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Continuous Tool-path Generation for High Speed Machining

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ABSTRACT

A continuous tool-path, that is to cut continuously with the minimum number of cutter retractions during the cutting operations, is developed in order to minimise the fluctuation of cutting load and the possibility of chipping on the cutting edge in HSM (high-speed machining). This algorithm begins with the offset procedure along the boundary curve of the sculptured surface being machined. In the offset procedure, the offset distance is determined such that the scallop height maintains a constant roughness to ensure higher levels of efficiency and quality in high-speed machining. Then, the continuous path is generated as a kind of the diagonal curve between the offset curves. This path strategy is able to connect to neighbor paths without cutter retractions. Therefore, the minimum tool retraction tool-path can be generated. And, it allows the sculptured surface incorporating both steep and flat areas to be high-speed machined.

Keywords : continuous tool-path, high-speed machining, offset

Nomenclature

a , b , c	:	Components of the normal direction vector of a surface
$\mathbf{C}$	:	Curve on a sculptured surface
$\mathbf{C}^o$	:	Offset curve of the curve $\mathbf{C}$
h	:	Scallop height
l	:	Path interval
$\mathbf{N}$	:	Unit normal vector of a curve
$\mathbf{p}$	:	Point on a surface
$\mathbf{r}$	:	Parametric form of a surface
r	:	Tool radius
R	:	Radius of normal curvature
$\mathbf{S}$	:	Sculptured surface
t	:	Curve parameter
$\mathbf{U}$	:	Set of surface parameters
u , v	:	Surface parameters
$\mathbf{x}$	:	Cutter contact point
α	:	Normal plane

1. Introduction

As more industrial products are being designed with free-formed surfaces, efficient manufacturing of curved objects and dies is an important issue in modern industry, [1] As productivity increase and cost reduction is becoming the major target of industries due to the worldwide economic competition, the application of HSM (high-speed machining) is recognized as an economically viable manufacturing technology for higher productivity and throughput, and is thus creating considerable interest for die and mould manufacture for many years. [2] HSM is so called to reduce real machining time through the increase of machining speed. Additionally, HSM process can produce more accurate results, an improved surface quality, and better chip disposal. The use of HSM offers some advantages over conventional machining. Even though much more high-speed machining centers have increasingly been utilized in industries, the conventional cutting conditions and tool path generation methods are usually employed in practice.

Because the cutting speeds typically used in HSM are about ten times higher than the speeds applied in conventional machining, the realization of HSM demands new unconventional solutions for tool-path optimization, cutting conditions, tool materials, and process stability. This paper is concerned with tool path generation. In order to accomplish machining to a high speed, it is essential to prepare high-quality cutting path, which minimises the tool retractions, makes the cutting load constant and controls the scallop height. Conventional tool-path generation methods have inherent limitations for the HSM application. For high-speed finish machining a sculptured surface, a new tool-path generation algorithm is presented by minimising the tool retractions, keeping the cutting load constant, and controlling the cusp height.

2. Existing Approaches

Before presenting the methodology, the research related to tool-path generation is briefly summarised. Recently, a large amount of research has appeared in literatures and commercially available CAM systems.

The simplest and most popular approach of the conventional path generation methods is the iso-parametric method. Iso-parametric curves are extracted from a surface, usually in equally spaced in parametric steps. Although iso-parametric method possess merits such as easy calculation of cutter paths and less computer memory required for path calculation, the uneven 3D distance between iso-parametric curves defined on a sculptured surface may cause redundant or under-cut machining. [3]

Another popular method is the Cartesian method. This method generates a series of line-by-line linear cuts, which are parallel to X, Y or any user defined angle and can be uni-directional or bi-directional. Though this method requires heavy computation for surface-surface intersection, it is frequently used for the area milling because it can handle the complex surface consisting of multiple trimmed surfaces in a seamless manner. But the Cartesian method is defective because this needs many cutter lifts and the cutting force tends to fluctuate. Commonly, the property of HSM tool materials has high hardness and low toughness. The insufficient toughness is the biggest problem since the materials; chipping on the cutting edge can arise even at the beginning of the cutting process. In HSM, tool chipping occurs due to the high mechanical and thermal shocks. And fluctuation in cutting force may result in breakout of the cutter. [4-6] In HSM, there is little time for human intervention in the event of a problem, even if the operator is watching the machining process. Choi proposed the chip-load-levelling algorithm that was achieved via pencil-trace cutting operations along the sharp edges before the Cartesian machining. [7] But the method could not reduce the number of tool retractions.

