A Study for the Extraction of Dynamic Characteristics in CNC Machine Tools from Trajectory Measurement

Ben-Fong Yu, Jenq-Shyong Chen

Abstract*— In the present production environments, machining centers are increasing required to be fast, accurate, and stable at the same time during processing. The dynamic characteristic of CNC machine tool is an important factor that has influence in high-speed movements. First we were analyzing the kinematic profiles (position, velocity, acceleration, and jerk) for tool-path planning that have significant effects on the dynamic behavior of machine. In order to define the machine's dynamic characteristics along feed motion, this paper builds method on the measurement for motion trajectory by using the motor encoder, linear scale, and cross grid encoder (KGM). The KGM is mounted on the tool center point (TCP) in machine tools. The position of TCP was related to the tool and table in the machine tool, it's useful to guarantee obtain the machine's dynamic response completely. Finally we have modified the relevant variables for kinematic profiles, and we have proposed to stimulate the mechanical resonance for machine by the simple tool-path. In experimental results of the TCP measurement, it's shown that the machine resonance can be decreased effectively.

***Keywords* —Dynamic characteristics, TCP measurement**

I. Introduction

CNC (computer numerical control) machining center is an equipment of multiple cutting functions, such as milling, turning, drilling, tapping…etc. For the current CNC machine tools, the largest challenge for processing comes from parts that have the shorter product life cycle and complex shapes such as home appliances, cell phone, automobiles...etc., therefore how to increase productivity of the machine tools is an important theme. Fast, accurate, and stable machining operations places completely new demands on the dynamic behaviour of the machine tools. The goal of this study is to develop a trajectory measurement methodology that can easily extract the dynamic characteristics of the CNC machines to match the kinematic motion profiles for the tool-path planning.

A number of studies have been analysed the effect of interpolation algorithms performance on kinematic profiles of tool-path planning in the CNC controllers. Brock et al. [4], Lin et al. [8], and Tsai et al. [11] [12] proposed their interpolation algorithms enable to obtain the anticipated contour error along the reference command from NC program (or means NC code), the measured actual position is applied to the "Iterative Learning Control (ILC)" method in order to reduce the contour error [12]. The studies presented their algorithms can even achieve better tracking and contour accuracies. Altintas et al. [1] [2] and Erkorkmaz et al. [5] have been devoted to develop the virtual machine tool technology which predicts the dynamic characteristics of the feed-drive system of the CNC machine tools. The virtual machine tool technology proposed a mechatronic model which integrates the CNC controller, servo driver, the feed-drive mechanism, and the dynamics of the mechanical structure. Although, most of the studies have been presented that the effect on the machine's dynamic characteristic in different kinematic profiles, and builds the trajectory measurement on motor encoders and linear scales, but they didn't establish or propose the TCP measurement in the machine tools.

During the high acceleration and deceleration (Acc/Dec) motion, the feed driving force could further excite the vibration in machine tool due to the mechanical resonance effects and cause the amplification of relative position between the tool and workpiece. Bringmann et al. [3] introduced a measurement device base on the "R-test" for measuring displacements in the three linear degrees of freedom, and evaluating the dynamic behavior of the machine. But the R-test is a contact-measurement method, the measuring precision and resolution will be affected for the system friction and the finite application range which limits the maximum acceleration and jerk for the tool-path. Lee et al. [7] presented a servo tuning methodology for the machine tools to optimize its contouring accuracies, and the method is based on iterative measurement to observe the contouring performance in motion by using the KGM. The KGM is a non-contact-measurement method, this mean that the KGM is more suitable for high speed and high accuracy measurement. Parenti et al. [9] proposed compensation filter that is able to estimate the oscillation at the machine's TCP from the feed motion. They have placed an accelerometer near the tool tip, but the measured acceleration must to be integrated for obtaining the TCP displacement. On the other hand, the displacement is only represented to the position of near the tool tip, it's not for the relative position between the tool and workpiece.

This paper describes the mechanical vibrations due to high Acc/Dec motion in tool-path planning, the oscillations effects on the relative position between tool and workpiece. The dynamic characteristics of the machine have evaluated by

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Ben-Fong Yu, Department of Mechanical Engineering, National Chung Hsing Unversity, 250 Kuo Kuang Road, Tai-Chung 40227, Taiwna, ROC.,

Jenq-Shyong Chen, Department of Mechanical Engineering, National Chung Hsing Unversity, 250 Kuo Kuang Road, Tai-Chung 40227, Taiwna, ROC.,

using motor encoder, linear scale, and KGM approaches for feed motion. In the experimental results, it's shown that the KGM measurement is better than others device measured. Finally, this paper modified the kinematic profiles in tool-path planning by CNC parameters, the results of the experiment are verified that the machine resonance can be reduced effectively.

