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Spiral cutting operation strategy for machining of sculptured surfaces by conformal map approach

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Abstract

Although compound surfaces and polyhedral models are widely used in manufacturing industry, the tool path planning strategies are very limited for such surfaces in five-axis machining and high speed machining. In this paper, a novel conformal map based and planar spiral guided spiral tool path generation method is described for NC machining of complex surfaces. The method uses conformal map to establish a relationship between 3D physical surface and planar circular region. This enables NC operation to be performed as if the surface is plat. Then through inversely mapping a planar spiral defined by a mathematical function into 3D physical space, the spiral cutter contact paths are derived without inheriting any corners on the boundary in the subsequent interior paths. The main advantage of the proposed method is that a smoother, longer and boundary conformed spiral topography tool path is developed. Therefore, the machined surface can be cut continuously with minimum tool retractions during the cutting operations. And it allows both compound surfaces and triangular surfaces can be machined at high speed. Finally, experimental results are given to testify the proposed approach.

Keywords: Spiral tool path; High speed machining; Conformal map; Freeform surface machining; CAD/CAM

1. Introduction

Rapid and efficient manufacturing of sculptured objects and dies is an important issue in modern industry. Over the years, surfaces of industrial products have become more complex because of the customers' increasing requirements for function and aesthetic reasons. In this case, five-axis NC machining tools have gained wide applications. At the same time, due to the properties of high cutting speed and high feed rate, high-speed machining (HSM) centers have increasingly been utilized in industries. However, the conventional cutting conditions and tool path generation methods are usually employed in practice [1]. Currently, the available commercial CAD/CAM software for five-axis machining especially for HSM still lacks flexibility when specifying the tool orientation and tool path distribution for complex surface machining [2]. These systems mostly have limited functionality for the generation of multi-axis tool paths. When machining compound surfaces and triangular surfaces, the tool path generation methods are very limited, and the iso-planar method, which often needs many cutter lifts and the cutting force tends to fluctuate, is often used. As a result, the tool paths are very defective and also are no longer boundary conformed. Hence, gouge- and collision-free tool paths with smooth cutter movements are highly appreciated for their relatively higher surface quality, machining efficiency and superior dynamic property. Especially in high speed machining setting, such a path with smooth path dynamics rather than maximum machining strip width turns out to be very advantageous. For reducing lifts and achieving smooth path dynamics, in this paper a new spiral tool path generation method is presented based on conformal map for compound surfaces and triangular meshes machining.

1.1. Existing approaches

The quality of tool path planning affects the quality of machining to great extent. In order to generate an accurate tool path in an efficient manner, there are some new tool path strategies apart from iso-parametric method, iso-plane method and iso-cusp method in recent years. Examples are principal axis method [3], multiresolution analysis based tool path generation [4], fractal tool path strategy [5], guide surface based tool path generation [6], machining potential field approach [7], max-

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imum kinematic performance based tool path generation [8], contour-parallel offset machining [9] and boundary conformed tool path generation [10]. In overall, some of commonly used methods try to increase the path interval for reducing machining time, some try to get the optimal kinematic performance to reduce tool wear and improve machining quality, and others are provided for some special usages such as keeping boundary conformity for trimmed freeform surface. Which of these criteria is better depends on the applications and machining tools. It is very difficult to find a compromised method to simultaneously satisfy various requirements such as maximum path interval and feed rate. For example, iso-cusp method with a shorter path length sometimes leads to the dramatic curvature change of tool paths. Consequently, it will result in change of cutting force and stress on the tool. On the contrary, when feeding along maximum feed rate direction at each local sampled point, there inevitably exists overlap. In addition, for trimmed freeform surface, Yang et al. [10] provided a boundary conformed Zigzag tool path generation method by means of Coons or Laplace parameterization. Need to mention that the existing boundary conformed tool path generation methods are all based on the idea of reassigning parameters. In essence, these methods belong to the category of iso-parametric method. In general, using conventional Zigzag pattern tool paths needs many cutter retractions and causes additional tool movements which do not contribute to the actual machining. If a spiral cut is used, only one of the up or down milling effects occurs in the cutting processes. Therefore, spiral cuts have better machining conditions and also have an important status in milling even though they are more difficult to construct. In this case, some spiral tool path generation strategies are developed. The difficulty in generating spiral tool paths arises from the complicated intersection calculations of the offset entities [11].

