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# Geometric Simulation of Five-Axis Ball-End Milling

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## Abstract

The current emphasis of CAD/CAM technology is to verify and optimize the NC code in terms of the productivity and machining accuracy prior to the actual machining. This research develops a new method to calculate the chip geometry for five-axis ball-end milling operations. The chip geometry in five-axis machining is continuously varying along the tool path. In order to obtain accurate and reliable chip geometry, it is essential to construct a B-rep model of the work-piece and update the model as the tool removes material. Also, the material removal in ball-end milling is precisely simulated for finishing five axis-milling operations, in order to construct the feed-mark and scallop geometries. The method developed can be used to verify and optimize NC codes, thus contributing to improving reliability, accuracy, and productivity in CNC machining.

**Keywords: "Milling Simulation" - "Ball-end milling" - "CAD/CAM".**

## Introduction

The various CAD/CAM systems are used to generate G-codes (NC codes) to machine free-form or sculptured surfaces. The current state of CAM technology is capable of generating 5-axis tool paths for multi free-form surfaces with ball-nose cutters; however, the NC codes may still contain shortcomings due to following reasons:

1) excessive chip load on the cutting edge resulting early wear of some portions of the edge
2) improper width of cut (WOC) and feed resulting poor surface finish
3) tool paths computed regardless of the material remained on the surface

Traditionally, machining verifications were performed by first examining the generated tool paths overlaid on the work-piece drawings and then proof-running tests conducted on soft materials prior to actual machining operations. But complex motions of five-axis milling make identifying significant errors impossible. In addition the procedure was time-consuming. With the development of solid modeling techniques that provide a reliable model-based environment for 3D part representation, pre-process machining simulation and verification systems are investigated.

One of the most widely used methods for 3D part representation is Boundary Representation (B-rep). It can support a variety of mathematical surfaces including non-uniform rational B-spline (NURBS). The data structure of B-rep contains faces and edges and the underlying geometry. With the geometric information of the B-rep model together with algorithms available in CAGD, it is possible to either extract required geometric information or modify the 3D model of work-piece. For example, swept objects encountered in CAM verifications are effectively modeled in the B-rep. In the work presented a 3D B-rep geometric kernel (ACIS), developed by Spatial Technology Inc., is used as a geometric engine to simulate the machining process. ACIS can support the NURBS as well as analytical surfaces.

The published research work in geometric modeling of machining processes can be summarized as follows. Wang and Wang [1] [2] investigated the swept volume of solids of revolution. Based on the equation of surfaces representing the boundary of the solid and the

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motion function (feed), a family of curves lying on the envelope of the moving surface was generated. The authors then constructed the 3D pixel space swept volume which was used for subsequent Boolean operations. However, their spatial partitioning approach is view-dependent, i.e. in the case of changing the eye-view, the entire representation must be reconstructed which limits its applications. Huang and Oliver [3] also used the spatial partitioning approach to assess NC milling errors. The instances of the tool are generated along the tool path, which is used consecutively in updating the part by one-dimensional regularized Boolean operations. They overcome the view dependency problem by introducing a contour display method. To accelerate the machining simulation and verification, Menon and Robinson [4] enhanced the work by Menon and Voelcker [5] with parallel computation. They also extended the range of verification to the machining tolerance and static deflection assessments. Takata et al [6] and Tsai et al [7] [8] also developed a milling simulation system to predict instantaneous cutting forces. The geometric simulation was based on a method which combines the z-buffer technique and swept volume generation. Although the above spatial partitioning approaches degrade much more slowly with the complexity of the updated work-piece as opposed to the B-rep, and it is relatively easy to implement parallel spatial partitioning, these methods generate an approximated representation of 3D solids. To increase the level of precision, a large amount of memory is required. Based on Constructive Solid Geometry (CSG) part representation, Spence [9] performed computer simulations of flat-end milling operations. The instantaneous immersion geometry (entry and exit angles) was computed using a semi-circle sweeping the tool path. Ball-end milling simulation was reported in El-Mounayri et al [10] using a B-rep polyhedral-based solid modeler. The removed volume was computed and the cutting edge, modeled with a cubic Bezier curve, was intersected with the volume to find the in-cut segments. Studies for 3-axis chip geometry calculation are limited to (Feng and Menq,[11]). They used a commercial CAD/CAM software (CATIA) to determine the boundary of engaged surface between tool and work-piece. The in-cut segments were then computed using the boundary curves. However, the geometric calculations were not based on an informationally complete (B-rep) model of in-process part. Accurate B-rep model of the in-process part together with accurate tool geometry are two essential requirements for obtaining accurate and valid chip geometry.

