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Penetration–elimination method for five-axis CNC machining of sculptured surfaces

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Abstract

In this paper, a new tool positioning strategy for five-axis machining, called the penetration–elimination method (PEM), is introduced. The PEM gains from two innovative techniques that can considerably improve the computational efficiency during the calculation of the optimal tool orientations.

The first technique includes developing a quantitative definition for the gouging concept and using this definition in conjunction with powerful numerical root-finder algorithms to determine the optimized tool orientations. The second technique dynamically detects the ineffective grid points and drops them from calculations and consequently takes a great role in reducing the computational burden. The ability of the PEM in removing various types of gouging has been shown via several examples. The computational efficiency of the PEM has been compared with another recently described method named the arc-intersect method (AIM). This comparison shows that although the two methods reach the same solution for the tool orientation, the PEM is averagely 7.5 times faster than the AIM.

Keywords: Five-axis machining; Interference grid points; Instant worst gouging

1. Introduction

Five-axis machining has certain advantages over three-axis machining in production of sculptured surfaces. These advantages include more material removal rate (MRR) and better surface finish [1]. In five-axis machining, the machining strip width in each cutter contact point (CCP) is a function of the relative orientation of the tool with respect to the workpiece. Therefore, to achieve the maximum MRR, a suitable tool positioning strategy should be developed. The expected role of such strategy is to place the tool in an optimal orientation for each CCP along the tool path. On the other hand, one of the main limitations that should be concerned concurrently is the possibility of gouging between the tool and the designed surface.

During the past two decades, many researches in the field of five-axis machining has been concentrated on developing cutter positioning methods that end to gouge-free and optimized tool orientations.

The Sturz method, also known as the inclined tool method, is recognized as one of the first developments in this way [2]. This method simply uses a constant inclination angle during machining.

After the Sturz method, numerous cutter positioning strategies have been presented subsequently. Most of them are based on curvature matching between the tool and the workpiece in CCP [3–10]. Although these methods provide better surface finish in comparison with Sturz method, they cannot guarantee gouge-free tool positions. This weakness is due to considering the geometric properties of the tool and the surface only at a single point. To solve this problem, these methods use secondary gouge checking and avoidance strategies that complicate the implementation of these techniques.

Another approach to the cutter positioning problem is to investigate the entire regions of the surface that are prone to be gouged. The proper inclination angle for each CCP is then selected based on this investigation. Methods based

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on this idea include point accessibility cone method [11], multi-point machining (MPM) method [12,13], rolling ball method (RBM) [14–15] and arc-intersect method (AIM) [16].

There are also some hybrid methods that use both ideas mentioned above [17–19].

Even though the improvement of these methods over the time is undeniable, there are still some common deficiencies in the tool positioning strategies. For example most of these methods lead to suboptimal results (like RBM and method described in [20]). The reason is that they usually overestimate the area that should be considered in rear gouging elimination phase. Furthermore, they do not guarantee that the proposed inclination angle is the smallest one that provides gouge-free tool position [16].

Another common aspect in previous methods is the approach of dealing with gouging problem as a qualitative problem, so the main question in these methods is that "Whether gouging exists in a certain condition or not?" But there is no straight concern to the question "How much the gouging problem is severe in a certain condition?". This standpoint of view prevents these methods to use the power and speed of the available numerical optimization and root-finding algorithms in solving the gouge avoidance problem.

In this paper, a brief review of the AIM by Gray et al. [16] is first presented because it is the basis of comparison to show the enhancements of our new method. Next, in Section 2, the geometric relation between the tool and the part surface is described and a physically sensible function to quantify the definition of gouging is introduced. Based on this definition, a new method called penetration–elimination method (PEM) that leads to exactly optimal solutions for cutter orientation in each CCP is presented. Section 3 of this article is devoted to show the competency of the PEM. In that section, PEM-assisted machining of three sculptured surfaces has been demonstrated. These surfaces have been chosen such that the ability of the PEM in eliminating various types of gouging can be illustrated. Finally, the computational efficiency has been compared between the PEM and the AIM, and the results have been analyzed.

1.1. Arc-intersect method

The idea behind AIM is to force the forward pseudo insert to contact the surface at the CCP and then tilt the tool until it touches a second point on the part surface [16]. To reach this aim, a circular shadow checking area is first used to identify surface points that are in the tool's shadow. The shadow checking area is then discretized into a set of points, which are referred to as shadow grid points. In the next step, a corresponding tool rotation angle is computed for each shadow grid point. The final inclination angle for the tool position is selected as largest rotation angle computed from all shadow grid points.

In the AIM, each rotation angle which causes the corresponding shadow grid point to be placed on the surface of the tool is computed with the aid of a bisection search routine. Although the bisection is a robust algorithm, unfortunately it is computationally slow. Furthermore, in the AIM all of the shadow grid points are equally contributed to the process of calculating the optimal inclination angle. It is obvious that all shadow grid points do not carry the same weight in causing the gouging problem. For example, some of them removed from the boundary of the tool after a slight tilting of it, while others remain inside the boundary until larger inclination angles are exerted. The main deficiency in the structure of the AIM algorithm is that it spends a lot of time to compute the rotation angles for many shadow grid points. However, at the end, only one computed angle is used to determine the inclination angle of the tool. The question is, why the positioning algorithm should spend a vast period of time to determine the exact rotation angles that finally have no use? The AIM has no way to overcome this weakness, which acts as a source of computational inefficiency. The reason is that, it is impossible in the AIM to determine the largest rotation angle, unless all other rotation angles are also computed.

Finally, since the AIM gathers insufficient information from the interaction status of the tool and the workpiece, it cannot be generalized to involve the global interference avoidance option, and if in some cases the global interference problem arises, it cannot be detected within the AIM. Consequently, a separate subroutine is needed beside the AIM for detecting and eliminating the global collision problem.

2. Penetration–elimination method

2.1. Geometric relation between the tool and the part surface

To describe the relative orientation of the tool with respect to the surface of the workpiece in each CCP, a local coordinate system should be defined. In this coordinate system, the z-axis is along the surface normal, the x-axis follows the feed direction and the y-axis is determined using the right-hand rule.

Generally, the equation of the part surface is defined in a global coordinate system. So the surface of the part can be represented as follows:

$$S_{\mathrm{g}} = \begin{bmatrix} S_x(u,v) \\ S_y(u,v) \\ S_z(u,v) \\ 1 \end{bmatrix}. \tag{1}$$

To obtain the equation of the part surface in each local coordinate system, a kinematic transformation should be used that relates the global coordinate system to the local coordinate systems: