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A tool path generation method for freeform surface machining by introducing the tensor property of machining strip width

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HIGHLIGHTS

- A regional based tool path generation method is proposed and tested.
- A tensor is derived to evaluate machining strip width using ball end mill.
- A surface division method is presented based on machining strip width tensor field.

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ABSTRACT

Due to the complexity of geometry, the feed direction with maximal machining strip width usually varies among different regions over a freeform surface or a shell of surfaces. However, in most traditional tool path generation methods, the surface is treated as one machining region thus only local optimisation might be achieved. This paper presents a new region-based tool path generation method. To achieve the full effect of the optimal feed direction, a surface is divided into several sub-surface regions before tool path computation. Different from the scalar field representation of the machining strip width, a rank-two tensor field is derived to evaluate the machining strip width using ball end mill. The continuous tensor field is able to represent the machining strip widths in all feed directions at each cutter contact point, except at the boundaries between sub-regions. Critical points where the tensor field is discontinuous are defined and classified. By applying critical points in the freeform surface as the start for constructing inside boundaries, the surface could be accurately divided to such that each region contain continuous distribution of feed directions with maximal machining strip width. As a result, tool paths are generated in each sub-surface separately to achieve better machining efficiency. The proposed method was tested using two freeform surfaces and the comparison to several leading existing tool path generation methods is also provided.

1. Introduction

Freeform surfaces are widely used in design of complex parts in the field of automotive and aeronautics to meet the aesthetic and functional requirements. The machining of freeform surfaces is time-consuming with significant manual interactions by using the current CAM systems. Thus how to generate the tool path automatically and optimally has become one of the most popular aspects in the current research of freeform surface machining [1].

Quality and efficiency are two criteria to evaluate the tool path. First, requirements in surface tolerance should be satisfied and no interference or gouging is permitted. Then the machining time should be reduced as much as possible. Great efforts have been made in machining strip width optimisation in tool path computation to increase the machining efficiency [2–4]. In most of these methods, the whole surface is considered as one machining region. Tool paths of the surface are computed by shifting an initial tool path which may be one of the surface boundaries or a curve within the surface generated under some rules. However, for complex surfaces machining, the feed directions with maximal machining strip width usually present varies among different regions. If the surface is still treated as one region in this condition, only local optimal machining results could be achieved. In this paper, machining

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strip width is evaluated using a rank-two tensor and the surface may be divided into several sub-surface regions. Each region contains continuous distribution of feed directions with maximal machining strip width. Then tool paths in each sub-surface could be generated separately to achieve optimal tool paths.

2. Related work

This part will first review the recent research work about machining strip width optimisation in freeform surface machining. Then a survey about region-based freeform surface machining methods will be given.

2.1. Machining strip width optimisation in freeform surface machining

Basically, the approaches to increase the machining efficiency in freeform surface machining could be classified into tool path length reduction and optimal feed speed assignment. Machining strip width is defined as the range of the machined region that lies within the required tolerance. Wider machining strip width leads to less machining passes which also means shorter tool path length. Cutter shape, feed direction and tool orientation are factors to decide the machining strip width at each cutter contact point. Normally, the maximisation of machining strip width is integrated with the optimisation of cutter shape, tool path as well as tool orientation.

