical and servo control errors. The most prominent factor of the mechanical errors is friction that is inevitable in mechanical systems. Sources of friction forces such as coulomb, viscous and stick-slip include the servomotor and ball screw bearing, the interface between the screw and nut and the linear guideway[1,2,3]. Friction reduces positioning and tracking accuracy in servomechanism. To improve the contouring accuracy of servomechanism the frictional effect should be accurately identified and controlled in the vicinity of zero velocity.

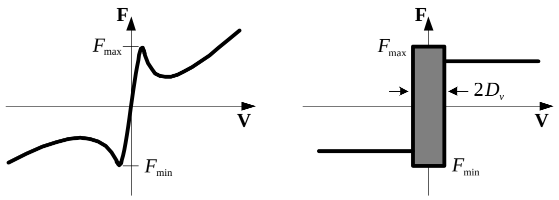
In this paper, friction is studied as a model between velocity and friction force(torque) that depends upon the sign of velocity. Quadrant protrusion errors are identified with the proposed stick-slip friction model. Control design to compensate for friction is studied by using the optimal design and control of the feed drive system. There are several control strategies to compensate for the quadrant protrusion error of feed drive systems such as the adaptive control and disturbance observer. However, since there are lots of control parameters, it is difficult to tune optimal parameters at once. With the genetic algorithm as an optimization tool, parameters of the control strategy are to be tuned in this paper.

Circular profiled tests and simulations are introduced to examine the control performance of the integrated design.

2. Friction Model

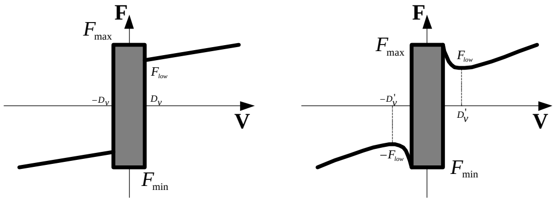
When velocity of a table, which is a moving part of the feed drive system, is reversed, quadrant protrusion error caused by stick-slip friction appears. The friction force and velocity relationship is plotted in Fig1. The modeling and simulation of stick-slip friction is difficult because strongly nonlinear dynamic behaviors exist in the vicinity of zero velocity.

Many researchers such as Kaneko, Karnopp, and Tsutsumi have proposed stick-slip friction model[2,3]. In this model, friction force is constant in the small velocity region ($-D_V < V < D_V$) and increases or decreases outside this region. In this paper, new linear and nonlinear models of the stick-slip friction similar to the actual slick-slip behavior are proposed. As in Fig.2, friction force is constant in the small velocity region and increases linearly (see Fig.2(a)) or exponentially (see Fig.2(b)) outside small velocity region. These model become as follows:



(a) Actural behavior (b) Karnopp model

Fig. 1 Friction force and velocity



(a) Linear model (b) Nonlinear model

Fig.2 Proposed stick-slip models

$$F_f = F_{stick} + F_{slip} = f(V)$$

$$F_{stick} = \begin{cases} linear \begin{cases} F_{\max} \ (-D_V < V < D_V) \\ 0 \quad (otherwise) \end{cases} \\ nonlinear \begin{cases} F_{\max} \ (-D_V^{'} < V < D_V^{'}) \\ 0 \quad (otherwise) \end{cases} \end{cases}$$

$$F_{slip} = \begin{cases} linear \begin{cases} m(V - D_V) + F_{low}, \ (V > 0) \\ m(V + D_V) - F_{low}, \ (V < 0) \end{cases} \\ nonlinear \begin{cases} p(V - D_V^{'})^2 + F_{low}, \ (V > 0) \\ -p(V + D_V^{'})^2 - F_{low}, \ (V < 0) \end{cases} \end{cases} \tag{1}$$

$$p = \frac{F_{\max} - F_{low}}{(D_V^{'} - D_V)^2}, \ D_V \approx 5 D_V^{'}$$

In Eq(1), D_V is the upper limit or lower limit of small velocity region and m is the friction coefficient. Parameter values are obtained from experimental identification processes.

3. Identification of Friction Models

Rotational dynamics of the servomechanism becomes

$$T_m = K_t \cdot I_{rms} = J_e \frac{dw}{dt} + B \cdot w + T_f + T_c \tag{2}$$

where T_f is the frictional torque, T_C is cutting torque, T_m is the motor toque, K_t is the torque constant of servomotor, I_{rms} is the root mean square value of motor current, J_e is the equivalent inertia of the servo mechanism, B is the damping coefficient and w is the angular velocity of the servomotor.