II. Analysis of Tool-path p Planning

In the typical CNC system (as shown in Figure 1), the feed-drive system obtains only one reference command - the demanded position for NC code. The trajectory of motion has been generated by interpolator in the CNC controller. Thus, the algorithm of the tool-path planning includes the kinematic profiles of the position, velocity, acceleration, and jerk.

A. Kinematic Profiles along the Tool-Path

The function of interpolator is to generate a path velocity profile which has smooth velocity change during the contour machining by a multi-axis machine tool. The tool-path planning algorithm is to maintain a smooth velocity transition during the high speed feed motion. Most of the commercial CNC controller in today's market use S-curve velocity profile along the function with jerk control [6] [10]. The kinematic profiles used in feedrate generation are illustrated in Figure 2(a). According to specified feedrate and displacement from NC code, acceleration of the tool-path have trapezoidal profiles with specified jerk and time constant of Acc/Dec. For feed motion along the tool-path, acceleration profiles are linear, feedrate profiles are parabolic and position profiles are cubic for regions 1, 3, 5, and 7 where time constant of Acc/Dec with constant jerk occur. Acceleration values are constant and jerk is zero for regions 2 and 6, where velocity profiles are linear and position profiles are parabolic. In region 4, jerk and acceleration values are zero, feedrate is constant and position is linear. If initial conditions for jerk at time region $t_i (i = 0,\ 1,\ \dots 7)$ are known the acceleration $a(t)$, velocity $v(t)$, and position $s(t)$ profiles can be obtained by integrating the jerk profile $j_k(t)\ (k = 1,\ 2, \dots 7)$ as,

$$j_k(t) = \begin{cases} J, & t_0 \le t < t_1 \\ 0, & t_1 \le t < t_2 \\ -J, & t_2 \le t < t_3 \\ 0, & t_3 \le t < t_4 \\ -J, & t_4 \le t < t_5 \\ 0, & t_5 \le t < t_6 \\ J, & t_6 \le t \le t_7 \end{cases} \tag{1}$$

$$a(t) = a(t_i) + \int_{t_i}^{t} j_k(\tau_k)\, d\tau_k \tag{2}$$

$$v(t) = v(t_i) + \int_{t_i}^{t} a(\tau_k)\, d\tau_k \tag{3}$$

$$s(t) = s(t_i) + \int_{t_i}^{t} v(\tau_k)\, d\tau_k \tag{4}$$

where t denotes absolute time, k is defined seven interval, τ_k is the relative time parameter that starts beginning of the kth phase, J is the magnitude of jerk that have been specified based on CNC parameters.

Typical commercial CNC controllers have CNC parameters to describe finite feedrate, acceleration, jerk and time constant of Acc/Dec, which purpose is to constraint the result of feed motion profiles. Eqs. (1)-(4) are defined actual feedrate, acceleration, and time constant of Acc/Dec for displacement and pre-specified jerk. When actual acceleration value less than pre-specified finite acceleration value, actual acceleration value must be used for acceleration profiles generation. Acceleration of the tool-path have triangular profiles, where the region 2 and 6 will not occur in feed motion planning, the result is illustrated in Figure 2(b). According to this reasoning, when actual feedrate less than pre-specified feedrate, actual feedrate must be used for velocity profiles generation.

B. Tool-Path Planning Effect on the Dynamic Behavior of the Machine

During high Acc/Dec motion, a limitation of machine tool productivity is due to inertial vibrations. The inertial forces stimulate resonance of the mechanical structure to generate oscillations that are translated into surface geometrical errors on the machined workpieces. In order to reduce these problems, the acceleration or jerk of the feed motion must be reduced, thus affecting productivity.

Figure 2 gives a constraint of trapezoidal, or triangular acceleration profiles in tool-path planning. When the machine undergoes high accelerations along the feed system, distributed inertial forces are generated and cause severe positioning error in CNC machine tools. This means that by measuring contour error and correlating it to effective acceleration, maximum allowable acceleration values for each axis can be set depending on the anticipated path accuracy. On the other hand, the jerk profiles are similar to impact force on the mechanical structure. The jerk is a dynamic excitation of the machine, which will cause oscillation in its structure resonance, meaning that they are causing relative displacements between tool and workpiece. The oscillating behavior is created by the driving torque or force. This means the measured torque or following error the relevant resonance frequencies can be identified with a Fast Fourier Transformation (FFT). In this reason, the allowable jerk values for each axis can be identified at the same time.

