

# A STUDY ON MODEL-BASED ANALYSIS OF THE DYNAMIC MOTION ACCURACY OF CNC MACHINE TOOLS

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## 1. Introduction

In the past, the solution to increase machine tool accuracy and speed has been to make incremental innovations to both the machine design and the numerical controller. There have been many improvements to the feed-drive mechanism including ball screw, supporting member, and coupling design and material improvements, rotary motor and encoder developments, and guideway redesigns (air and lubrication oil additions) to minimize friction. From the controller side, additional peripheral functions have been included to compensate for non-linearities such as backlash (quadrant protrusion compensation), guide-way stiction, and pitch errors.

One cause for machine tool inaccuracy lies in the area of the feed-drive system. In today's machine tool industry, the most common mechanism to actualize the table position is still the conventional ball screw mechanism, which introduces three main sources of error: thermal expansion, static/dynamic friction, and elastic deformation of the components such as ball nut, supporting bracket and bearings, ball screw, etc.

During high-speed machining, the machine table is required to accelerate and decelerate extremely rapid. Due to the sudden high torque applied to the end of the shaft, some of the motor's energy is employed to elastically twist the ball screw material. The severity of this elastic deformation of the ball screw depends not only on the magnitude of the torque, but additionally the table position. With increased table position the effective ball screw length is increased and thus the rigidity of the ball screw shaft decreases. Consequently, the decreased rigidity is a source of machining errors: it creates an initial time delay in the response and a transient oscillation of the table around the desired position as the shaft 'untwists.' Therefore the problem exists to enhance the feed-drive mechanism to significantly improve the machining precision and reduce these dynamic motion errors.

The objective of this research is to develop an accurate simulation model for multi-axis feed drive system motion in a CNC vertical machining center by accounting for the torsional deformation that occurs within the ball screw shaft during the high acceleration and deceleration process. This model can be used to improve the positioning accuracy of the ball screw feed drive system.

## 2. Modeling of the feed drive system

There are four basic components of a CNC feed-drive system. These are the Interpolator and Trajectory Generator, the Servo Controller, the Actuator System (containing the amplifier), and the Mechanism for both the X and Y axes which operate independently.

### 2.1 Machine Tool Interpolator and Trajectory Generator

The first part of the model is the command creation, which is achieved by a Trajectory Generator. In the physical system the Interpolator reads the program code and the Trajectory Generator creates the motion command accordingly. In the simulation model only the motion command creation is necessary to serve as the input to the feed-drive model in order to conduct tests. Among the interpolated motions, a circular interpolation will be modeled because circular tests are most popularly used to evaluate the machine motion performance. The X and Y positions are determined at each time step based on the equations:

$$\begin{aligned} X &= \text{Radius} \cdot \cos(t \cdot \text{Feed} / \text{Radius} / 60) \\ Y &= \text{Radius} \cdot \sin(t \cdot \text{Feed} / \text{Radius} / 60) \end{aligned} \quad (1)$$

The feed-rate (Feed) and radius are first specified. In the model, after these values are calculated they are compared to a function to check if it is the end of the circle. If not, they are each multiplied by a filter which has the form:  $1/(t_s s + 1)$ , and generates the radius reduction phenomenon that occurs in the real machine. The outputs from both X and Y axes are used as inputs to the model's feed-drive system.

## 2.2 PID Servo Controller

The first component of the machine tool that receives the motion command from the Interpolator and Trajectory Generator is the servo controller. A simplified diagram of the CNC machine tool controller is shown in Figure 1. Multi-loop feedback is used to control position, velocity, and current of the motor and mechanism. The parameter values input to the simulation model are the same values as the machine in which we are trying to model.

## 2.3 Actuator System

The third component of the CNC Machine Tool Feed-drive System is the Actuator System, which consists of an amplifier and an electric servomotor to drive each axis. A model of DC motor was used.

## 2.4 Feed-drive Mechanism

The last component of the feed-drive system is the mechanism. The mass-spring-damper model of a precise feed-drive mechanism to account for the friction existing on the guide surfaces and brackets, which would affect the response of feed-drive mechanism is given in Figure 2. This model includes the parameter of ball screw torsional stiffness  $K_q$ . The dynamic calculation of this parameter is crucial in this research. Furthermore, the axial rigidity of the supporting members (ball screw, supporting bearings and bracket) between a ball screw and machine base,  $K_s$ , and the axial rigidity between the ball screw and table,  $K_n$ , are included. The following are the governing equations of this new model.