The aim of the geometric simulation system developed in the current work is:

1) To accurately represent various geometric objects encountered in ball-end milling, for example the cutter swept volume and the cutting edge swept surface for 5-axis milling;
2) To update the part and verify the G-codes for 3- to 5-axis milling operations;
3) To calculate the instantaneous chip load, i.e. in-cut segments and chip thickness, required for 5-axis milling force prediction; and
4) To construct B-rep model of the machined surface to estimate the surface quality of the work-piece.

Henceforth, the paper is organized as follows. The swept volume generation technique is discussed in the second section followed by the part updating for roughing and finishing operations which is implemented on a turbine blade with the complexity of sculptured surfaces. In the next section the instantaneous chip geometry is computed based on the B-rep model of the updated part. Surface texture for five-axis milling is also modeled and the surface quality is evaluated. The last section concludes the paper and proposes future research work.

## Swept volume generation technique

The kinematics of the milling operation consists of simultaneous rotational motion of cutting edges and linear motions of the work-piece. This system can be replaced by an equivalent system in which the work-piece is stationary and the cutting edges have simultaneous rotational and linear motions. Thus, the true path of points on the cutting edge for 2-axis milling is trochoidal, as demonstrated by Martelloti [12]. Since the material is removed by trochoidal path of consecutive cutting edges, cusps (or feed marks) with the spacing of feed per tooth are generated on the machined surface.

To precisely simulate the material removal of milling operations, the volume removed must be constructed based on the true path of each point on the cutting edge. However, for the non-functional surfaces, the cusp height is either one or two order of magnitude smaller than dimensional. Therefore, the true swept volume can be simplified as the volume generated by linear sweeping motions of a solid of revolution, which was proposed by Wang [1] [2] and Menon and Voelcker [5].

For the case of ball-end milling the solid of revolution (i.e. cutter), consists of a cylinder and a semi-sphere representing the envelope of rotating cutting edges on the cylindrical and spherical parts of the ball-end mill. Ten faces are required for the construction of a valid 3-axis cutter swept volume, as shown in Figure 1. The boundary of swept volume consists of two categories of faces.

Analytical faces (Faces 5 to 10) which represent portions of the cutter at initial and final positions. These planar, cylindrical, or spherical faces are supported in the geometric kernel. The second category (Faces 1 to 4) are tool path dependent. It was proposed to use advanced sweeping/skinning techniques to construct precise NURBS representation of these faces which results in a higher level of precision. The details of the method are reported in Imani et al [13].

**Part updating for roughing operations**

A turbine blade with complexity of sculptured surfaces has been chosen to illustrate the part updating process for the 3-axis ball-end milling operations, refer to Figure 2. In the part updating process, the swept volume is first constructed. The B-spline tool path used for the swept volume represents a few blocks of the NC code generated for roughing operation. The number of blocks depends on the part geometry. The Boolean subtraction between part and swept volume is then performed which consecutively updates the part (Figure 3). Thus, it is possible to observe the precise simulation of the machining operation step-by-step. And, in case of any error, corrective actions can be taken prior to actual machining.

The rough-cut B-rep model of the part includes valuable information for tool path planning of the following operation, i.e. finishing. Removing the material with a ball-end mill leaves scallops on the surface as depicted in the Figure 3. The scallop geometry can precisely be represented by the B-rep techniques. Thus, in the finishing operation tool path can be computed based on the material remained on the surface. Obviously, if the subsequent tool motions could be confined to only the areas where material remained, then there would be no wasted motions. This would create a highly efficient tool path. In addition, the chip load can be extracted from the updated B-rep model that is required for predicting the cutting forces as well as edge wear in the finishing operations. The B-rep model, therefore, can assist the finishing tool path planning in order to achieve higher metal removal rate (MRR) and smaller scallop heights.

**Part updating for finishing operations**

In the finishing operation of sculptured surfaces, ball-nose cutters are extensively used. For these cutters, the inserts are designed to produce a radius within a certain tolerance on the work-piece. The cutting edge of the insert introduced for the simulations is one quarter of a circle which is tilted by 3 degrees, (Figure 4). The surface swept by the cutting edge is constructed through skinning **n** instances of the cutting edge (in the current work **n** is equal to 31), which are transformed according to true cutting motions of the edge.

In addition to primary cutting motion, 3-axis linear and 2-axis rotary feed motions are taken into consideration. For the current implementation, the effects of tool run-outs and tool deflections are ignored. Elbestawi et al [14] investigated the influences of tool run-out and deflections on the surface texture.

