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Collision-free tool orientation optimization in five-axis machining of bladed disk

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Abstract

Bladed disk (BLISK) is a vital part in jet engines with a complicated shape which is exclusively machined on a five-axis machine and requires high accuracy of machining. Poor quality of tool orientation (e.g., false tool positioning and unsmooth tool orientation transition) during the five-axis machining may cause collision and machine vibration, which will debase the machining quality and in the worst case sabotage the BLISK. This paper presents a reference plane based algorithm to generate a set of smoothly aligned tool orientations along a tool path. The proposed method guarantees that no collision would occur anywhere along the tool path, and the overall smoothness is globally optimized. A preliminary simulation verification of the proposed algorithm is conducted on a BLISK model and the tool orientation generated is found to be stable, smooth, and well-formed.

Keywords: Five-axis machining; Tool orientation; Optimization; Bladed disk

1. Introduction

In five-axis machining, tool orientation formed by the two rotary axes plays a crucial role in machining complex parts like aeronautic BLISKs. Poorly defined tool orientations in such applications can cause fatal collisions and damage the in-processing part, while unsmooth patterns of tool orientation may lead to unwanted vibrations due to sudden fluctuations in tool motions, and thus inevitably lowering the machining accuracy.

Much effort has been dedicated to the five-axis tool orientation determination and optimization. Currently, there are three main considerations, namely:

- interference (local gouging and global collisions) – free between the tool and the machine and the workpiece itself [1–5];
- machine kinematics (feedrate, acceleration and jerk for each axis) [6–9];
- finished surface quality [10–12].

Most of the current studies are mainly carried out considering only one or two of these aspects. However, to optimize one aspect may compromise the others. For instance, some kinematic-based optimization methods strive to smooth the tool orientation under the constraints of maximum allowable angular acceleration and jerk, while at the same time the hard requirement of collision-free is ignored. On the other hand, due to the fact that the input part geometry pattern can be arbitrary, most collision-free tool orientation determination methods in commercial software are based on trial-and-error and require large amount of human involvement. As the modification of tool orientation is inherently a local operation, unsmooth geometrical patterns of tool orientation tend to appear, thus undermining the kinematics performance of the tool path as well as adversely affecting surface finish quality.

Still, a great deal of effort has been contributed towards better planning and determination of tool orientation in five-axis machining, by settling several aspects as boundary conditions and others as optimization goals. Choi [13] proposed a configuration space method to map the obstacles and machine's limits to a 2-D configuration space to give a feasible tool orientation range. Balasubramaniam [2] proposed

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a visibility based method which captures tool accessible ranges in 3-D Cartesian space. Castagnetti et al. proposed a DAO (Domain of Admissible Orientation) concept to optimize a tool path [14]. The general idea of these methods is to geometrically limit the tool orientation selection to a certain area, namely an accessible area for the machine tool. In such an area, a number of aspects are considered. For instance, collisions and local gouging can be strictly forbidden by constricting the tool accessible range. The drawbacks of this kind of schemes are obvious. Firstly, they usually demand a huge amount of computational resource to compute the tool accessible range for every CC point along the tool path. Then, the theoretical tool accessible range often has complex and irregular boundaries, under which it is often very difficult to solve the optimization problem.

In this paper, a plane based accessible region calculation algorithm is proposed. This algorithm simplifies the accessible region by expressing it on a reference 2D plane. For each CC point along the tool path, a reference plane is assigned, on which the tool accessible range will be calculated. And finally, tool orientations are selected and optimized in those ranges. One advantage of our plane based algorithm is that the smoothness of the tool orientation can be pre-determined to some extend in the earlier plane asignment phase. The task of tool orientation smoothing is thus divided into two stages, i.e., the reference plane assignment stage and the tool orientation selection stage. Both stages contribute to the final overall tool orientation patterns. Dividing the task into two phases makes the optimization task more manageable.

The rest of this paper will provide a detailed description of the proposed algorithm. Chapter 2 introduces the algorithm for calculating a planar accessible region. Chapter 3 develops the optimization scheme for the tool orientation selection and smoothing. Chapter 4 presents the simulation results, together with a conclusion.