Typical acceleration spectrum of the trapezoidal and triangular acceleration profiles is illustrated in Figure 3. Therefore, dependent on the value of the jerk and the duration of the acceleration, which significant effects on the behavior of dynamic characteristics in the CNC machine tools.

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III. Experimental Validation

The experiments are performed on a three-axis machine tool with PC-based CNC controller, PANASONIC MINAS-A5N servo motor and servo driver is illustrated in Figure 4. The built-in absolute encoder of motor and the linear scale mounted on the feed system of this machine. The resolution of the encoder and linear scale are 3,125 pulse/rev and 1 μm, respectively. The software of PANATERM is used to ensure the operating system with real time performance. In addition, this paper is proposed the KGM method is illustrated in Figure 5. The experiments are placed the HEIDENHAIN KGM on the machine TCP, used to measure the position of TCP which related to the tool and table in the machine tool. The resolution of the KGM is 1nm (with EIB 74x).

A. Trajectory Measurement

According to the circular testing, the contour error can be evaluated due to the limited circle radius R. With small circle and feedrate F, the required acceleration values $A = F^2/R$ can be defined. The measurement for encoder, linear scale, and KGM have been compared in circular tool-path (at 1 mm radius with 600 mm/min feedrate) is illustrated in Figure 6 and 7. The magnification factor is 20, and the reference trajectory is R=1 mm (dashed line) in Figure 6. In Figure 7, the horizontal axis is meant the position of circle. During high Acc/Dec motion in the quadrant of circle, the significant oscillations can be excited at the TCP.

The measurement for encoder, linear scale, and KGM have been compared in square tool-path (5 mm length with 3000 mm/min feedrate) is illustrated in Figure 8 and 9. The reference trajectory is dashed line. According to the square path testing, the corner errors can be observed at each corner in Figure 8. And the oscillation can be seen on the straight segment after the corner in Figure 9. During Acc/Dec motion at each corner, the significant oscillations and corner errors can be observed at the TCP measurement.

B. Analysis of the Dynamic Reponse

This paper proposes to 2D contour movement in order to excite the machine's dynamic characteristics. Following compared with results of the three measurement devices and found that the KGM method is suited for extraction of the machine's dynamic characteristics. According to the measuring position of the TCP which related to the table at the machine tool, we completely obtain the dynamic response of the machine tool.

According to the straight path testing, the mechanical resonance can be identified with the acceleration profile is illustrated in Figure 10. The solid line is X-axis and the dashed line is Y-axis in Figure 10. After the FFT for acceleration profiles, the first resonance of the Y-axis in this machine is about 38 Hz is illustrated in Figure 10. If the acceleration profiles is trapezoidal or triangular, the allowable jerk J can be evaluated due to time constant of Acc/Dec T and allowable acceleration A (maximum values $J = A/T$). This result is useful to modify allowable jerk and time constant of Acc/Dec is illustrated in Figure 11. The first resonance of the Y-axis in this machine has been decayed effectively (dashed line in Figure 11). This means that the mechanical resonance can been estimated by TCP measurement and the CNC parameters related to jerk can been modified to reduce the oscillations.

Conculsions

The dynamic characteristic of the CNC machine tool is an important factor that has influence in the machining performance. Fast and high-quality machining operations require high dynamic behavior of the machine tool. The high jerk motion have excited to the mechanical resonance in high Acc/Dec feed process. Most of the machine tool users minimize these problems by reducing machine axes velocity, thus affecting productivity. Complementary to the work done on tool-path planning, in this paper a device is introduced for direct 2D contour measurement of dynamic path deviations at the TCP. This paper has placed on a KGM device at the TCP to estimate the relative displacement between the tool and table for high Acc/Dec feed motion along a given 2D contour to extract the dynamic response in the machine tool. In this paper, the novel contribution includes the TCP measurement method, and also enables to constraint the relevant variables for kinematic profiles in tool-path planning.