**Table1 Cutting conditions for finishing**

| Tool Rad. | Feed | Speed | Step-over |
|---|---|---|---|
| 5 | 0.1 | 5000 | 1 |
| mm | mm/th | rpm | mm |

In practice, four- or five-axis tool path strategies are implemented for ball-end milling finishing operations to keep the dead zone of the ball-nose cutter, the area within 15 degrees to the tool axis, out of the cut. For the airfoil one-way tool paths aligned with y-axis are computed. Also, the ball-nose is tilted -15 degrees around x-axis at each tool position. Thus, the dead zone of the cutter is not engaged. The cutting conditions used for finishing operations are reported in Table 1.

The ith transformation matrix corresponding to the edge angular position $\theta$ can be expressed by Equation (1). $\delta\theta_i$, which the increment of rotation angle about spindle, is constant and equal to 6°. The feed motion is assumed to lie in $yz$ plane. The components along y- and z-axis are computed based on the instantaneous slope of the tool path and given in Equation (2). $\delta\alpha_i$ is the increment of rotation angle about x-axis (A rotation axis) which is calculated by Equation (3). Where $\delta t$ is time increment equal to 0.0002 sec corresponding to 6° rotation of spindle and $\omega_{Ai}$ is instantaneous angular velocity of the A-axis.

In the performed simulation A-axis is always oriented along the x-axis. After generating 31 instances of the edge which simulate the true motion of the cutting edge in actual cutting operation, a NURBS surface is skinned through them refer to Figure 5. To avoid the surface degeneration at the ball-nose tip, the area within 5 degrees to the vertical axis is omitted.

$$Tr(\delta\theta_i, \delta\alpha_i) = \begin{bmatrix} \cos\delta\theta_i & -\sin\delta\theta_i & 0 & 0 \\ \sin\delta\theta_i & \cos\delta\theta_i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times$$

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & f_{ty} \\ 0 & 0 & 1 & f_{tz} \\ 0 & 0 & 0 & 1 \end{bmatrix} \times$$

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\delta\alpha_i & \sin\delta\alpha_i & 0 \\ 0 & -\sin\delta\alpha_i & \cos\delta\alpha_i & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1)$$

$$f_{ty} = \frac{f_t \cos(\phi_i)\delta\theta_i}{360}$$

$$fz = \frac{f_t \sin(\phi_i)\delta\theta_i}{360} \qquad (2)$$

$$\delta\alpha_i = \omega_{Ai}\,\delta t \qquad (3)$$

**Five-axis part updating**

The swept surface simulates the true motions of the cutting edge at each feed per tooth along the tool path. Thus, the material removal process of five-axis ball-end milling can be precisely simulated by performing consecutive Boolean subtractions between the B-rep model of part and the swept surface at each feed per tooth. Figure 6 illustrates the B-rep model of the part after finishing operation at a desired spot. The feed marks along the feed direction as well as the scallops along the step-over direction are precisely constructed and depicted in Figure 6.

**5-axis chip load calculation**

The physical simulation of the milling process requires the following geometric information:

1) the tool geometry, such as cutting edge design and
2) the chip geometry, i.e., in-cut segment of the cutting edge and undeformed radial chip thickness.

The following sections describe procedures for determining or extracting the above geometric information from the B-rep model of the rough-cut part.

**Tool geometry**

The tool geometry, which is provided by the manufacturer, is depicted in Figure 4. The cutting edge is one quarter of a circle tilted by 3 degrees.

**Chip geometry**

The chip geometry is continuously varying along the tool path. In order to obtain accurate and reliable chip geometry, it is essential to construct a B-rep model of the work-piece and update it as the tool removes the material. In addition to the updated work-piece, the chip geometry depends on the cutting edge design, the tool path, and the feed.

**Cutting edge immersion**

The immersion or engaged portion of the cutting edge during machining is computed in two steps. First, the boundary of the contact face between the ball nose and the part is constructed. In 5- axis ball-end milling this boundary consists of three B-spline edges, see enlarged top section of Figure 7. The B-splines are intersection curves of the surface swept by the cutting edge and the faces of rough-cut updated part. The second step is to find the intersection points of cutting edge with the boundary of the contact face. The edge-edge intersection function finds the closest point on the edges with a prescribed tolerance. The segments on the cutting edge are then classified into in-cut and out-of-cut segments, in-cut segments are shown in Figure 7. The endpoints of each in-cut segment represent the integration limits required for the physical simulation of the machining process.

