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Improving machined surface texture in avoiding five-axis singularity with the acceptable-texture orientation region concept

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ABSTRACT

The singular phenomenon is common in five-axis machining process. Most of the existing methods try to solve the problem by deforming the tool orientations or inserting extra cutter locations after the tool path is generated, with the drawbacks that (1) the machining geometry errors are not respected and (2) irregular machined surface textures might be caused. This paper dedicates to improve the machined surface textures in the scenario of avoiding the five-axis singularities. In this paper, the acceptable-texture orientation region (ATOR) concept is proposed. If the tool orientation is picked inside the ATOR, the resulted surface texture is considered to be acceptable. Based on this concept, the tool orientations are optimized locally. For a given tool path, if the orientation curve crosses the singular circle, it is locally modified out of the circle with a bridge point locating schema and a cubic B-spline interpolation technique. Eventually, the obtained new orientation curve goes around the singular circle like a rubber band to avoid the singular problem and remains unmodified to achieve the best machined surface qualities for the rest pieces. As the process is implemented at the tool path planning stage, the machining geometry errors can also be respected.

1. Introduction

The singular phenomenon is common in five-axis machine tools. It happens when the rotary axes traverse the singular point. Different five-axis machine tools may have different singular configurations. For an AC-type machine tool, for example, the singular problem happens when the tool axis in the P-system is (nearly) parallel to the Z axis. In this situation, it can be observed that even slight changes of the tool orientations will stimulate dramatical rotations of the C axis, which often involves great correction displacements of the translation axes and an important reduction of the feedrate. This phenomenon is very similar to the case when a man stands close to the North Pole (singular point) of the earth, a small step could have meant half the earth from the perspective of longitudinal extent (C axis rotation), as shown in Fig. 1. Apparently, the singular problem is harmful to five-axis machining and therefore must be avoided.

Most of the previous studies tried to avoid the five-axis singular problem after the tool path has been generated. Affouard et al. [1] blamed the singular problem to the positioning uncertainties of the rotary axes. They proposed a path deformation method to prevent the tool axis traversing the singular cone. Yang and Altintas [2] expressed the tool orientation vectors in a quaternion space by a fifth degree B-spline curve. This curve is deformed to avoid the singular problem if it crosses the singular circle. Castagnetti et al. [3] optimized the tool axis orientations using the Domain of Admissible Orientation (DAO) concept. The singular problem is detected if the DAO contains the vertical axis and is automatically eliminated since the DAO is acted directly on the axis coordinates in the M-system. Sørby [4] studied the inverse kinematics close to the singular configuration for a machine tool with non-orthogonal rotary axes. His algorithm modifies the exact inverse kinematics in order to give robustness to singularities at the expense of a small tool orientation deviation. She and Huang [5] developed a postprocessor for a machine tool with nutating head and table configuration, in which a linearization algorithm is used to solve the singular problem. Munlin et al. [6] tried to reduce the influences of singularity by optimally selecting the axis rotating angles from the multiple solutions of the inverse kinematics equations. Ivanenko et al. [7] and Makhanov and Munlin [8] presented similar methods in their research studies, respectively.

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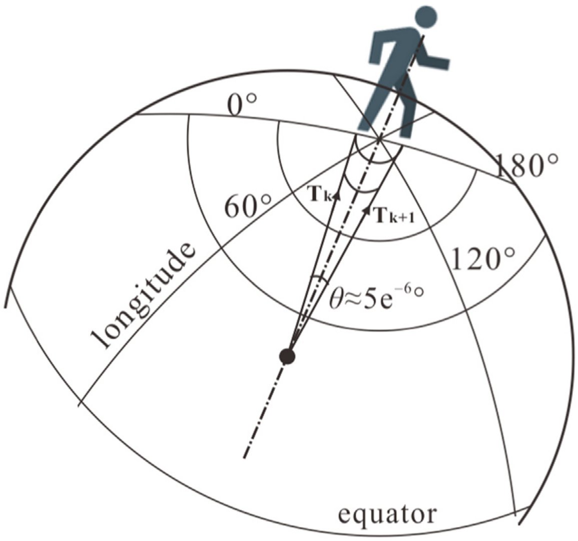

Fig. 1. Five-axis singular problem compared with the situation a man walks on the North Pole.

Srijuntongsiri and Makhanov [9] proposed a numerical algorithm to reduce the kinematic errors for the existing industrial G-codes. Some other interesting work has also been found to avoid singularity or improve machining efficiency at the machining stage by optimal workpiece setup on the working table [10–12].