Acknowledgment

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Figure Captions List

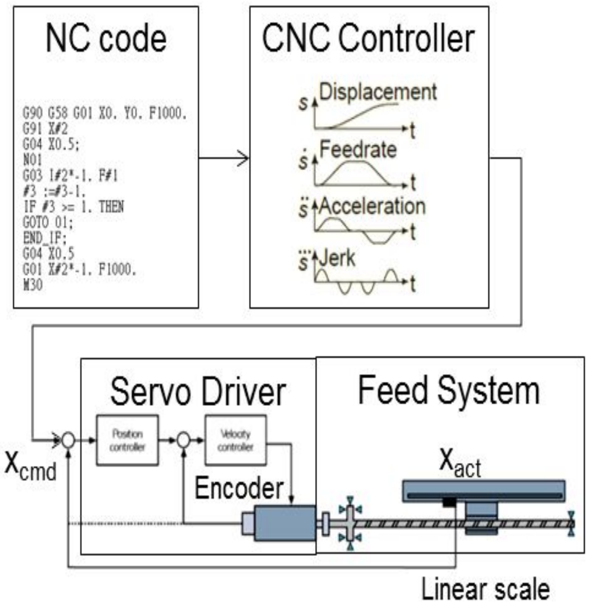

Fig. 1 Typical CNC system

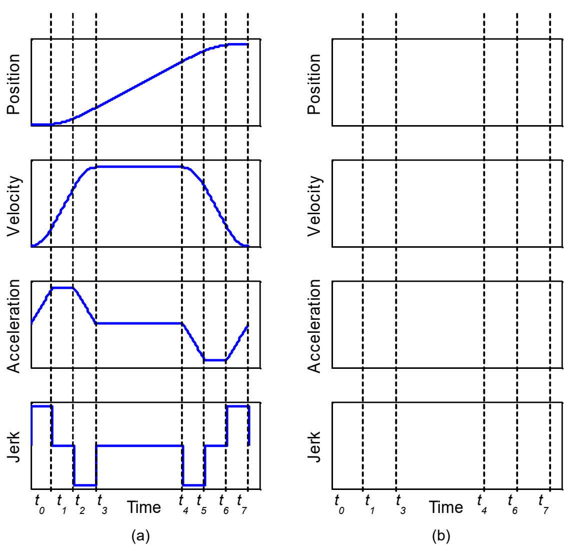

Fig. 2 Kinematic profiles: (a) trapezoidal acceleration, (b) triangular acceleration

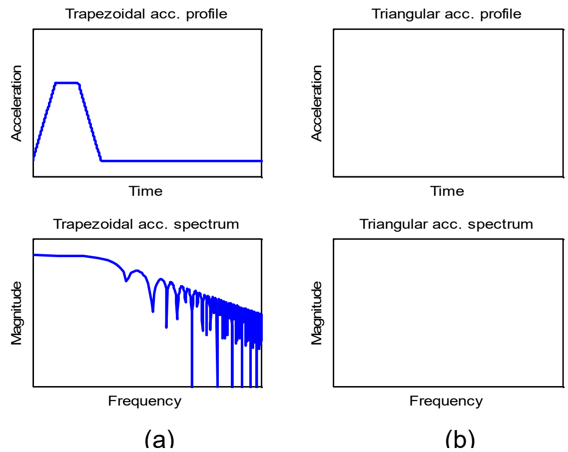

Fig. 3 Acceleration spectrum: (a) trapezoidal acc. profile, (b) triangular acc. profile

Fig. 4 Experimental platform for three-axis CNC machine tool

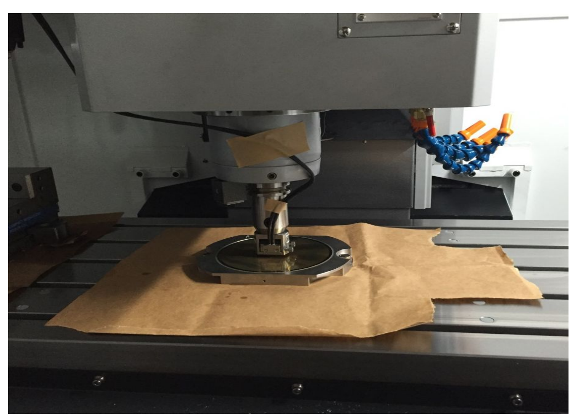

Fig. 5 Experimental setup with KGM

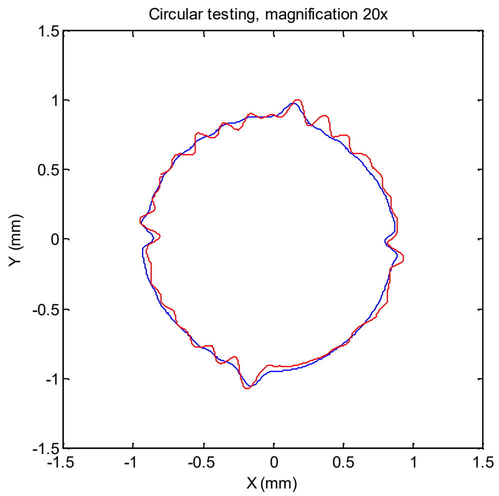

Fig. 6 Circular testing results

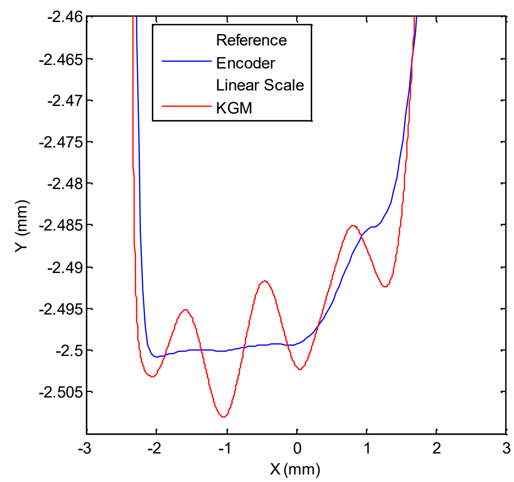

Fig. 9 Oscillation on the straight segment

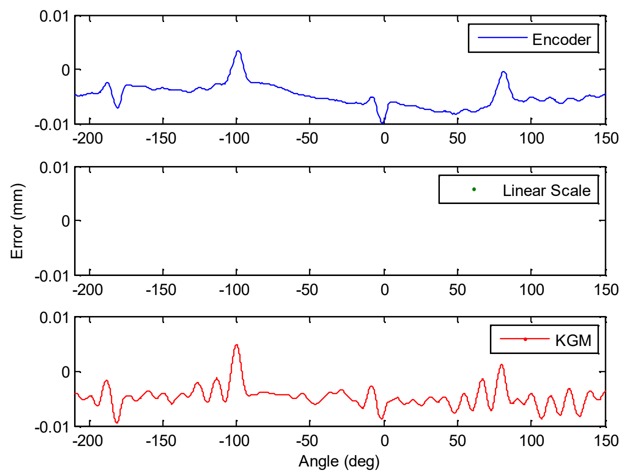

Fig. 7 Contour error on the position of circle

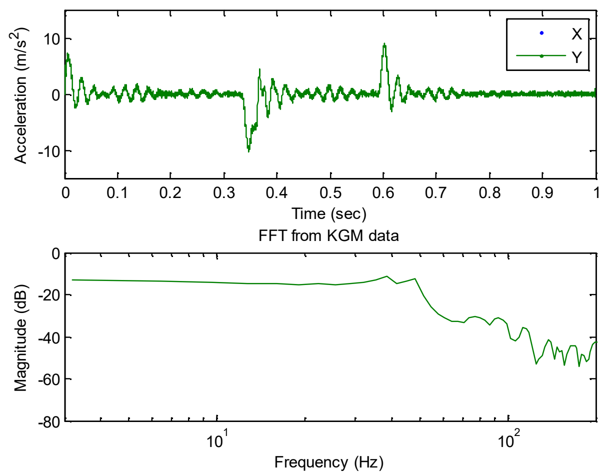

Fig. 10 FFT with acceleration profiles by KGM

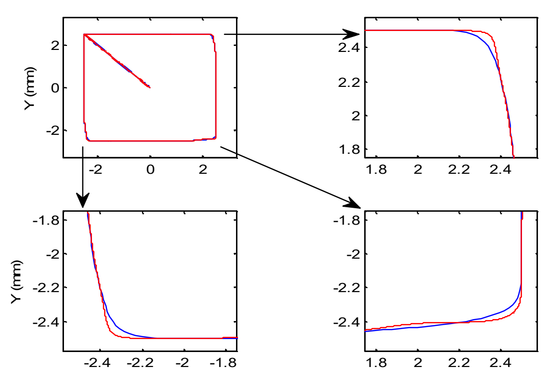

Fig. 8 Contour errors at each corner

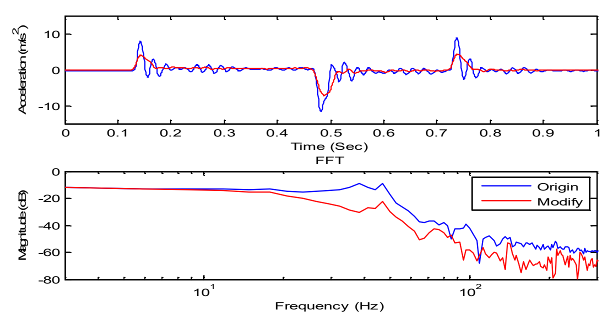

Fig. 11 CNC parameters have be modified to reduce the mechanical resonance