Available online at www.sciencedirect.com

ScienceDirect

International Journal of Machine Tools & Manufacture 48 (2008) 914–921

INTERNATIONAL JOURNAL OF MACHINE TOOLS & MANUFACTURE DESIGN, RESEARCH AND APPLICATION

www.elsevier.com/locate/ijmactool

Machining accuracy improvement in five-axis flank milling of ruled surfaces

C.H. Chu[a], W.N. Huang[a], Y.Y. Hsu[b,*]

[a]*Department of Industrial Engineering and Engineering Management, National Tsing Hua University, Hsinchu, Taiwan, ROC*
[b]*Department of Mechanical Engineering, Chung Hua University, Hsinchu, Taiwan, ROC*

Received 21 May 2007; received in revised form 26 October 2007; accepted 30 October 2007
Available online 1 January 2008

Abstract

The aim of this study is to develop a new adjustment method for improving machining accuracy of tool path in five-axis flank milling of ruled surfaces. This method considers interpolation sampling time of the five-axis machine tools controller in NC tool path planning. The actual interpolation position and orientation between G01 commands are estimated with the first differential approximation of Taylor expansion. The tool swept volume is modeled using the envelope surface and compared with the design surface to determine the deviation, which corresponds to the machining error induced by the linear interpolation. We propose a feedrate adjustment rule that automatically controls the tool motion at feedrate-sensitive corners based on a bisection method, thus limiting the maximum machining errors and improving the machining accuracy. Experimental cuts are conducted on different ruled surfaces to verify the effectiveness of the proposed method. The result shows that it can enhance the machining quality in five-axis flank milling in both simulation and practical operation.

Keywords: Ruled surface; Five-axis flank milling; Machining accuracy; Interpolation; Envelope surface

1. Introduction

Five-axis machining has received much attention in both industry and the research community since 1980s. With two extra rotational degrees of freedom, it offers numerous advantages over three-axis machining, such as higher production rate and fewer setups, and thus is widely used in the manufacture of complex geometries like turbine blade, impeller, and molds. There are two different milling methods in five-axis CNC machining. In point milling, the cutting edges near the end of a tool perform the material removal. In contrast, the side face of a cutter does the machining in flank milling. Users can select an appropriate one according to the workpiece geometry, surface finish, machining time, and cost [1].

Five-axis flank milling is considered more suitable for the part consisting of ruled surfaces. Many studies have focused on improving the tool path planning of the ruled surface machining. Several methods are now available, which automatically adjusts the tool position and orientation for producing good surface quality [2–4]. However, these studies did not consider the effect of the interpolation in NC controller. In particular, when CNC machine tools advance towards high-speed production with a feedrate of 40 m/min, an acceleration of $2 \times g$ [5], an interpolation sampling time of approximately 1 ms, and a single-interpolation straight length of 0.667 mm, overlarge chord errors may occur in the interpolated tool motion and thus deteriorate the "actual" machined quality. This problem is particularly serious along the tool path with a small curvature radius, known as feedrate-sensitive corners.

Five-axis flank milling uses the cutter side to perform the machining, and the chord error commonly used in end milling obviously cannot reflect the machining error [6,7]. Therefore, sophisticated geometries have been employed to describe the five-axis tool motion. Among them, the envelope surface was proposed to characterize the trajectory of tool sweeping in this space and the resultant part geometry after the cut. In addition, different error

*Corresponding author. Tel.: +886 3 5186498; fax: +886 3 5186521.
E-mail address: yyhsu@chu.edu.tw (Y.Y. Hsu).

0890-6955/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijmachtools.2007.10.023

estimation methods were used to define machining errors and establish the machining errors of five-axis flank milling, e.g. the distances from sampling points on the envelope surface to the design surface [8].

Generally speaking, there are three different types of parametric interpolator designs: uniform, speed-controlled, and adaptive feedrate interpolators [9]. Bedi et al. [10] reported that the next interpolation position can be obtained from the fixed curve parameter increment, but it cannot control feedrate because the calculation of interpolation position is time-independent. Shpitalni et al. [11] as well as Yeh and Hsu [12] used first- and second-order numerical approximations, respectively, to reduce the speed fluctuation caused by a uniform interpolator. To obtain a uniform feedrate reference, Wang and Wright [13] proposed a quintic parameter curve for suitable interpolation by re-parameterization of the curve with consideration of the approximate arc length. All these methods were attempted to fix the interpolated feedrate without taking the machining accuracy into account. Yong and Narayanaswami [14] summarized past research and proposed an off-line method that discovers feedrate-sensitive corners in the machining tool path and adjusts the feedrate in the areas.