From the above literatures, there are basically two operations for the cutter location near the singular position, either (1) by inserting additional cutter locations or (2) by deforming the tool axis orientations. The first operation can reduce the kinematic errors, but the expense is a feedrate reduction. And the second operation can improve the situation of the feedrate reduction, but the drawback is, as pointed by Castagnetti et al. [3], the lack of error control. The fact is, if the machining geometry of the designed tool path is to be respected, the cutter contact (CC) points should be used as the pivots during the tool axis reorientation process, as illustrated in Fig. 2(a). Unfortunately, traditional five-axis cutter locations contain only the tool reference points and the axis unit vectors. Such information is not sufficient enough for the mathematical deduction of the original CC points. Another drawback of the deforming approach is that irregular machined surface textures might be generated, as shown in Fig. 2(b). These textures are caused mainly by the uncontrolled adjustments of the tool rotational angles in the local P-systems.

The best opportunity of avoiding the singular problem is at the time before the tool path is generated. Realizing that, a tool orientation translation method has been proposed in the authors' previous research [13,14]. However, as this method is applied on the whole cutter locations of a tool path, the machined surface still suffers from the global texture changing problem. Theoretically, the best machined surface textures can be obtained if the tool axes incline forwards the feed direction without any rotations in the local P-system. However, this is practically impossible if the collision and singular problems are considered. Observation results have revealed that acceptable surface textures can be achieved if the tool rotational angles are small enough [14]. Realizing that, in this paper, the concept of the acceptable-texture orientation region (ATOR) is proposed, in which thresholds are set to the tool axis rotational angles. The advantage of the method in this paper over those in the previous studies is that the tool orientations are adjusted in a local way, so that the majority of the machined surface textures under a tool path can remain their designed best quality. The ATOR concept is implemented at the tool path planning stage, so that the machining geometry as shown in Fig. 2 (a) can also be respected.

The remainder of the paper is organized as follows. In the following section, the concept of the ATOR will be detailed introduced. Based on that, in Section 3, the mythology of non-singular and acceptable-texture tool orientation optimization method is presented. In Section 4, a cutting experiment is carried out to verify the proposed method. The last section given concluding remarks.

2. The ATOR concept

As it has been mentioned in the previous section, the appearance of the irregular machined surface textures is the result of the uncontrolled adjustments of the tool rotational angles in the local P-system. The fact is, if the rotational angles are small enough, the resulted surface textures will still be acceptable. To confine these angles, the acceptable-texture orientation region (ATOR) concept is defined. The task of this section is to build and express the ATOR on the $Z=1$ plane of the P-system. Before that, the cutter location equations in the P-system is introduced.

In five-axis machining, the tool axis can be orientated to any direction desired. In the P-system, for a given CC point C, the tool axis unit vector $\mathbf{T}$ can be expressed as

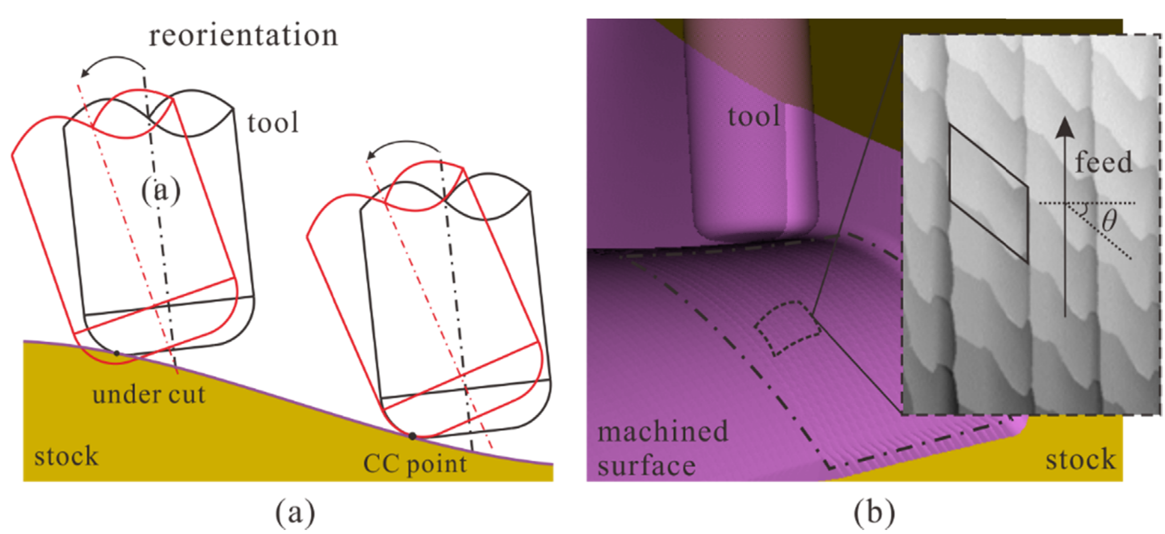

Fig. 2. Problems with the tool path deformation method; (a) machining geometry error are not respected; (b) irregular finished surface textures appear.