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Tool orientation optimization for 3 + 2-axis CNC machining of sculptured surface

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ABSTRACT

This paper presented an optimization method to select a tool orientation for machining a sculptured surface by the 3+2-axis machining strategy. The optimization method could select the tool orientation for the maximum average strip width in 3+2-axis machining. The method could also be used to determine the workpiece setup for general 3-axis machining. The average strip width estimation method was presented as well. Quasi-feasible sectors containing the optimal tool orientation could be found according to the projection planes and the normal vectors of sample points. And the method can find the optimal tool orientation based on projection planes. A freeform surface was parted into 9 sub-surfaces firstly, and then the presented method was applied on those sub-surfaces to determine the optimal tool orientations. The tool paths were generated with the optimized tool orientations and used to mill the sub-surfaces without interference. The method presented could also be applied on the trimmed surface, the surface with a boss, and the blade on a blisk. The machining results indicate that our method can improve machining efficiency through reducing the number of tool paths for 3 + 2-axis sculptured surface machining.

1. Introduction

Sculptured surface, also called freeform surface, has been widely used in aerospace and mold industries. 3+2-axis machining uses the three linear motion axes during cutting and fixes the two rotary axes in a particular gesture. It could be treated as a special 5-axis machining strategy. This strategy has high rigidity and low motion error during machining. Generally, fillet-end cutters could be used with this strategy to mill the sculptured surface.

1.1. Research motivation

A lot of researches on 5-axis machining have been performed to improve the quality and the efficiency of sculptured surface machining [1–13]. Compared with the researches on tool orientation optimization for 5-axis machining, the publications [14–21] on 3 + 2-axis sculptured surface machining strategy are not enough. Especially, few researches take the tool orientation optimization into consideration for 3 + 2-axis machining.

Generally, the cost of using a 5-axis machine tool is much higher than that of using a 3+2-axis machine tool. And the 3+2-axis machining could improve the rigidity during machining and increase efficiency comparing with the traditional 3-axis machining. The purpose of our research is to apply the 3 + 2-axis machining strategy to mill the sculptured surface with high efficiency and low cost. Previous researches always focus on surface partitioning. But the detail for choosing the setup gesture for each sub-surface has not been studied enough. This paper will present an optimization method to find a suitable tool orientation for machining a sub-surface with a given torus cutter.

The principle for choosing tool orientation is improving the machining efficiency. Generally, the machining strip width and the feed rate have deep influence on machining efficiency. Redonnet et al. [10] and Lee [13] have illustrated that the productivity could be improved through expanding the effective cutter radius or sweep curve for end milling of freeform surface. It suggests the strip width could influence the machining efficiency. At the same time, the feed rate is always constrained by material, tool life and machining surface roughness. In this paper, it is assumed that the feed rate is constrained at a certain value. Then the purpose of this paper is to study the strategy to improve machining efficiency through enlarging the strip width. Therefore, the principle for tool

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orientation optimization would be finding the tool orientation corresponding to the maximum machining strip width.

1.2. Application field

The method presented could be used in finding an optimal tool orientation for a sub-surface with 3 + 2-axis machining strategy, which is a complement for traditional 3 + 2-axis machining. It could be used in fixed axis machining and index axis machining. It could also be used to decide the workpiece setup for general 3-axis machining.

1.3. Research approach

This paper presents a strategy to optimize the tool orientation for 3 + 2-axis machining. The method chooses a tool orientation that is used to generate tool paths for machining the entire surface with a wider strip width. This paper gives a method that estimates the average strip width for a sculptured surface by a series of sample points, and it defines the quasi-feasible sector (QFS) for tool orientation optimization. A given surface should be distributed into plenty of grid points firstly, and then sample points would be selected from those points. Projection planes will be defined, and then the QFS domain for each plane will be found. The optimal tool orientation for those planes will be searched in those QFS regions. We find the best tool orientation from each projection plane. Then those tool orientations will be compared to find the optimal tool orientation. This method is a global optimization method, and the optimal tool orientation could be used to generate tool paths by the iso-parametric method. This method can improve the machining efficiency for 3 + 2-axis machining.

The rest of the paper is organized as follows. Firstly, the overview of 5-axis machining and 3 + 2-axis machining is introduced in Section 2. Then in Section 3, the method for estimating the average machining strip width of a surface is presented. Section 4 proposes the method to find the quasi-feasible sector (QFS) in which the optimal tool orientation will be searched. The tool orientation optimization method based on multiple projection planes is presented in Section 5. Some practical examples are given in Section 6, and then followed by the conclusions and discussion in Section 7.