Eq.(2) is simplified with the assumption of zero viscosity and cutting torque at the steady state as

$$T_m = K_t \cdot I_{rms} = T_f \tag{3}$$

Considering the relationship between motor torque and friction force, following relationships are obtained.

$$h \cdot T_m \cdot q = F_f \cdot d$$

$$F_f = h \cdot T_m \frac{q}{d} = h \cdot T_m \frac{2p}{p} \tag{4}$$

In Eq.(4), h is the efficiency of ball screw ($\simeq 0.9$), d and p are ball screw diameter and pitch, respectively. The servomotor current is measured directly from the CNC unit. The velocity and position are obtained from the encoder of the servomotor.

4. Modeling of Feed Drive Systems

Most controllers of CNC machine tools are organized in the cascade structure, comprising the position, velocity and current control loops as shown in Fig.3. Important controller parameters, which have major influence on the accuracy of CNC machine tools, are velocity control loop parameters which are the proportional and integral gains[4].

The transfer function of the velocity control loop in Fig.3 can be represented as

$$G_V(s) = a \cdot V_p \cdot \left(1 + \frac{V_i \cdot b}{t\,s + 1} \right) \tag{5}$$

Where t is the time constant of the servomechanism, a, b are coefficients that convert analog values to digital values and V_p ,V_i are the proportional and integral gains of the velocity control loop, respectively.

For CNC machine tools, the table moving along the machine tool slideway can be simplified as the slider moving along the surface with friction (see Fig.4(a)).

Considering frictional effects, a block diagram of Fig.4(b) is constructed, and input forces become

$$\begin{aligned} F_{total} &= M_{eq} \cdot \dot{V}_{table} \\ F_{total} &= F_C + F_k - F_f \\ F_C &= C_{eq} \cdot (V_{motor} - V_{table}) \\ F_k &= K_{eq} \cdot (\int V_{motor} - \int V_{table}) \\ F_f &= function\ of\ table\ velocity \end{aligned} \tag{6}$$

where, M_{eq} is the equivalent mass and C_{eq} ,K_{eq} are the damping coefficient and spring coefficient,

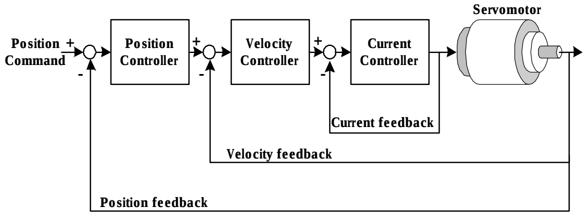


Fig.3 Schematic diagram of feed drive controller

respectively. Mechanical and controller parameters of the feed drive system are listed in Table 1.

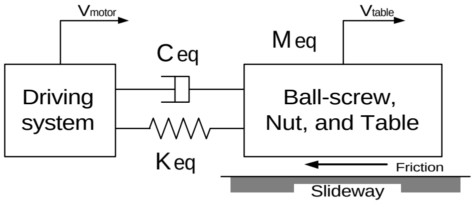
5. Formulation of optimization problem

To compensate for quadrant protrusion errors, a simple compensation algorithm has been proposed in this paper. As shown in Eq.(5), the velocity gain has significant influence on disturbances.

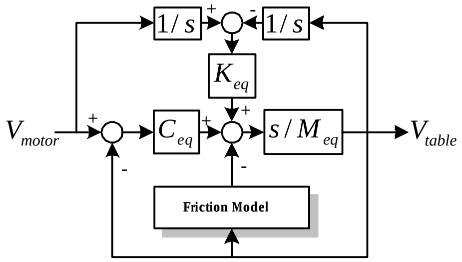
From the Fig.3, the velocity feedback, which is also the feed command fed into the driving mechanism, becomes

$$V_f(s) = H(s)\cdot V_{cmd}(s) + D(s)\cdot T_d(s) \qquad (7)$$

Where $H(s)$ is the transfer function of the closed velocity control loop, $D(s)$ is the disturbance transfer function between velocity feedback and disturbance, and T_d is the disturbance torque. Therefore, increasing velocity loop gain can reduce the disturbance transfer function $D(s)$. As a result, the disturbance component in the feed drive system, such as quadrant protrusion due to stick-slip friction, can be effectively suppressed.



(a) Schematic diagram



(b) Block diagram

Fig.4 Feed drive systems with frictional effects

Table 1 Identified system parameters

Parameter		Value [unit]
Friction	$F_{\max}$	1127.8 N
	F_{low}	951.3 N
	D_v	0.5 mm/sec
Feed Drive	M_{eq}	335 kg
	C_{eq}	73.8 Nsec/mm
	K_{eq}	151 N/mm

Using the model of feed drive systems and stick-slip friction, optimal parameter tuning problem to minimize quadrant protrusion errors is constructed as follows:

$$\begin{aligned}
&\textit{Find} \quad : V_p,\, V_i \\
&\textit{Minimize} : \frac{1}{a\cdot V_p\left(1+b\cdot V_i\right)} \\
&\textit{Subject to} : M_p = \tan^{-1}\left(\frac{2z}{\sqrt{\sqrt{1+4z^4}-2z^2}}\right) \ge M_p^* \qquad (8)\\
&\qquad T_r = \frac{2p\cdot N}{60\cdot T}\left(J_{eq}+R^2\cdot M_{eq}\right) \le T_r^*
\end{aligned}$$

To minimize the sensitivity to disturbances of the feed drive system, which is the same as maximizing the servo stiffness, reciprocal of the velocity gain is selected as an objective function. And the proportional and integral gain are selected as design variables. The gain margin and phase margin of feed drive systems are used for constraints to discriminate system stability in this optimization problem.