Effective cutting shape (ECS) was defined as the approximation of the cutter surface to find the machining strip width by calculating the intersection between the offset surface and the ECS [5]. However, this approximation may cause unwanted collisions. Yoon et al. [6] used Dupin indicatrices of cutter surface and the designed surface at the contact point to find out the locally millable cutting positions. Then the second order approximations of the machining strip width were applied to generate the optimal cutting positions for cutting directions. Effective cutter radius (ECR) is the core attribute to describe ECS. To overcome the deficiencies of less flexible and time-consuming in traditional ECR computation based on numerical approach and geometric approximations, Redonnet et al. [7] proposed a relation authorising an analytical calculation of the ECR for torus milling cutter. They also concluded that the increasing of the ECR had a direct improvement in machining strip width. To extend this conclusion in a more general manner, the increasing of machining strip width is induced by the increasing of proximity of ECR and the surface normal curvature. Jensen et al. [8] presented a tool selection method for five axis curvatures matched machining. The machining strip width was evaluated by ECR and the surface curvature. Lu et al. [9] also used curvature matched method to approximate the cusp height for machining strip width maximisation. 3D configuration space is established to guarantees that the cutter is gouge-free and that the cusp height is less than the machining tolerance. Gong et al. [10] gave a new local optimisation method for tool positions to maximise the machining strip width by minimising the relative normal curvature between the tool envelope surface and the designed surface. Anotaipaiboon and Makhanov [4] utilised the concept of adaptive space-filling curve (SFC) for tool path generation. Two iso-parametric tool paths will be first overlapped and then SFCs are generated adaptively by following the direction with optimal machining strip width to construct tool paths from the existing iso-parametric tool paths. However, the iso-parametric tool paths usually do not follow the local optimal feed direction with maximal machining strip width especially for complex surfaces. Fard and Feng [3,11] applied the maximisation of machining strip width as the optimisation goal for tool orientation determination. Their study indicated that although the minimum curvature direction was mostly not the optimal feed direction in free-form surface machining, the minimum curvature direction did represent a good approximation of the optimal feed direction at a CC point, in particular for a free-form surface with low-curvature relative to the cutter size. Similarly, Fan and Ball [12] proposed a method for cutter orientation optimisation method for flat-end cutter milling on a quadric.

Chiou and Lee [2] established the concept of machining potential field to select the tool path curve with the maximum average machining strip width among the potential paths across the surface as the start tool path. And during the generation of adjacent tool paths, if the cutting efficiency of a newly generated adjacent tool path falls below a predefined value, the procedure will stop and a new initial tool path will be selected to continue the tool path computation in the blank area of the surface. This work applied the similar procedures to generate tool paths as the abovementioned research work: (1) construct an initial tool path curve, this curve could be selected from the boundaries of the surface or generated based on other specific considerations; (2) discrete the initial tool path curve into a set of points under the tolerance requirement; (3) offset these points in directions orthogonal to the initial tool path curve with proper path intervals and form the consecutive tool paths; (4) select the tool path curves generated by step (3) as the new initial tool path curves and repeat step (2) and (3) until the tool paths cover the surface completely.

According to the above procedures, it could be concluded that once the initial tool path curve is selected, the overall tool paths are largely determined [2]. However, for complex freeform surfaces, feed direction, tool orientation and cutter shape for optimal machining strip width usually vary in different regions. Tool paths generated by the above procedures usually follow the same or similar regularity all over the surface thus only local optimal solution could be achieved. To overcome this deficiency, the surface may need to be subdivided into several sub-surfaces according to the regularity of the feed direction, cutter shape or tool orientation. As a result, region-based freeform surface machining strategy becomes more and more imperative in real manufacturing industry.

2.2. Region-based freeform surface machining

Region-based freeform surface machining is based on dividing the freeform surface into regions by identifying meaningful features [1]. Usually, there are various optimisation goals in freeform surface machining like machining strip width optimisation, feed rate optimisation, cutter or machine tool determination. Tool paths for these optimisation goals may present a regional regularity overall the surface. For example, surface could be subdivided into regions with different curvature bounds, each of which can be milled using tools appropriate to that region. Convex and relatively flat regions can be machined using flat-end cutters in milling, regions with small curvature can be accurately milled faster with larger ball-end cutter. In [13], a surface is divided into several regions to generate tool paths for even cusp height. But the division algorithm is restricted to specific surface geometry. In [14], tool paths will be generated by constructing geodesics on an abstract Riemannian manifold for constant cusp height. However, those geodesics may intersect with the others. Thus the surface cannot be machined completely as one machining region and should be subdivided into distinct segments to avoid the intersections of the tool paths. In Lee's method for machining strip width optimisation [2], a surface may be divided into multiple regions with different initial tool paths. In Tuong's method [15], the chain code technique in the image processing field is applied to divide the surface for cutter selection optimisation. Han et al. [16] used the iso-photo concept for surface segmentation. Surface is divided into regions with similar normal vectors for tool path computation. In the method proposed by Chen et al. [17], the surface is first divided into a