2. Literature review

2.1. Tool orientation optimization for 5-axis machining of freeform surface

Much work in 5-axis machining has been done on the optimization of tool orientations for making the cutter osculate with the surface at each cutter contact point [2,3], avoiding collisions between the surface and the cutter [4] and satisfying the geometric and dynamic constraints [5–8]. In order to optimize the tool orientation, we should detect the cutting shape in machining firstly, which could be used to compute the strip width at each tool position. Plakhotnik and Lauwers [9] proposed a method to compute the swept section in each cutter location to predict the real shape of the removed materials. Redonnet et al. [10] gave an analytical solution to compute the cutter effective radius by projecting the tool envelope profile into the plane that was perpendicular to the feed direction and take a curve parallel to an ellipse to be the actual cutting shape. Lin et al. [11] found the boundary of a machining band with a distributed machining surface, and then optimized the tool positions in the next tool path for maximizing the machining strip width. Fan and Ball [12] developed the tool orientation optimization method to maximize the machining strip width. Lee [13] studied the tool positioning method and the method to compute the instantaneous cutting profile from a geometrical standpoint for 4-axis and 5-axis machining with the end milling cutter, and presented that it was possible to maximize machining efficiency through optimizing the tool orientation to fit the instantaneous cutting profile with the local surface shape. Their method could improve machining efficiency through broadening the strip width, which is one of the hotspots in the research of 5-axis machining.

2.2. 3 + 2-axis machining strategy of freeform surface

However, the 3 + 2-axis machining, which is an alternative method to traditional 5-axis machining, has not been studied adequately. Generally a sculptured surface is subdivided into several sub-surfaces firstly. Then each sub-surface is milled individually with a unique tool orientation. Suh and Lee [14] firstly proposed this method to reduce the number of interaction axes when milling a freeform surface. A rotary/tilt table and a three-axis CNC machine tool were used to adjust the setup of the part and mill the relevant subarea. This theory was also called additional-axis machining technology [15].

Gray et al. [16] made a comparison between 3-axis machining and 5-axis machining, and concluded that the 3-axis machine with an additional rotary/tilt table would improve the surface finish. Chen et al. [17] systematically investigated a 3 + 2-axis machining strategy, and then applied the clustering method and the Voronoi method to divide a sculptured surface into several patches. The tool paths and the setup for each patch were calculated afterward. Roman et al. [18] explored a surface partitioning method and optimized the number of sub-divisions to reduce the machining time for 3 + 2-axis machining. Gray et al. [19] adapted the 5-axis AIM algorithm into 3 + 2-axis machining by optimizing the tool orientation for each path. Flores [20] summarized the surface partitioning method for 3+2-axis machining and proved that 3+2-axis machining could reduce machining times comparing with 5-axis machining using the "Sturz" method. Bi et al. [21] employed the accessibility cone to calculate the safe tool length and generate the collision free tool paths for 3 + 2-axis machining with a ball end cutter.

In 3 + 2-axis machining, few studies have been done on the tool orientation optimization for improving machining efficiency. Many researchers have chosen a fixed tool orientation without optimizing it. The 3 + 2-axis Arc Insert Method, proposed by Gray et al. [19], used a projection plane to find a fixed tool orientation for a path. This method chose the tool orientation from the plane defined by the average normal vector and the average feed direction. However this plane may not contain the finest tool orientation for machining the entire surface. Roman et al. [18] used the projection of the normal vectors to find the tool orientation for 3 + 2-axis machining, as shown in Fig. 1. Their method projected normal vectors onto **YOZ** plane and chose a vector outside the normal cone but near the boundary of the cone to be the target tool orientation. In this case, the generated tool paths would have a wider strip width when machining the location where the normal vector is close to the **Z** axis. But the strip width would be extremely narrow when the normal vector deviates significantly from the **Z** axis, as shown in Fig. 1. That is because this vector may not be the optimal tool orientation in this plane, and they have not taken the impact of the gesture of the projection plane into consideration.

3. Average strip width estimation

The tool orientation optimization is based on estimating the average strip width for a freeform surface. The method in this section applies the strip widths computed at a series of specially selected points to estimate the average strip width for the entire surface. The basis for the method includes the tool positioning method, the sample points selecting method and the average strip width estimating method.