A solid modeler based engagement model for 5-axis ball end milling

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Abstract

5-axis sculptured surface milling is a difficult machining process to model due to the complex geometrical engagement between the workpiece and the cutter. Due to the complexity of the process, the engagement cannot be found analytically with conventional methods. Therefore, solid modeler based simulations are utilized to compute the engagement map. This paper presents a comprehensive and efficient strategy for engagement modeling of ball end milling using a solid modeler kernel, namely Parasolid. Accuracy of the model is validated by simulating the cutting forces based on the calculated engagements and compare it with experimentally measured cutting forces.

Keywords: 5-axis milling; Engagement; Simulation;

1. Introduction

Accurate prediction of engagement between tool and workpiece at any instant along the tool path is desired because it is a critical input for force modelling and any other analysis and optimization of milling processes. Compared to the 3-axis milling, the engagement region cannot be calculated accurately and easily using analytical methods in the 5-axis milling. This is valid, especially for sculptured and free form surface milling operations. In such cases, solid modeler based simulations are required.

An extensive number of publications exist about engagement models for different milling operations. It is possible to classify these works in three main categories: solid modeller kernels based approaches, analytical approaches, and advanced geometrical modelling methods.

The first group is based on the solid modeller kernels such as Parasolid and ACIS. These kernels are highly advanced packages, allowing development of different applications and they can be integrated with existing CAD/CAM packages easily. It should be also noted that when using these kernels, the applications are limited by their capabilities, which makes them unsuitable for certain applications.

Imani et al. introduced an ACIS based engagement model for 3-axis ball end milling [1]. The developed geometric model is based on B-rep NURBS enhanced solid modeling techniques and it can obtain the in-process workpiece (IPW), engagement map and also the removed chip geometry.

D. Yip-Hoi and X. Huang presented a solid modeling based solution to consider the variation of depth of cut between two consecutive CL. This research work, extended the concept of features in CAD modelling to support machining process modeling. The cutter-workpiece engagement at each feed step of the end milling was modeled by considering the variation of prismatic stocks. ACIS solid modeler kernel was used in this research [2].

W. Ferry and D. Yip-Hoi presented a cutter-workpiece engagement prediction model based on the parallel slicing method (PSM) for 5-axis flank milling. In this model, semi-discrete solid modeling techniques of the ACIS kernel were used to simulate the swept volume, in-process workpiece and cutter-workpiece intersection. The removal volume was calculated by sweeping the tool along the toolpath. The engagement map was obtained by slicing the swept volume into a number of parallel planes along a given axis, and intersecting of them with the updated workpiece. This model was compared with z-buffer technique and it was concluded that the results were more accurate [3].

Lazoglu et al. used Parasolid kernel by utilizing the exact Boolean approach to model the engagement for 5-axis ball-
end milling process [4]. In this approach a mechanistic cutting force model was used to validate the results.

The second category includes analytical models. Analytical models such as the researches conducted in [5], [6] are not sufficient enough for complicated geometries such as impellers and blisks. The reason is that the variation of the engagement geometry during freeform surface machining is hard to be modelled analytically.

The third category is advanced geometrical modelling. The publications in this category can be divided into two main subcategories: special partitioning representation and CSG (constructive solid geometry) models. Dextel [7], Z-buffer [8,9], G-buffer [10], ray casting [11], Graf-tree[12], Gauss map[13] etc. are examples of special partitioning presentation approaches. The second subcategory is CSG techniques which employ Boolean operations to model swept volume and in-process workpiece [14, 15].

In this research, Parasolid kernel is used for the engagement modelling. Engagement modelling is introduced under two main sections, namely the setup and the loop modules. The loop module will be further divided into two sections. These are the “compute engagement” section and “update workpiece” section. The advantage of this approach is using the library of Parasolid in an efficient and robust way to generate accurate engagement map for 5-axis milling of free-form and complicated geometries. The proposed method is also capable of modelling multiple engagements that frequently happen in 5-axis milling operation. Effectiveness of the proposed strategy is validated with experimental data from 5-axis machining center.