**Chip thickness**

One of the most important parameters affecting the cutting forces is the radial chip thickness. Martelloti ([12] derived the following equation for the chip

$$t_c = R + f_t \sin\theta - (R^2 + f_t^2 \cos^2\theta)^{1/2} \qquad (4)$$

thickness by assuming a circular path for the tooth Where θ, R and $f_t$ are edge angular position, tool radius and feed per tooth, respectively. For 3-axis ball-end milling the effect of the vertical feed on the chip thickness reported in Imani [13] is as follow:

$$t_c(\theta, z) = R_2(z) + f_h \sin\theta - [R_1^2(z) - f_h^2 \cos^2\theta]^{1/2} \qquad (5)$$

where $f_h$ is the horizontal component of the feed along the tool path. $R_1$ and $R_2$ are the ball-nose radii at two successive positions in the same z value. However, for the case of five-axis ball-end milling the radial chip thickness must be extracted from two consecutive surfaces swept by the cutting edge at desired spot along tool path, see Figure 5.

### Feed mark and scallop profiles

The surface texture in milling is defined in terms of roughness, waviness, lay and flaws, deteriorates due to several factors, e.g. built-up edge formation, dynamics of structure, periodic engagements of the cutting edge and the form of the cutter.

The available B-rep model after updating for finishing operation contains feed mark geometry as well as cross-feed scallop geometry. Thus, the feed mark and scallops profiles can be extracted from the B-rep model. The faces readily available in the B-rep model precisely represent the surface texture can be intersected with a vertical planes aligned with feed direction and the step-over direction. The resulting intersection curves represent the feed marks and scallop profiles, which are depicted in Figure 8 and 9. The profile shown in Figure 8 is rotated in order to clearly show feed marks remained on the designed surface. The important parameters in ball-end milling which influences the surface texture are feed, tool radius and step-over. The feed marks profile greatly depends on feed while the scallops profile depends on tool radius and step-over.

### Conclusion

In this work roughing and finishing ball-end milling operations are simulated. The method can accurately and efficiently update the B-rep model of the part, extract the instantaneous chip geometry, and construct the B-rep model of the surface texture. The material removal process is simulated based on the true path of each point on the cutting edge. Thus, the system is able to precisely construct the feed mark and scallop geometries on the surface.

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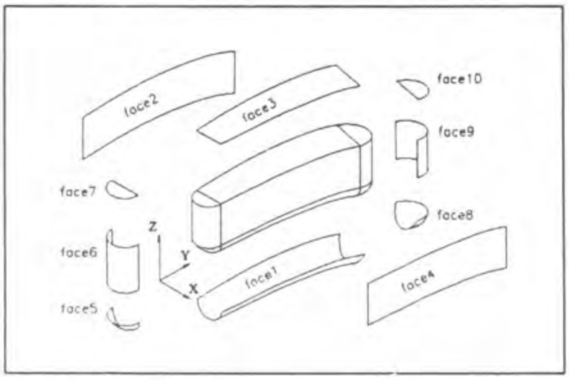

