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Simulation-based tracking performance estimation of CNC machine tool feed drive

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Abstract

Simulation of machine tool feed drive is utilized for machining process optimization. However, time consumption for optimization is huge because it requires repeated simulations. Therefore, this paper proposes the rapid simulation model for estimating the tracking performance of a CNC (computerized numerical control) machine tool feed drive. The velocity profiler in CNC was modeled to estimate the overall shape of the tool path for each block. The combination of the CNC control loop and feed drive was described using a transfer function. The analytical solution of feed drive response was acquired by combining the velocity profiler model and the feed drive model. Using the generalized solution, tracking error can be estimated at an arbitrary instance. The proposed method showed similar estimation accuracy when compared to the conventional simulation that used interpolated tool path.

Computer numerical control (CNC); Estimating; Modelling; Simulation;

1. Introduction

Demand for simulation-based optimization in machining is increasing. Without operating real machine tools on a factory floor, a simulation model can estimate the result of the manufacturing process. Using the models, machining accuracy estimation [1], energy consumption estimation [2] and machining condition optimization [3] can be performed.

The simulation model consists of a CNC (computerized numerical controller) model and a feed drive model. The main role of the CNC model is tool path generation and feed drive servo control. The CNC model generates a reference tool path using velocity profiling algorithms such as trapezoidal, sinusoidal, etc. The feed drive model with the servo controller describes the dynamic behavior of an actual system. It is built by identification processes such as recursive least squares method [4].

To select optimal parameters for machining, an iterative computation process of simulation and parameter tuning should be executed. To analyze the feed drive response such as tracking error, in the finest accuracy, the CNC model usually adopts the interpolation period and the cycle frequency of an actual CNC system for the tool path generation model and the feed drive controller model, respectively. As interpolators and servo controllers in commercial CNCs work in thousands of Hz, the CNC model should run in identical time steps. Calculating numerous samples for each set of parameters becomes a bottleneck in simulation-based optimization.

This paper proposes a novel simulation model that calculates tracking error in interval-by-interval to reduce or eliminate the sampling process of the conventional time-domain model. The proposed method analyzes each block in a part program to calculate its acceleration, constant velocity, and deceleration intervals. For each interval, the general solution of tracking error is derived. The estimation accuracy of the proposed model is evaluated experimentally. It was shown that the proposed method can estimate tracking error using the derived analytical solution, without using the interpolated tool path.

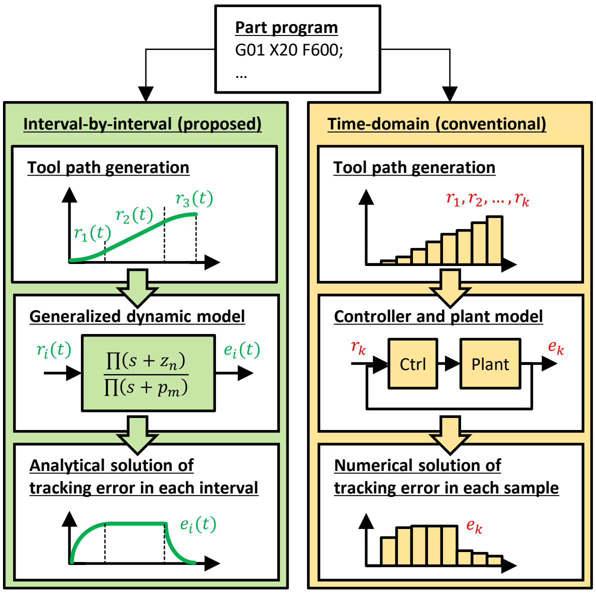

Figure 1. Comparison of the proposed method and time-domain model

2. Rapid simulation model

The objective of the rapid simulation model is to avoid dependency on sampling in the tool path generation and the feed drive controller. We focus on expressing the tracking error of a feed drive in the closed-form solution for each interval such as accelerating, constant velocity, and decelerating region. The concept of the proposed method is shown in Fig. 1.

Tool paths are generated in the discrete-time domain in actual CNC systems. They can be approximated as functions of time if the interpolation period is short enough. Here, the trapezoidal velocity profiler was chosen. The tool path generated by the selected acceleration-deceleration algorithm is expressed as $r(t)$ where r_0, $\dot{r}_0$, A, t are initial position, initial velocity, commanded acceleration, and time, respectively.

$$r(t) = r_0 + \dot{r}_0 t + {}^{1}/_{2}\, At^2$$

The dynamic model of the feed drive is composed of the servo controller model and the feed drive model. For the controller, commercial CNC generally uses a P-PI cascade controller. It has been reported that a combination of the P-PI controller and rigid body dynamics model with equivalent mass and Coulomb friction can capture dynamics under 30 Hz [5]. The proposed model utilizes the reported model but without Coulomb friction. The dynamic model is reduced into the transfer function that estimates tracking error e where r is the input reference tool path. a_i and c_i are coefficients that determine poles p_n and zeros z_m, respectively.

