



Cutting force and machine kinematics constrained cutter location planning for five-axis flank milling of ruled surfaces

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ARTICLE INFO

Article history:

Received 24 November 2016

Received in revised form 12 January 2017

Accepted 17 February 2017

Available online 27 February 2017

Keywords:

Flank milling

Cutting force

Ruled surface

Cutter location generation

Five-axis machining

ABSTRACT

Five-axis flank milling has been commonly used in the manufacturing of complex workpieces because of its greater productivity than that of three-axis or five-axis end milling. The advantage of this milling operation largely depends on effective cutter location planning. The finished surface sometimes suffers from large geometrical errors induced by improper tool positioning, due to the non-developability of most ruled surfaces in industrial applications. In addition, a slender flank-milling cutter may be deflected when subjected to large cutting forces during the machining process, further degrading the surface quality or even breaking the cutter. This paper proposes a novel tool path planning scheme to address those problems. A simple but effective algorithm is developed to adaptively allocate a series of cutter locations over the design surface with each one being confined within an angular rotation range. The allocation result satisfies a given constraint of geometrical errors on the finished surface, which consists of the tool positioning errors at each cutter location and the sweeping errors between consecutive ones. In addition, a feed rate scheduling algorithm is proposed to maximize the machining efficiency subject to the cutting force constraint and the kinematical constraints of a specific machine configuration. Simulation and experimental tests are conducted to validate the effectiveness of the proposed algorithms. Both the machining efficiency and finish surface quality are greatly improved compared with conventional cutter locations.

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1. Introduction

Five-axis flank milling has been commonly used in the manufacturing of complex parts such as compressors, impellers, turbine blades, and molds. This milling operation provides higher productivity than that of end milling because material removal is conducted by line contact with the cutter. Moving the tool flank in 3D space can efficiently sculpt out a complex shape with only one cutting pass. Tool path planning in 5-axis flank milling of complex geometries can be nevertheless very challenging. Poor tool positioning may produce large geometrical errors, both undercut and overcut, especially in twisted regions of the finished surface. In fact, using a cylindrical cutter, geometrical deviations are inevitable in machining of most parts in industrial applications, which belong to non-developable ruled surfaces. A machined surface is considered acceptable in practice as long as the errors are within

a given tolerance. However, to precisely control the errors on the finished surface still remains to be a difficult task.

On the other hand, the cutting force produced by 5-axis flank milling is normally larger than that of end milling due to its greater contact area during the cutting process. Most flank mills are featured with a high length/diameter ratio in order to increase its accessibility into the material. As a result, substantial cutter deflection is likely to occur under improper tool engagement conditions. This may induce excessive profile errors, degrade the surface quality, and possibly break the cutter in the worst-case scenario. To eliminate these issues, feed rate planning plays an important role to generating favorable cutting force conditions.

Most studies concerning cutter location planning in 5-axis flank milling have been focused on reducing geometrical errors produced on the finished surface. For tool positioning at a cutter location, Liu (1995) first derived the analytical cutting error in flank milling and proposed the single cutter offset (SPO) and double cutter offset (DPO) methods to determine the tool position with reduced errors. Redonnet, Rubio, and Dessein (1998) developed a novel approach to positioning the tool on a ruled surface with two degrees of freedom, further reducing the machining errors

Peer review under responsibility of Society for Computational Design and Engineering.

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<http://dx.doi.org/10.1016/j.jcde.2017.02.003>

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induced by a cylindrical cutter. Senatore et al. proposed a new concept named the improved positioning based on the envelop surface swept by the cutter (Senatore, Monies, Redonnet, & Rubio, 2005). Their later study applied the concept to choose the maximum tool radius within a given error constraint at a cutter location (Senatore, Landon, & Rubio, 2008). However, the errors induced by the tool motion in real machining cannot be represented only by the positioning errors at discrete cutter locations. Thus, the swept volume between cutter locations was analytically represented by considering the singular behaviors in Abdel-Malek and Yeh (1997). Chiu (2004) proposed a numerical method to generate the swept envelop described by a set of points along the trace of the cutter. Lartigue et al. derived an analytical description of envelope surface (Lartigue, Duc, & Affouard, 2003), in which the tool trajectory is deformed to better fit the nominal surface. Zhu, Zhang, Zheng, and Ding (2009) presented a sophisticated method to theoretically construct the swept surface of a cylindrical cutter with torus. Tool trajectory is optimally adjusted to reduce the deviations between the swept surface and the design geometry.