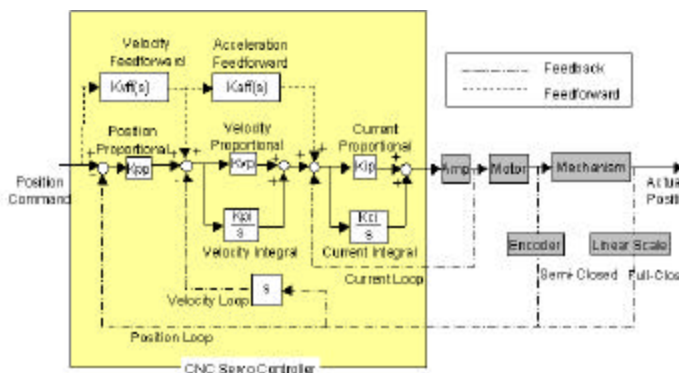


Figure 1: CNC Machine Tool Servo Controller

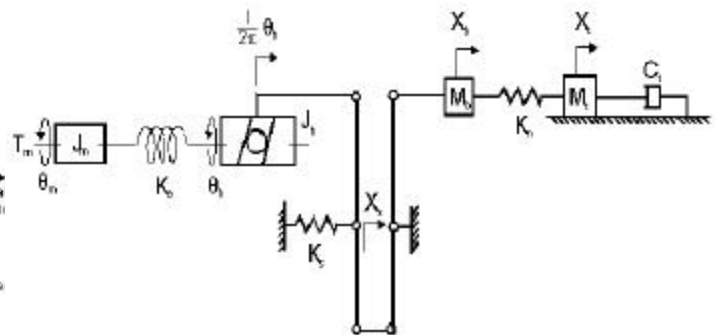


Figure 2: Mass-Spring-Damper Model of Feed-Drive Mechanism[1]

$$\begin{aligned}
J_m \ddot{\mathbf{q}}_m + K_q (\mathbf{q}_m - \mathbf{q}_b) + T_{mf} (\dot{\mathbf{q}}_m) &= T_m \\
J_b \ddot{\mathbf{q}}_b + K_q (\mathbf{q}_b - \mathbf{q}_m) + \frac{l}{2p} K_s (\frac{l}{2p} \mathbf{q}_b - X_b) + T_{bf} (\dot{\mathbf{q}}_b) &= 0 \\
M_b \ddot{X}_b + K_s (X_b - \frac{l}{2p} \mathbf{q}_b) + K_n (X_b - X_t) + F_{bf} (\dot{X}_b) &= 0 \\
M_t \ddot{X}_t + C_t \dot{X}_t + K_n (X_t - X_b) + F_{tf} (\dot{X}_t) &= 0
\end{aligned} \tag{2}$$

Where  $T_m$  is the motor torque,  $J_m$  is the inertia of the motor,  $J_b$  is the inertia of the load (Coupling, Ball Screw, and Table),  $M_n$  is the mass of the nut,  $M_t$  is the mass of the table, and  $l$  is the pitch of the ball screw shaft.

The states are  $\mathbf{q}_m$  (position of the motor in radians),  $\mathbf{q}_b$  (ball screw position in radians),  $X_b$  (ball screw position in millimeters),  $X_t$  (table position in millimeters).

These equations also consider four frictional non-linearities  $T_{mf}$  (frictional torque on the motor),  $T_{bf}$  (bracket frictional torque on the ball screw),  $F_{bf}$  (frictional force on the nut and supporting parts) and  $F_{tf}$  (frictional force between the guide and table).

The followins is the torsional rigidity equation that calculates the ball screw stiffness from the table position, which affects L.

$$K_q = pr^4 G / 2L \tag{3}$$

### 3. Evaluation and optimization of simulation model

#### 3.1 Parameter optimization of simulation model

Because this research also investigates how the ball screw mechanism contributes to machining errors, variables considered for comparison are the motor's position at each point along the trajectory

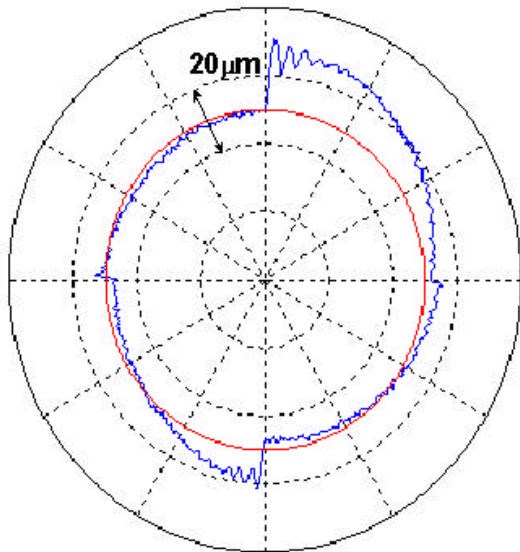


Figure 3: Physical Result Magnified 2-Axes Error Plot for F=5, R=50, XP0=2769, YP0=1584