2. Engagement model

The model consists of two main parts as shown in Figure 1. The first part of engagement model is the setup where the model is prepared for operation and initial computations are made. The second part is the loop which iterates through all the cutter location (CL) points. Inside the loop there are two parts. The first part is where the engagement is computed and the second part is where the workpiece is updated so that the engagement calculation can be carried on for the following CL points. The loop will start with computing the engagement and end with updating the workpiece.

2.1. Setup Module

The setup module starts with taking several inputs as shown in Fig. 2. First the tool properties such as tool type, radius of the tool, height of the tool and the number of slices are set. Then, CL points are fed into the algorithm. Finally, the blank workpiece is given. The developed model is flexible to work with different geometries.

![Fig. 2. Setup module of the engagement model.](image)

The instantaneous position and orientation of the tool can be extracted from the generated CL file of the CAM package. This file contains the location of the tool tip and the orientation of the tool in three-dimensional space. For the purpose of this paper, an impeller containing free form surfaces is selected. The impeller and the blank parts are given in Fig. 3. With the selection of this geometry, it is shown that the model can handle complex 5-axis geometries.

![Fig. 3. The geometry used for simulation and validation.](image)

Since curvature of the tool changes more rapidly at the tool tip, the heights of the planes, which are used for the slicing operation, are generated exponentially to have more slices at the tip of the tool. The higher number of slices connotes higher accuracy, but it also requires longer calculation time. There are several vectors, which are used multiple times in the model and are required for different operations such as creating the tool, generating sweep path or displaying relevant directions. These vectors are the sweep direction, sweep reference direction, feed direction, tool
normal and tool reference direction. The vectors are calculated in advance to avoid additional computations.

Before the loop is initiated, the last step is to create the tool. The geometry of the ball end mill is modelled in Parasolid with uniting the spherical part with the cylindrical part. “Create solid sphere” function requires radius, location, tool axis as normal direction and cross feed direction as reference direction. The radius of the tool is denoted by $r$. The location coordinates define the center of the sphere. Since each CL point represents the position of the tooltip, they are shifted as much as the radius of the tool in the normal direction (tool axis direction) to find the center of the spherical part of the tool. The tool location coordinate can be found using the following equations:

$$X_i = X_{i0} + r \times I_i$$  \hspace{1cm} (1)
$$Y_i = Y_{i0} + r \times J_i$$  \hspace{1cm} (2)
$$Z_i = Z_{i0} + r \times K_i$$  \hspace{1cm} (3)

Above, $X_{i0}, Y_{i0}$ and $Z_{i0}$ are the coordinates of the current CL point. $I_i, J_i$ and $K_i$ are the cosine directions of the tool axis that can be extracted from the CL file. Next, the cylinder is created, starting at the center of the sphere and extruding towards the tool reference direction. The cylinder requires the same parameters as the sphere as well as height. The two solid bodies are united to form a single tool body.

### 2.2. Loop Module

The loop module is initialized after setup module and forms the main part of the engagement model. The loop is divided into two main parts. The first part is where the engagement is computed. In the second part, the machining process is simulated by updating the workpiece. The flowchart of the loop is given in Fig. 4. The importance of the second part is due to the fact that workpiece should be updated to be used as in-process workpiece (IWS) so that the engagement can be completed successfully for the remaining CL points in the loop.

In order to compute the engagement at a given CL point, the tool body is intersected with slicing planes which results in rings at each height increment. These rings are then intersected with the IPW. The intersection results in several engagement curves. The beginning and the end coordinates of these curves give the engagement points. Ultimately, engagement points are used to calculate the entrance and exit angles with respect to the cross feed direction.