**Fig. 1 Swept volume of ball-end mill**

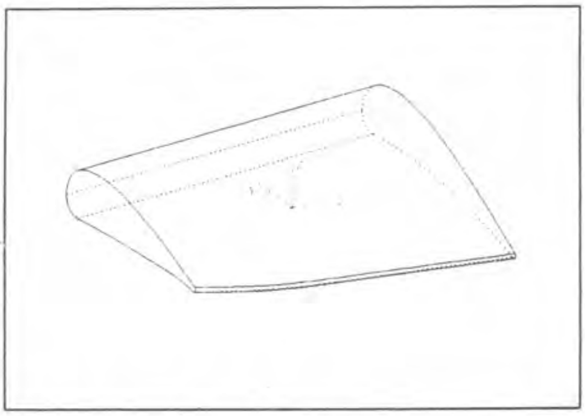

**Fig.2 B-rep model of turbine blade**

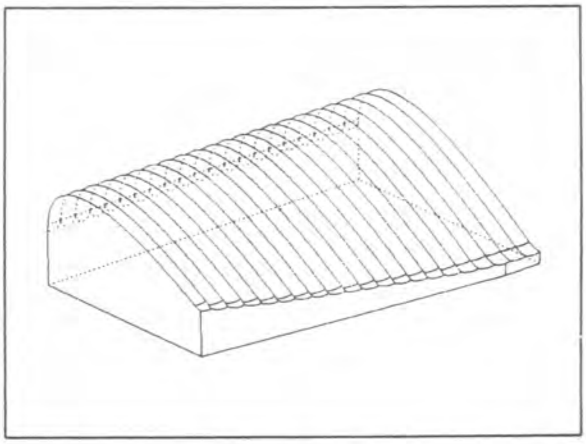

**Fig. 3 B-rep model of rough-cut part**

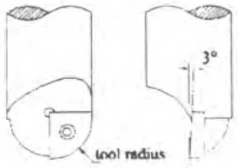

**Fig. 4 Insert geometry**

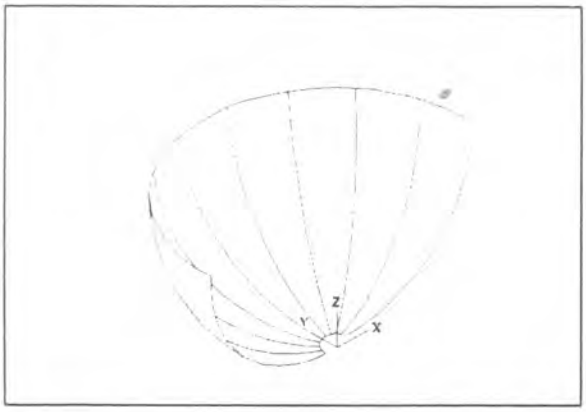

Fig. 5 Surface swept by cutting edge

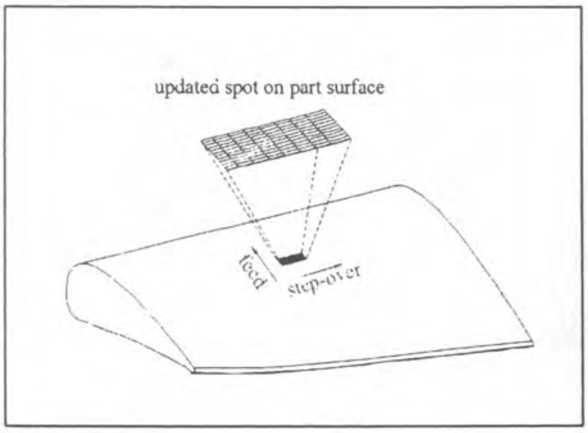

Fig. 6 Five-axis part updating process

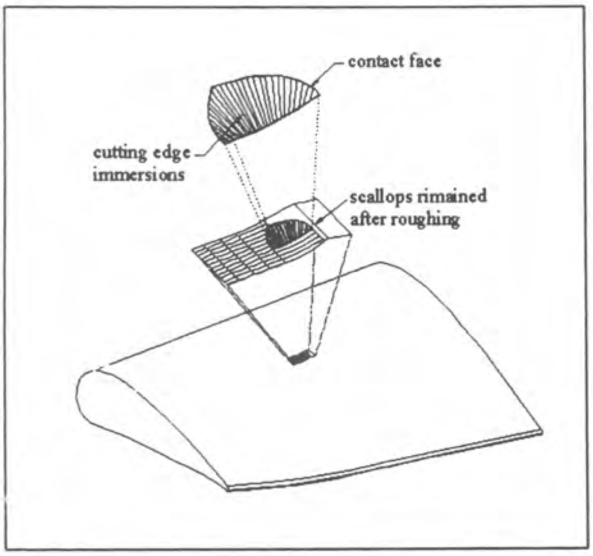

Fig.7 Contact face and cutting edge immersion

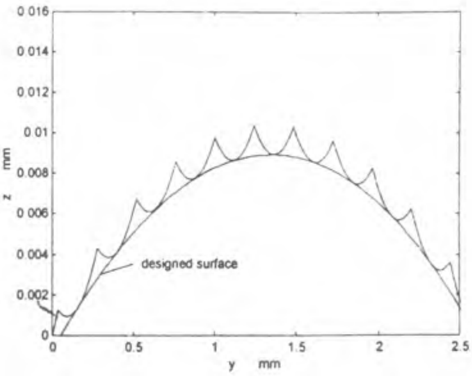

Fig. 8 Feed marks profile (rotated)

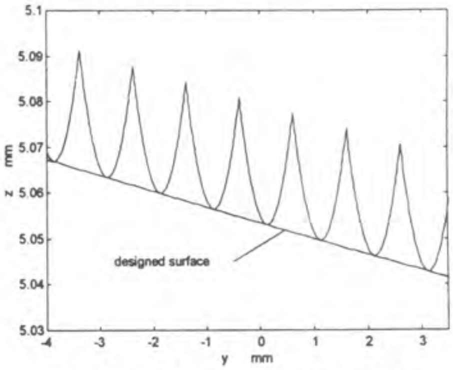

Fig. 9 Scallops/step-over profile

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