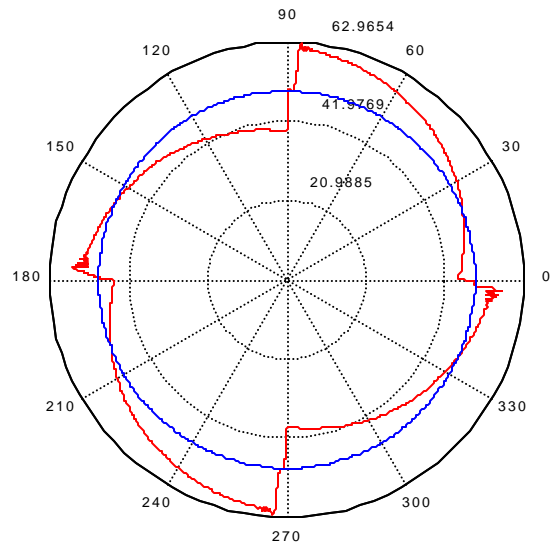


Figure 4: Simulation Result Magnified 2-Axes Error Plot for F=5, R=50, XP0=2769, YP0=1584

(in order to gage the difference between the table and motor position at each instance), and the time delay between the motor and table positions. After comparing the motion curves of the machine and model, the simulation model parameters were optimized. The parameters considered were the friction model parameters, namely the dynamic and static friction constants, and the stiction velocity because these were the most difficult to predict.

In the two-axes case, the magnitude of the error at the quadrant changes and the reduction in error after each quadrant will be considered. The plot of the 2-axis physical results with the experimental conditions of  $F=5000\text{mm/min}$ ,  $R=50\text{mm}$  is shown in Figure 3. After changing the X frictional constants, increasing the supporting member rigidity, and changing the Y frictional constants, increasing the supporting member rigidity the simulation result is very close to the physical result and is shown in Figure 4. The main differences between the two plots are the magnitude of the stiction after crossing the x-axis, and the amount of radius reduction after crossing the desired trajectory, the model exhibits the same feature of machine circular motion. The magnitude of the stiction errors at the y-axis are 23 microns compared to the physical results of 16 and 20 microns.

### 3.2 Table position error trend

In order to reveal how this trend-line behaves in the simulation model, and estimate how much affect the ball screw elasticity has on the motion errors, the simulation model was used for estimate of the contribution of the ball screw. Figure 5 and 6 shows the simulation model's stiction error verses ball screw length (table initial position). The stiction error increases linearly with table position and increases over the entire length of the ball screw.

## 4. Conclusions

(1) In order to develop an accurate simulation model for multi-axis feed drive system motion in a CNC vertical machining center, the model of each component of the machine tool were generated and the entire model was revealed.

(2) Each parameter of the model was optimized by comparing to physical test results and the simulation model exhibited the same feature of machine tool.

(3) The effect of the ball screw elasticity on the motion error was clarified.

## References

- [1] Tsutsumi, M., Ohtomo, S., Okazaki, Y., Sakai, K., Yamazaki, K. and Ge, D., [1996], "Mathematical Model of Feed Drive Mechanical System and Friction for CNC Machine Tools," Journal of Japan Society for Precision Engineerin

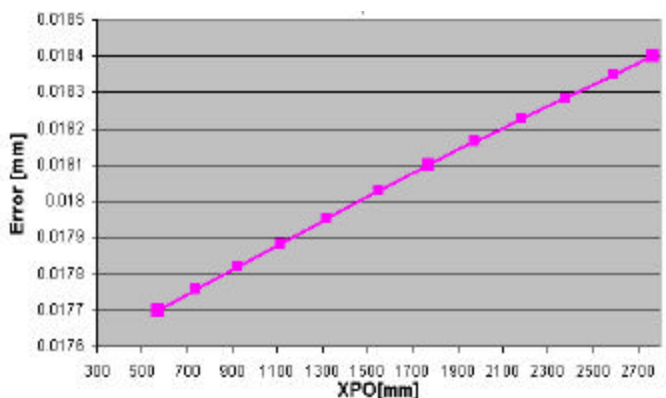


Figure 5: Simulation Stiction Error Verses Table Initial Position For  $F=5000\text{mm/min}$ ,  $R=50$

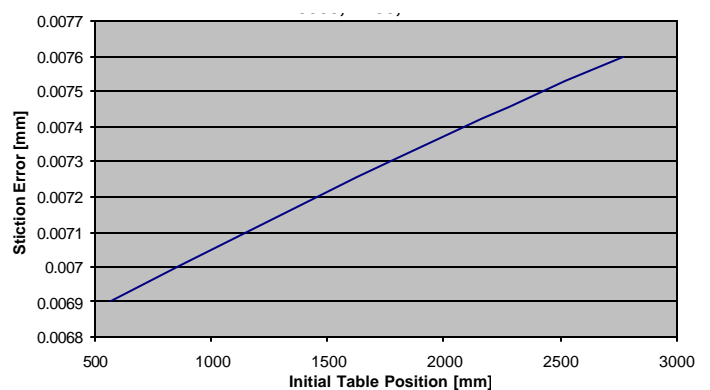


Figure 6: Simulation Stiction Error Verses Table Initial Position For  $F=10000\text{mm/min}$ ,  $R=50$