#### 2.2.1. Compute the engagement

The engagement computation forms the main part of the model. It also consumes most of the computational resources. Tool body is sliced into discs as is shown in red circles in Fig. 5(b). Next, desired number of planes are created perpendicular to the tool axis at each plane height. These plane heights are calculated as covered in setup module. In order to create the plane, location, normal direction and reference direction are required. The normal direction and reference direction are the same as of the tool. The location is calculated using the equations below where $h$ represents the disc heights and $n$ is the disc number:

$$P_{X_i} = X_i + h_n \times I_i$$  \hspace{1cm} (4)
$$P_{Y_i} = Y_i + h_n \times J_i$$  \hspace{1cm} (5)
$$P_{Z_i} = Z_i + h_n \times K_i$$  \hspace{1cm} (6)

These planes are perpendicular to the normal direction of the tool and start from the tip of the tool extending until the end of the tool with very small height increments. The planes will be used in combination with the tool body for creating the tool discs. In the following step, the planes and the tool body are intersected using the “intersect surface” function of Parasolid. Each intersection operation will result in a disc lying on the corresponding plane, which was created previously at the beginning of the loop.
The discs are then intersected with the copy of the IPW. The IPW is duplicated to preserve the original IPW to be used in the following iterations of the loop. The intersection results in an arc for single engagement or multiple arcs for multiple engagement case. Generally, the engagement model will output a single engagement curve, but also as is shown in section 3, the model is capable of detecting the frequently occurring multiple engagement conditions during freeform 5-axis milling.

From each arc the coordinates of the start and the end points are extracted and stored. These are named engagement points and are used in angle calculation. The angle between vector pointing to the current engagement point from the center of the tool and the cross feed direction vector is calculated. Fig. 5 represents the output of a sample CL point of the impeller geometry. For the sake of simplicity, the tool body is not shown in Fig. 5(b). In this figure, the green and the red points respectively present entrance and exit points.

The entrance and exit angles are calculated by utilizing appropriate transformation to view them in the tool axis direction. This allows for engagement angles to be computed with respect to the cross feed direction.

As is depicted in Fig. 6, the engagement angles are defined for the engagement points. The calculated entrance and exit angles for each disk are saved as engagement map, to be later used as a boundary condition for force model or other pertinent applications.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{figure6.png}
\caption{Engagement angle calculation.}
\end{figure}

\subsection{2.2.2. Update the workpiece}

The required steps to update the workpiece are listed in Fig. 4. At any given cutter location point CLi, the algorithm first generates a line between CLi and CLi+1. This line is a vector at CLi pointing towards CLi+1, thus facing towards the feed direction. This line is used as the path for the sweeping operation. At the next step the projection of the tool is taken perpendicular to the current sweep path (which is also the feed direction). This projection of the tool gives us the effective cross section which removes material from the workpiece during the real machining operation. Then, the projection is swept across the sweep path.

In this model, the swept volume of the tool is generated by sweeping the effective cross section of the tool. The effective cross section is basically the projection of the tool on a plane which is perpendicular to the feed direction. Unfortunately, the current version of Parasolid kernel has not proven to perform well for taking the projection of solid bodies at certain projection angles. Hence, different types of tools require different approaches. In this research work, ball end mill tool is used for the simulation and the experiment. For the ball end mill, if it is known that only the spherical part of the tool is in contact with the workpiece, the projection of the tool can be modelled as a simple circle. If the cylindrical part of the tool is in contact, a different approach is required. In this case projection of the tool has to be modelled as a simple circle united with a rectangle on top of it.

Using the generated line representing the sweep path and the projection of the tool, the swept volume is generated using Parasolid features between CLi and CLi+1. However, this volume does not fully represent the volume that the tool would cover in reality. To tackle this problem, the total volume, which the tool sweeps is modeled in three steps. First the tool body is created at the current CL point. Next, the swept volume is generated as was mentioned before. Finally, the tool body is generated again at next CL point.

