Evaluation and modeling of productivity and dynamic capability in high-speed machining centers

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Abstract The current standards for machine tool performance evaluation do not consider productivity and dynamic capability at high feed rates. Therefore, industry does not have a basis for machine tool comparison. Testing was conducted with the Heidenhain KGM 181 grid encoder to record the actual path of the machine at high feed rates (up to 16 m/min). This paper shows the significance of linear vs. circular interpolation, acceleration and rate of change in acceleration (jerk) on the productivity and dynamic capability of this type of machine. Under high feed rate interpolations, the actual cycle time can differ significantly from the ideal cycle time (calculated with the traveled distance and programmed feed rate). A modeling approach with simple testing protocols is presented in order to predict the cycle time during machining with high feed rates. The proposed modeling approach provides less than 6% error in estimating cycle time.

Keywords High-speed machining · Machine tool performance evaluation · Cycle time · Following error · Acceleration · Jerk · Sculptured surface machining · Grid encoder

Nomenclature
- \( a_e \) stepover distance (mm)
- \( a_{\text{max}} \) maximum machine acceleration (mm/s\(^2\))
- \( a_i \) instantaneous acceleration (mm/s\(^2\))
- \( e \) following error (mm)
- \( J_{\text{max}} \) maximum machine jerk (mm/s\(^3\))
- \( L \) segment length (mm)
- \( l \) cumulative distance (mm)
- \( s \) standard deviation of the following error (mm)
- \( t \) cycle time (s)
- \( t_p \) cycle time in test part (s)
- \( t_a \) actual cycle time in case study (min)
- \( t_m \) estimated cycle time in case study (min)
- \( t_{sa} \) actual cycle time per segment (s)
- \( t_{si} \) ideal cycle time per segment (s)
- \( V_{fp} \) programmed feed rate (mm/min)
- \( V_{fi} \) instantaneous velocity (mm/min)

1 Introduction

1.1 Background

During the performance evaluation of high-speed machining centers, there are number of uncertainties regarding the combination of productivity and dynamic capability offered by a given configuration. At the high feed rates (between 16 and 20 m/min) typical of high performance operations,
the productivity is strongly influenced by the machine dynamics such as velocity profiles (trapezoidal or parabolic), maximum acceleration, rate of change in acceleration (jerk) and CNC controller processing speed. Under these high feed rates, the same machine dynamics and additional factors like the interpolation type (linear vs. circular) will influence the dynamic capability (following error).

Currently, the standards for machine tool performance evaluation do not consider productivity and dynamic capability at high feed rates. Therefore, industry does not have a basis for machine tool comparison. Through extensive testing and modeling, this study attempts to bridge the gap between the current standards for machine tool performance evaluation and the need to test machines under high speed conditions.

1.2 Related work

There are a number of works that study the problems associated with following error in high speed interpolation, based on data collected from the machine encoders and with simple geometric shapes (lines and circles) [1–5]. Those works that use a direct method to collect machine position data (x-y table or grid encoder) [6, 7] have conducted testing with feed rates up to 7.5 m/min. In the study reported in this paper, the machine position data was collected with a grid encoder and feed rates up to 16 m/min.

There are some works that report cycle time estimation for high-speed machining [8–11]. However, in these related works there is no explicit consideration of the rate of change in acceleration (jerk). This paper shows a model for estimating cycle time, considering different levels of allowed jerk.

2 Methodology

The methodology used in this study is based on extensive machine performance evaluation, modeling and case studies. The first stage provides detailed information to determine the most important factors that influence machine productivity and dynamic capability. The second stage provides models that can be easily adapted for industrial use. Finally, the third stage shows the validity of the proposed models.

2.1 Machine tool performance evaluation

Testing was conducted with the Heidenhain KGM 181 grid encoder to record the actual path of the machine at high feed rates (up to 16 m/min). Testing was also conducted by machining standardized geometries. A number of high-speed machining centers (two different models of dual-column machines and four different models of single-column machines) were tested to evaluate productivity and dynamic capability in terms of following error. Testing was conducted on tool paths typical of prismatic part machining and tool paths typical of sculptured surface machining, under linear and circular interpolation. For sculptured surface machining, the dimensional errors and surface finish were measured.

The use of the Heidenhain KGM 181 allows the recording of actual position of machine spindle, following 2D paths at high feed rates. Once the actual position data is recorded, together with the associated time stamp, this data can be processed to generate velocity, acceleration and jerk (rate of change in acceleration) profiles. Figure 1 shows an example of the position data produced by this instrument.