$$\frac{e(s)}{r(s)} = \frac{\prod_{m=1}^{2}(s+z_m)}{\prod_{n=1}^{3}(s+p_n)} = \frac{c_0 s^2 + c_1 s + c_2}{s^2 + a_1 s + a_2 + a_3\, {}^{1}/_{s}}$$

By combining the tool path generator model and the dynamic model, the general solution of tracking error $e(t)$ is derived. Coefficients H_i and P_i are determined by model parameters, initial conditions, and the commanded acceleration.

$$e(t) = H_1 e^{p_1 t} + H_2 e^{p_2 t} + H_3 e^{p_3 t} + P_1 + P_2 t$$

3. Experimental setup

The detail of the experimental setup is shown in Table 1. The feed drive system was driven by the commercial CNC. By using the controller monitoring program provided by the CNC manufacturer, the commanded and actual position was gathered from the system. From the collected data, a_i and c_i were identified using least squares method.

To estimate tracking error, the time-domain model used interpolated command position acquired from actual CNC. The proposed model used commanded acceleration extracted from the part program. For example, if the block G01 X10 F600 and the acceleration time 0.1 s is given for trapezoidal velocity profiler, the acceleration is 100 mm/s2 for 0.1 s, 0 for 0.9 s, and -100 for 0.1 s.

The time consumption and estimation performance were compared between the two models. The computational performance was evaluated by measuring the time consumed to simulate 1,000 times. The estimation performance was compared using the prediction error e_{pred}, where e_{act} is the actual tracking error, and e_{estm} is the tracking error estimated by each model.

$$e_{pred}(t) = e_{act}(t) - e_{estm}(t)$$

Table 1 Specification and parameters used in the experiment

CNC	
Model name	FANUC 0i-MD
Sampling frequency	1000 Hz
Acceleration time	0.1 s
Simulation model	
Sampling frequency (conventional)	1000 Hz
Sampling frequency (proposed)	20 Hz
Feed drive model	$\frac{s^2 + 3213s + 531}{s^2 + 3213s + 96976 + 15782\, {}^{1}/_{s}}$
Simulation computer	
CPU	Intel i7-9700 (w/o Turbo Boost)
RAM	16 GB
Models developed in	MATLAB 2020b

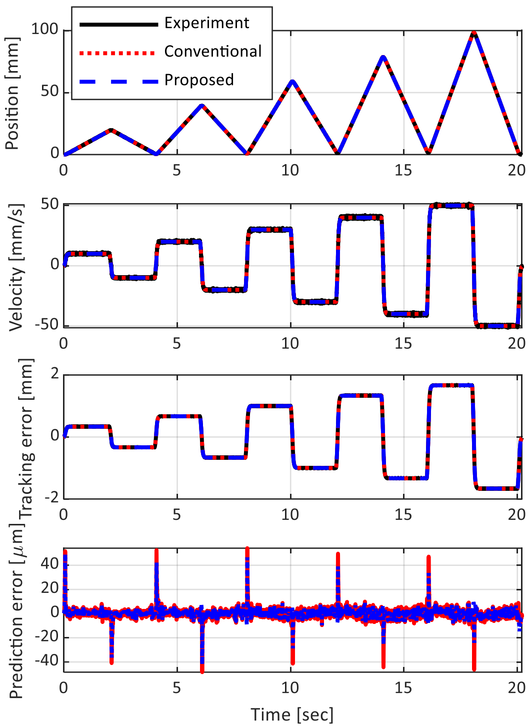

Figure 2. Result of experiment and simulation models

4. Results

As shown in Fig. 2, the tracking error was estimated within prediction error under 50 µm for both models. The proposed model was able to estimate the overall behavior of tracking error, with only one-fiftieth number of samples. Computation time consumed was 268 s and 13 s for the conventional and proposed model, respectively.

5. Conclusion

In this paper, the rapid simulation model for estimating tracking error was proposed. Because the conventional time-domain model utilized time properties such as interpolation period and control cycle frequency of actual CNC, numerous sampling process was a bottleneck in simulation-based optimization. To avoid dependency on the sampling period, the tool path was expressed as a function of time in each accelerating, constant velocity, and decelerating interval. By combining the velocity profiler model, servo controller model, and feed drive model, the analytical solution of tracking error was derived for each interval. The experimental result shows that the proposed simulation model can capture overall tracking behavior with the one-fiftieth frequency of actual CNC, with shorter simulation time.

References

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