To reduce the fluctuation in cutting force, the contouring algorithm or the constant Z-level algorithm is used. One of the major drawbacks of the contour method is that the contour curves can be very uneven if the surface has regions that are almost coplanar with the contouring surface. Even if an algorithm could be created to space a next cutting plane adaptively on the basis of the co-planarity of one region of the surface, this spacing would be fixed over the next entire tool path, being much closer than might be necessary in another non-coplanar region. For controlling scallop height, the commercial CAM system, CAM-Tool (Graphic Products Inc.), uses an alternative method based on inserting additional curves between the conventional Z-level contour curves whose path interval is larger than the mean distance. But the method still suffers from the complicated tool-path layout.

In order to minimise the fluctuation of cutting load and the possibility of chipping on the cutting edge for HSM, it is clear that the best possible way to machine a sculptured surface would be to do it in a continuous fashion, that is to reduce the number of interruptions or rapid traversals during the cutting operations. Therefore, spiral and helical strategies are commonly used for HSM and give particularly good surface finish results whilst ensuring consistent loading on the tool. But it is not easy to generate the spiral tool-path along a free-formed surface. Choi suggested the guide surface method, which generates the spiral path by projecting parametric curves onto the sculptured surface. In the proposed method, it is not obvious to select correctly the guide surface and the projecting direction required to create a valid tool-path. [8]

3. Offset Curves

The first step of the proposed tool-path generation method is the curve-offset procedure along the boundary of a sculptured surface being machined. The finish machining should maintain a user-defined roughness relative to the surface. Therefore, the offset distance is determined to be the tool-path interval such that the scallop height is no larger than the allowed surface roughness. To generate spiral paths in the next step, the offset curves are used as a kind of guide curves. The continuous path is generated as a kind of the diagonal curve between the offset curves.

3. 1 Contour Offset

The parametric form of an offset curve $\mathbf{C}^o(t)$ of a given parametric curve $\mathbf{C}(t)$ is another parametric entity simply written as

$$\mathbf{C}^o(t) = \mathbf{C}(t) + l(t)\cdot\mathbf{N}(t) \tag{1}$$

where $\mathbf{N}(t)$ is the unit normal, and $l(t)$ is the offset distance computed at t. [11] In this paper, a given curve $\mathbf{C}(t)$ is defined on a sculptured surface $\mathbf{S}(u,v)$ as expressed in the equation (2).

$$\begin{aligned}\mathbf{C}(t) &= \mathbf{S}(u(t), v(t)) \\ &= [x(u(t), v(t)) \quad y(u(t), v(t)) \quad z(u(t), v(t))]\end{aligned} \tag{2}$$

Even though it is conceptually easy to define an offset curve of a free-formed curve along a sculptured surface, the efficient computation of an exact offset curve is not a trivial problem at all. Lines and arcs are the only geometric elements whose offset operations are closed to them. Therefore, an approximation should be employed to represent the offset of a free-formed curve.

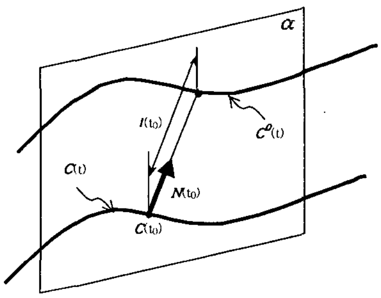


Fig. 1 Offset curve generation

In this article, the offset procedure is performed by finding a number of exact offset points of the given free-formed curve and to interpolate the offset points with line segments. [9] Since NC machines usually use linear interpolation; the offset generated by this approach is preferable for NC machining. [10]

The offset point of a point $\mathbf{C}(t_0)$ is defined on the corresponding normal plane α of the curve $\mathbf{C}(t)$ at t_0 shown in Fig. 1. The normal plane α can be expressed as the equation (3).