In the previous studies, Held [12] calculated helical tool path from the interior to the curvilinear polygons outside based on proximity maps, Voronoi diagram. Ranga Narayanswami and Pang [4] investigated the applicability of multiresolution analysis using B-spline wavelets to NC machining of contoured 2D objects. Choi and coworker [6] generated the spiral path by guide surface method. The method is very effective for common engineering parts. However, the most ideal guide surface is the original surface itself, how to correctly select guide surface and the projecting direction is not very obvious for a complicated sculptured surface. For the efficiency of the contour-parallel offset (CPO) machining, Park et al. [13] proposed a CPO tool path linking algorithm, which guarantees ‘zero’ number of tool-retractions. Lee [14] also developed a contour offset approach to spiral tool path generation with constant scallop height. The proposed path strategy is able to deal with multiple connected areas by means of self-intersection elimination and path-linking algorithms. In addition, some studies [15,16] showed the main influence of linking strategy of two successive path segments, the curvature continuity and curvature radius of the tool path on the machining time in NC machining especially in HSM, and aim to enhance the tool path by corner optimization and smooth connection. Bieterman and Sandstrom [17] described a novel curvilinear tool path generation method for planar milling of pockets. Through morphing a smooth low-curvature spiral path in a pocket interior to one that conforms to the pocket boundary via the solution of a partial differential equation, tool wear in cutting hard metals and machining time in cutting all metals are substantially reduced. Compared with conventional machining, in a high-speed machining setting, it seems like that the best tool paths must account for machine dynamics and have a smoother, generally longer path. At the same time, if possible the path should conform to the machined surface boundary without internal tight-radius corners. To reach this goal, there still need to develop some new spiral tool path generation strategies for 3D complex surfaces machining.

1.2. A summary of our approach

Considering NURBS or B-spline has been employed by many CAD/CAM system as a fundamental geometry representation and has also gained tremendous popularity in geometric modeling of sculptured surfaces, we assume that the machined part is represented by B-spline surface or compound B-spline surfaces. As shown in Fig. 1, the proposed approach consists of three stages: surface triangulation, conformal mapping, and tool path generation. Here, we hope to seek a generic method that can generate tool paths from compound surfaces and triangular meshes as well. Hence, in the first stage, the compound surfaces need to be transformed into triangular meshes. So far, there are numerous robust algorithms for converting all types of surfaces into triangular approximations. In addition, a part surface is often approximated into a triangular polyhedron, and tool paths are then generated from the tessellated surface model for compound surface machining [18]. Therefore, it is very reasonable and not a very tough task to realize such transformation. With a view to the complexity of completing tool path planning in 3D physical space, in the following step we define a mapping between circular region on the 2D plane and the surface embedded in the 3D space, and enables these operations to be performed as easily as if the surface is flat. Then a set of machining strip diagram at each sampled point is established. Thus, we can easily generate guided spiral paths in the planar circular region according to a mathematical function constrained by the given machining strip map. The tool paths on the machined surface are subsequently derived by inversely mapping guided planar spirals into the physical space.

As abovementioned, the previous boundary conformed methods basically are to reconstruct the parameterization relations between the machined surface and its parameter region by various ways of reassigning parameters. By contrast, the proposed method seeks to reduce the complexity of computation and design some new types of tool paths by establishing the mapping of 3D complicated physical surface and some simple topography regions such as rectangular region, circle region and other polygon region. The objective of this paper is to develop a spiral cutting operation strategy for high speed machining of sculptured surfaces based on conformal map based and planar spiral guided approach. The overall structure of the paper is as follows. The next section gives the map between circular planar region and the 3D physical space in Section 2. Then we describe a spiral