In order to finalize updating the workpiece, the previously generated bodies need to be subtracted from the IPW. To accomplish this, the Boolean operation subtract is used. First the tool body at the current CL point and the swept volume is subtracted from the IPW. Next, the CL point counter for the loop is incremented by one and the tool body at this CL point is subtracted. As a result the IPW is updated and becomes ready for engagement computation of the remaining CL points. Finally, the tool body is created to be used again in the next loop iteration.

\section{3. Simulation and experimental results}

Following the completion of the engagement model, the final workpiece will be obtained as is given in Fig. 7. The engagement map file containing the corresponding engagement angles for each slice of the tool will be generated as well. Fig. 8 illustrates an example of engagement file containing multiple engagements for CL number 3825 of the impeller example. The leftmost column in Fig. 8 depicts the row number in the output engagement file. Columns two to seven represent the CL number, the disc number, and the entrance and exit angles in degrees for each engagement curve, respectively.

The sample engagement output given in Fig. 8 shows a case of multiple engagement where the entrance and exit angles for curve 1 and curve 2 are denoted, respectively as En1, Ex1, En2 and Ex2. Fig. 9 and Fig. 10 shows 2D and 3D map of the engagement projected on the tool surface. In both of the figures, the red curves represent the second set of engagement that frequently happens during 5-axis milling of
freeform surfaces.

Fig. 7. A sample output of the developed model for the 5-axis machining of an impeller geometry.

Fig. 8. A sample of engagement output (entrance (En1, En2) and exit (Ex1, Ex2) angles are in degrees).

Fig. 9. 2D map of engagement for multiple engagement case.

Fig. 10. 3D map of engagement projected on the tool in multiple engagement case.

In order to assess the performance of the proposed model, experiments were carried out using 5-axis milling center. The output of the engagement model shown in Fig. 8 was used as an input in a mechanistic force model developed by authors in previous research works [4], [16]. The engagement data is utilized as the upper and lower bounds (θ_{En}, θ_{Ex}) in Eq. 7 to estimate the cutting forces. In this equation, \( \int_{\theta_{Ex}}^{\theta_{En}} dF_{x,y,z}(\theta) \) is the elemental cutting forces in X, Y and Z directions as a function of angular position of the tool (θ). More details about force model can be found in reference [4] and [16].

\[
\int_{\theta_{Ex}}^{\theta_{En}} dF_{x,y,z}(\theta) \ d\theta
\]  

Fig. 11 shows the agreement between experimental and simulated data for the toolpath shown in Fig. 5. In this experiment, a 12 [mm] ball end mill was used for machining of the impeller introduced in Fig. 3. The spindle speed and the feedrate were respectively 2500 [rpm] and 250 [mm/min]. The force was measured using a rotary type dynamometer. All the experiments were conducted on Aluminium 7050 aerospace grade.

As can be seen in Fig. 11, the trend and the magnitude of the simulated cutting forces are in good agreement with experimental data. The upper section of the figure shows the experimental and the simulated cutting forces in X, Y and Z directions of rotary dynamometer. In order to show the accuracy of the simulated cutting forces, a zoomed view of the forces is represented in the lower section of Fig. 11.
According to the experimental data, using the output of the proposed engagement model, the force model is able to simulate the cutting forces with less than 10% error in maximum cutting force for all the experimental cases.

4. Conclusion

This paper introduced a solid modeler based engagement model to find the engagement map for 5-axis freeform surfaces milling operation. The proposed model is robust and efficient. The model is also capable of finding the multiple engagement conditions that frequently happen in 5-axis milling of freeform surfaces. The model can be incorporated in applications such as feedrate scheduling algorithms, tool orientation optimization and other relevant applications that needs engagement information. It was experimentally proven that the proposed model is accurate and able to be seamlessly linked with any 5-axis process mechanic model for the predictions of cutting forces and torques in the 5-axis ball end milling.

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