$$(\alpha - \mathbf{C}(t))\cdot\dot{\mathbf{C}}(t)\big|_{t=t_0} = 0 \tag{3}$$

where

$$\dot{\mathbf{C}}(t) = \frac{\partial \mathbf{C}(t)}{\partial t} = \frac{\partial \mathbf{S}(u,v)}{\partial t} = \begin{bmatrix}\frac{\partial x(u,v)}{\partial t} & \frac{\partial y(u,v)}{\partial t} & \frac{\partial z(u,v)}{\partial t}\end{bmatrix}$$

The normal direction vector of the plane α at t_0 is introduced as the equation (4).

$$[a \quad b \quad c] = \dot{\mathbf{C}}(t)\big|_{t=t_0} = \begin{bmatrix}\frac{\partial x(u,v)}{\partial t} & \frac{\partial y(u,v)}{\partial t} & \frac{\partial z(u,v)}{\partial t}\end{bmatrix}\Bigg|_{t=t_0} \tag{4}$$

Therefore, from the equation (2), (3), and (4), the intersection curve between the plane α and the sculptured surface $\mathbf{S}$ is written as the equation (5).

$$\begin{aligned}&(\mathbf{S}(u,v) - \mathbf{S}(t_0))\cdot\dot{\mathbf{C}}(t_0) \\ &= a\cdot x(u,v) + b\cdot y(u,v) + c\cdot z(u,v) + d = 0\end{aligned} \tag{5}$$

In this work, the offset distance is determined to be the path interval $l(t_0)$ calculated at t_0. The distance between the given curve and the offset curve is presented as the equation (6).

$$|\,\mathbf{S}(u,v) - \mathbf{S}(t_0)| = l(t_0) \tag{6}$$

The offset point can then be obtained by using Newton's method for solving systems of the nonlinear equation (5) and (6).

3.2 Self-Intersecting Loop Elimination

The generated offset curve may self-intersect and consists of a number of offset lines where some of them may be redundancies that do not contribute to the final offset curve. Therefore, a trimming process to remove these invalid offset lines becomes necessary.

At a self-intersection point of an offset curve,

$$\mathbf{C}^o(t_1)=\mathbf{C}^o(t_2) \tag{7}$$

where t_1 and t_2 are two different sets of curve parameters corresponding to the same offset point. The determination of self-intersecting loops is closely related with the arrangement of offset curve segments. A robust implementation of curve arrangement is one of the most difficult problems in geometric modelling. The only reliable robust implementation is to use line segments approximation of the offset curve and determine the arrangement of the resulting line segments. [9]

The offset curve may become a spatial curve rather than a planar curve. In this work, the offset curve is approximated by discrete points and their connecting piecewise line segments in the 3D. Therefore, sometimes the line segments nearly meet but do not form a real closed loop. For the purpose of robust line segments arrangement, the curve points are projected onto the xy-plane by the z-axis direction, and then the existence of self-intersections is tested. With this algorithm, the self-intersections are identified and removed.

Once a curve is determined, the next offset curve is soon to be ascertained. However, due to the variable widths of a multiple connected area, a certain offset curve does not allow the next offset curve of a single loop (Fig. 2).

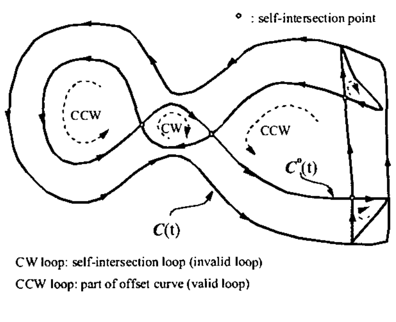
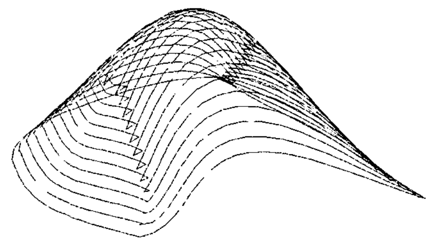


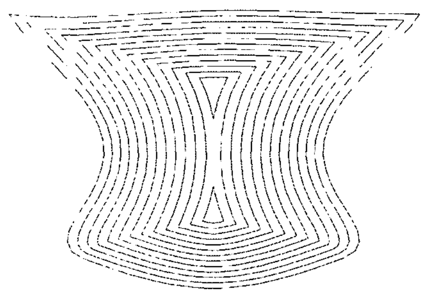
Fig. 2 Decision of the eliminated self-intersection loop

Therefore, it is inevitable that the next offset curve is divided into two loops. In this work, an offset curve is approximated by discrete points and their connecting piecewise line segments in CCW (counter clockwise) direction. After finding self-intersection points, some loops can be generated based on the points. The CW (clockwise) loops are decided to be invalid and then eliminated as illustrated in Fig. 2. And the CCW loops are decided to be the parts of the offset curve.