Chu and Chen (2006) converted the cutter location planning in 5-axis flank milling into a geometric modeling problem, in which a ruled surface was approximated by a series of consecutive developable patches with G^1 continuity. Pechar, Tournier, Lartigue, and Lugarini (2009) developed a geometric algorithm for finding an optimal flank milling cutter location that not only produces an acceptable geometric deviation but also preserves the smoothness of the tool motion. Chu, Lee, Tien, and Ting (2011) transformed the cutter location planning into a large-scale mathematical programming problem. An ACS (Ant Colony System) algorithm was developed to simultaneously adjust all cutter locations comprising a tool path to minimize geometrical errors. Their later work (Hsieh, Tsai, & Chu, 2013) applied the same concept to calculate multiple cutter passes that progressively reduce the errors. The errors produced by the tool motion between consecutive cutter locations may weigh over the positioning errors at discrete cutter locations and thus need to be considered in tool path planning (Hsieh & Chu, 2013). Advanced search algorithms based on meta-heuristics were developed to improve the search efficiency in the large-scale optimization problem (Chu, Wu, & Lei, 2012). A practical approach utilizing GPU acceleration was proposed to improve both the solution quality and computational efficiency of the PSO algorithm used in the search (Hsieh & Chu, 2011). Ding and Zhu (2009) developed the point-to-surface distance function to estimate geometrical errors in 5-axis flank milling of non-developable ruled surfaces. Positioning of a cylindrical cutter was analyzed from the perspective of surface approximation. Global optimization of the cutter location planning was modeled as an approximation of the tool envelope surface to the data points on the design surface following the minimum zone criterion. They extended the same methodology into cutter location planning of a conical cutter (Zhu, Zheng, Ding, & Xiong, 2010).

In addition to the above, the other branch of studies focuses on the error caused by the machine tool side. When a tool path is transformed into standard NC codes, it is likely that the execution of the NC codes would be deviated from the ideal case due to various reasons. Uddin, Ibaraki, Matsubara, and Matsushita (2009) investigated the kinematic error on a five-axis machine and compensate the error by modifying the original cutter location. Nishio, Sato, and Shirase (2012) successfully predicted the motion errors by a thorough research on the feed drive system, and unveiled the internal connection between the motion errors and the machined surface.

Most of the above studies attempt to reduce geometrical errors produced on the finished surface in an ideal manner, ignoring the

possible influence of tool deflection on the errors. In fact, few tool path planning works have considered real cutting conditions such as cutting forces or feed rate adjustment in 5-axis flank milling of complex geometries. Cutting force modeling has been thoroughly investigated over the last two decades, and most studies were focused on conventional point milling. Lee and Altintas presented a ball-end milling force model and predicted the force coefficients from orthogonal cutting data (Lee & Altintas, 1996). Lee and Lin (2000) established a 3D force model for flat-end milling of sculptured surfaces. Engin and Altintas (2001) extended the model to a variety of helical end mill profiles by finding the geometric relationship between the tool periphery and the height from the tool tip. The cutting force model in flank milling is quite similar to that in end milling and they only differ in cutter workpiece engagement (CWE) region. Larue and Altintas (2005) identified the CWE in flank surface milling for a general tapered helical cutter by the surface intersection technique. The estimated cutting forces were then applied to adaptively regulate the feed rate to keep tool deflection under a safe value. Ferry and Altintas (2008a) proposed a numerical method for cutting force modeling in impeller machining by dividing the cutter geometry into differential elements. The feed value is decomposed and calculated along two orthogonal directions for each element. The chip load is estimated as the integral of all the elements involved in the cutting. They optimized the feed rate by a PI controller (Ferry & Altintas, 2008b) according to the physical constraints including tool deflection and cutting torques. A remarkable reduction of 45% in total machining time is thus achieved. Xu and Tang (2014) extended the pure feed rate adjustment into a tool path optimization problem, in which a best feed direction is searched for every contact point on a surface with the largest potential material removal rate (MRR) while maintaining a regulated deflection force. It is however noted that the above studies overlooked an important factor that feed rate scheduling needs to comply with the machine's kinematic capacity. Any practical tool path planning methods should consider the kinematic limitation of each motion axis while adjusting cutter locations or the feed direction.

This work tries to improve the past studies on cutter location planning in 5-axis flank milling from the following perspectives. First, a simple but effective algorithm is proposed to adaptively allocate cutter locations on a ruled surface to satisfy a given tolerance of geometrical errors. This algorithm does not require heavy computation as the most optimization-based methods do. Second, the errors induced by the tool motion sweeping across cutter locations are estimated by CNC interpolation in the machine coordinate system. In addition, a feed rate scheduling algorithm incorporating cutting force models and machine kinematics characteristics is developed to improve the machining efficiency in consideration of real cutting conditions. Both simulation and physical experimental cuts are conducted using the cutter locations generated by the proposed algorithms. The results are compared with those of traditional cutter locations to demonstrate the advantages and practical values of this work.

2. Improved cutter positioning and its angular bounding

2.1. Improved cutter positioning scheme

Mathematically, a ruled surface is defined as a set of points swept by a moving straight-line segment in 3D space. A common way to guide the sweeping of a line segment is to define two rail curves as the trace of the two endpoints of the line segment, which yields the standard equation for a ruled surface:

$$S(u, v) = (1 - v)C_0(u) + vC_1 \quad (1)$$

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