6. Optimization Results

Traditional optimization tools cannot solve the problem shown in Eq.(8) However, there are some advantages when the problem is to be solved by the genetic algorithm. At first, we don't have to care much about the nonlinearity of object functions and constraints. The next advantage is that the GA doesn't need the initial design due to stochastic nature in itself, which is an empirical and intuitive element in the design process[5]. Table 2 shows the optimal velocity loop parameters obtained through the GA.

7. Experimental verification

Fig.5 shows the results of a circular test with the proposed stick-slip friction models. The simulated and actual circular profiles are corresponded to the dashed

Table 2 Optimal parameters for velocity loop

Symbol	Parameter value	
	Standard	**Optimal**
z	0.71	1.63
V_p	101.121	99.522
V_i	1.140	2.596

and solid lines, respectively. As shown in Fig.5, contouring error due to quadrant protrusion errors is about 25 § -and radius decrease error is 50 § -with feedrate of 2000mm/min and a radius of 150mm. After tuning the velocity loop parameters, a new circular profile is shown in Fig.6(b). Not only quadrant protrusions are reduced under 52%(12 §) but also the radius decrease error is largely suppressed.

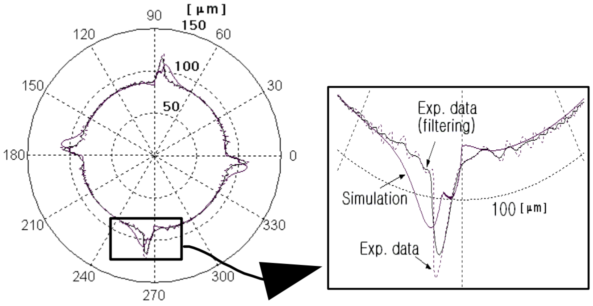
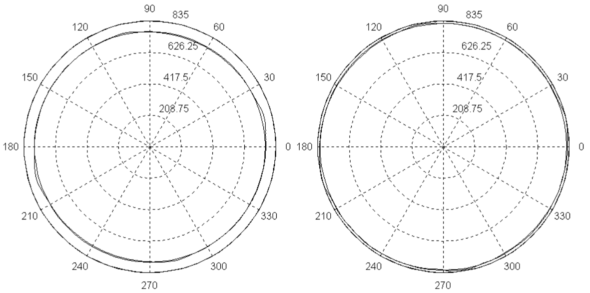


Fig. 5 Results of circular profile test (center : 149.875mm)



(a) Standard parameter (b) Optimal parameter

Fig. 6 Circular test with standard and optimal parameters (center : 149.200mm)

8. Conclusion

An investigation of the quadrant protrusion errors in CNC machine tools due to stick-slip friction has been reported in this paper. Simulation and experimental results have indicated that the quadrant protrusion produced by stick-slip friction and the radius decrease error due to servo characteristics are a primary contouring error in a circular test. It has also been demonstrated that an optimal tuning of velocity loop parameters in order to minimize the sensitivity to disturbances of feed drive systems can efficiently compensate for quadrant protrusion errors.

Further study is to develop an auto–tuning strategy to compensate for or remove the contouring errors due to frictional effects.

Acknowledgement

The authors wish to acknowledge the financial supports from Hwachen Machine Tool Co.,Ltd.

References

1. Y. Kakino, 1994, “A Study on the Total Tuning of Feed Drive Systems in NC Machine Tools”, JSPE, Vol.60, No.8, pp.1158-1164.
2. Dean karnopp, 1995, “Computer Simulation of Stick-Slip Friction in Mechanical Dynamic Systems”, ASME Journal of Dynamic Systems, Measurement and Control, Vol.107, Keynotepaper, pp.100-103.
3. M. Tsutsumi, 1995, “Mathematical Model of Feed Drive System and Friction for CNC Machine Tools”, JSPE, Vol.61, No.10, pp.1458-1462.
4. Y.Koren, 1997, “Control of Machine Tools”, ASME Journal of Dynamic Systems, Measurement and Control, Vol.119, pp.749-755.
5. Z.Michalewicz, 1994, “Evolutionary Computation Techniques for Nonlinear Programming Problems”, Int.Transactions in Operational Research, Vol.1, No.2, pp.223-240.