Then, a new offset procedure starts with one of the divided curves. The offset and division procedures are repeated until all area is filled with offset curves. The proposed algorithm can eliminate and divide the self-intersection loops of the offset curves as shown in Fig. 3.



(a) Offset curves with the self-intersection loops



(b) Eliminated self-intersection loops with top view

Fig. 3 Self-intersection loops elimination

4. PATH GENERATION

4.1 Path Generation

Tool-path generation procedure generates a sequence of CC (cutter contact) points. The CC point is a point on the sculptured surface, at which the cutter makes a tangential contact.

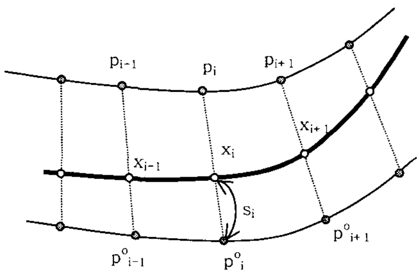


Fig. 4 Diagonal curve between offset curves

The offset curves play a key role as the guidelines for generating spiral paths. A spiral path is generated on the sculptured surface as a diagonal curve between two offset curves as depicted in Fig. 4. The j th point of the k th path segment is calculated by equation (8).

$$\mathbf{x}_j = s_j \cdot \mathbf{p}_j + (1 - s_j) \cdot \mathbf{p}_j^o \tag{8}$$

where $$s_j = \frac{\sum_{i=1}^{j-1} |\mathbf{p}_{i+1} - \mathbf{p}_i|}{\sum_{i=1}^{n-1} |\mathbf{p}_{i+1} - \mathbf{p}_i|}$$

The illustrated examples show the continuous spiral path generated by employing the proposed method as shown in Fig. 5..

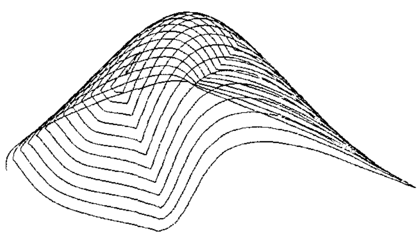


Fig. 5 Continuous tool-path

In Fig. 6, there is no tool retraction during the cutting process. The developed method can generate the continuous tool-path to reduce the number of cutter interruptions or rapid.

The proposed method allows the sculptured surface incorporating both vertical and horizontal areas to be high-speed machined. The main advantages of this approach are the ability to cut continuously with the minimum cutter retractions and to maintain the constant scallop height to ensure higher levels of efficiency and quality in high-speed finish machining. Based on these techniques, illustrative examples are given to verify the developed approach.

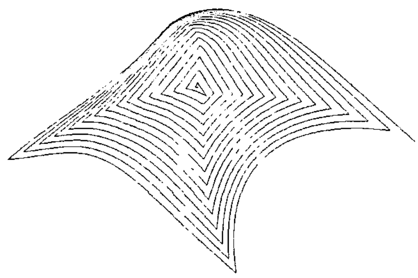


Fig. 6 Tool-path example without a tool retraction

5. Conclusions

A new tool-path generation method is presented for high-speed finish machining. The algorithm begins with the contour offset procedure along the sculptured surface boundary being machined. The offset distance is determined such that the scallop height is no larger than the allowed surface roughness. Therefore, this approach maintains the constant scallop height to ensure higher levels of efficiency and quality in high-speed finish machining.

Then, the continuous path is generated as a kind of the diagonal curve between the offset curves. The cutter can move into or out from the centre in the continuous path. This path strategy is able to connect to a neighbor path without a cutter retraction. Thus, the continuous spiral path can be generated to reduce the number of cutter interruptions or rapid traversals during the cutting operations. The main advantage of this approach is to minimise the fluctuation of cutting force and the possibility of chipping on the cutting edge for HSM by reducing the tool retractions. The scallop heights of the tool-paths are changed in the diagonalizing process.

This method allows the sculptured surface incorporating both steeper and flatter areas to be high-speed machined.

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