2. Identification of plane based accessible region

A particular tool orientation (usually represented by a 3D vector in workpiece coordinate system) should be assigned to every cutter location (CL) point after the CL curve has been generated. Due to the complexity of the blade geometry, the tool orientation should be confined inside a certain region to avoid potential collision and local gouging, which is also known as the accessible region of the tool orientation.

Normally, the real accessible region is a closed region on the unit Gaussian sphere centered at the specific CL point. However, to calculate the exact accessible region for every CL point is still a heavy workload for today's PCs. Besides, as we will pick up a group of smoothed tool orientations inside each corresponding region, the regions are desired to be simplified as regular geometric bodies such as cones on the Gaussian sphere, as illustrated in Fig. 1. As we require that the tool orientation for any CL point be restricted in a plane, the corresponding set of tool orientations for selection now degenerates to a geodesic arc on the Gaussian sphere.

2.1. Selection of the reference plane

The CL curve for machining a blade surface on a blisk, regardless of the root and hub surface, is usually in a spiral pattern, starting from the top and down to the bottom (see Fig. 2). To guarantee that the tool orientation along the CL curve changes smoothly, a set of continuously changing reference planes is the foremost necessity. Moreover, each plane should be uniquely determined for each CL point, thus to certify a fixed accessible region.

To fulfill these requirements, we determine the eligible reference plane $\mathrm{RP}_i : \{\boldsymbol{p} \in \mathrm{RP}_i | (\boldsymbol{p} - \mathrm{CL}\boldsymbol{p}_i) \cdot \boldsymbol{n}_i = 0\}$, per CL point $\mathrm{CL}\boldsymbol{p}_i$, through the following two steps:

Step 1: calculate the geometric center $\boldsymbol{C}$ of the blade to be machined, by connecting the center point $\boldsymbol{C}_0$ of the rotor, a virtual axis of the blade can be obtained as $\underrightarrow{C_0}C$.
Step 2: find out the blade surface normal $\boldsymbol{sn}_i$ at the CC point corresponding to the specified CL point; the normal vector $\boldsymbol{n}_i$ of the reference plane RP_i is calculated as the cross product of $\underrightarrow{C_0}C$ and $\boldsymbol{sn}_i$:

$$\boldsymbol{n}_i = \underrightarrow{C_0}C \times \boldsymbol{sn}_i \tag{2.1}$$

Therefore, the reference plane is now fully determined by a point $\mathrm{CL}\boldsymbol{p}_i$ and a normal vector $\boldsymbol{n}_i$, as shown in Fig. 2. All the possible tool orientations $\boldsymbol{T}$ for this particular CL point are restricted to lie in this plane as spanned by the two vectors

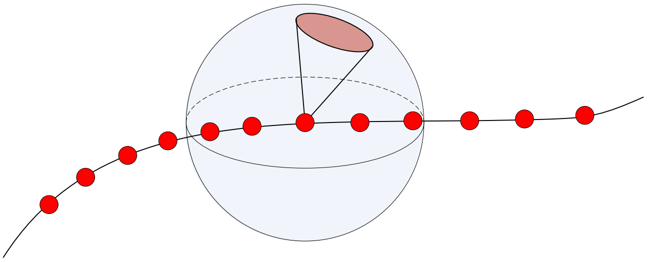

Fig. 1. An example of accessible cones on Gaussian sphere.

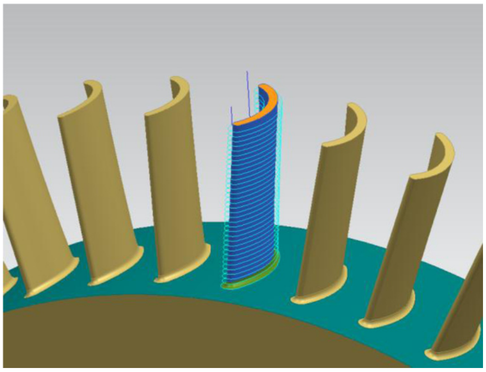

Fig. 2. Spiral pattern of the CL curve for a blade surface.