The above literature review shows that little research has been concerned with the machining error in flank milling induced by the interpolation in the NC controller. Therefore, this paper aims to establish a novel adjustment mechanism for the tool path in five-axis flank milling of ruled surfaces. This mechanism considers the interpolation capacity, specifically the sampling time interval, of five-axis machine tools in the NC part programming using CAD/CAM. The cutter feedrate is automatically adjusted by estimating the machining errors using an envelope surface to improve the machining accuracy around feedrate-sensitive corners. Experimental cuts are conducted with the adjusted tool path to demonstrate the improvement of the machined surface quality. The result verifies the feasibility of the proposed method as an effective off-line path planning tool in five-axis flank milling.

2. Error estimation model

2.1. Ruled surfaces

A ruled surface is defined by two boundary curves. The ruled lines, known as rulings, are constructed by connecting two points on the curves at the same parameter value u, as shown in Fig. 1. Such a surface can be expressed as [7]

$$S(u,v) = (1-v)C_0(u) + vC_1(u) \quad (u,v) \in [0,1]^2, \tag{1}$$

where u is the curve parameter of $C_0(u)$ and $C_1(u)$ curves, v is the parameter of the ruled lines. $C_0(u)$ and $C_1(u)$ are the two boundary curves of the ruled surface.

A simple way of generating the tool motion (position and orientation) in flank milling of a ruled surface is to guide the tool to follow the rulings. The tool locations can

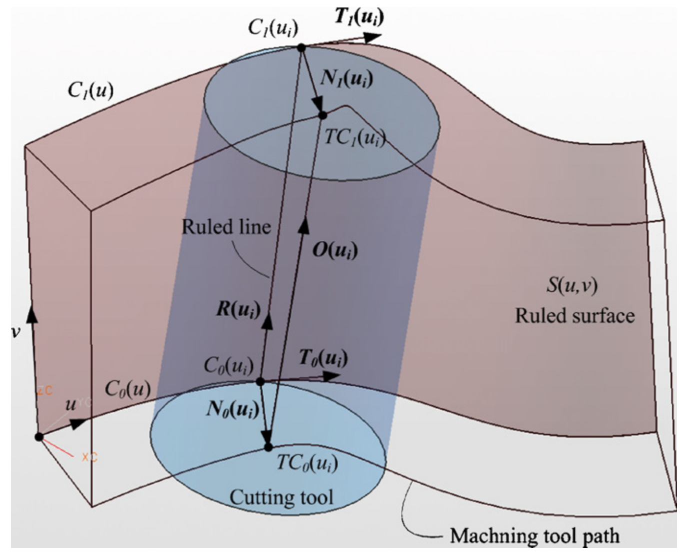

Fig. 1. Machining tool path of ruled surfaces.

be readily obtained in this case. $N_0(u_i)$ vector is determined as the cross-product of the tangent vector $T_0(u_i)$ at point $C_0(u_i)$ and the corresponding ruled line vector $R(u_i)$. The end-point position of the tool central line $TC_0(u_i)$ is calculated by shifting a distance of one tool radius along the $N_0(u_i)$ vector. The other end-point $TC_1(u_i)$ is determined in the same way. The tool orientation vector is given by

$$O(u_i) = TC_1(u_i) - TC_0(u_i), \tag{2}$$

where u_i is the curve parameter at the ith position, $TC_1(u_i)$ and $TC_0(u_i)$ are the top and bottom end-point position of the tool central line at u_i position, respectively.

Generally speaking, tool interference occurs along the tool path generated in this manner [15] unless the three vectors $N_0(u_i)$, $N_1(u_i)$, and $R(u_i)$ remain in a plane, i.e. the ruling surface becomes developable.

Given a curved path C, a CNC controller calculates the parameter u_i of interpolation points on the curves by using the first-order derivative approximation of the Taylor expansion [12]:

$$u_i = u_{i-1} - \frac{V_{i-1}\Delta t}{|dC(u_{i-1})/du|} + E(\Delta t)^2, \tag{3}$$

where u_i is the curve parameter of the ith sampling time, Δt is the sampling time of the controller, V_{i-1} is the feedrate of the tool to travel from $C(u_{i-1})$ to $C(u_i)$ and $E(\Delta t)^2$ is the first-order approximate error.

2.2. Machining error estimation

In order to estimate the machining error, a swept surface is generated for two consecutive tool locations using the envelope surface. Fig. 2 shows the construction process of the envelope surface for a straight end milling cutter. Compared with three-axis machining, five-axis machining allows synchronous motion on five axes, which