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# Discrete Cutting Force Model for 5-Axis Milling with Arbitrary Engagement and Feed Direction

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**Abstract**

5-axis machining operations bring new challenges for predicting cutting forces. Complex tool workpiece engagements and tool orientations make it difficult to adapt 3-axis process models for 5-axis operations. A new model is developed to predict cutting forces with arbitrary tool/workpiece engagement and tool feed direction. A discretization approach is used, in which the tool is composed of multiple cutting elements. Each element is processed to determine its effect on cutting forces, and global forces are determined by combining the elemental effects. Cutting tests are conducted to verify force predictions, where the tool/workpiece engagement is provided through a geometric software application.

*Keywords:* Milling, Cutting Forces, Discretized Force Model.

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## 1. Introduction

Cutting forces have a direct effect on form errors and surface quality of a machined part. Once cutting forces are simulated, tool and workpiece deflections, which result in form errors and vibrations causing surface quality issues, can be predicted.

Cutting forces depend on the tool and workpiece material, cutting tool geometry and cutting conditions. In 5-axis milling cutting conditions can vary considerably in process, and the varying cutting conditions can result in complex tool-workpiece engagements (TWE). Ozturk and Budak calculated such engagements analytically for 5-axis ball-end milling [1], and also simulated cutting forces throughout a toolpath after calculating the cutting parameters at discrete intervals [2]. Although this method gives accurate results for smooth machining operations, the analytical engagement model loses accuracy when the uncut surface is more complex.

For more accurate force prediction, alternative engagement calculation methods are needed. Several techniques have been developed to model the complex tool/workpiece engagements. These models operate by creating a virtual workpiece, and removing any material that interferes with the geometry of a tool moved along a path. For each tool motion, the surface patches of the tool that remove material are considered to be the TWE region. In the Solid Model based material removal simulation, the engagement area is derived from finding intersections between the solid models of both the tool and the workpiece [3, 4]. Others have represented the workpiece as a Z-map, also known as height map, a matrix/manifold of lines which are virtually cut when they interfere with the tool mesh [5]. A more advanced version of Z-map is the Dexel approach [6] that can model overhangs in the geometry, thus supporting 5-axis milling. The Dexel approach may be improved to so-called tri-Dexel model by introducing virtual grid lines in three directions to reduce dependence on grid directionality in the geometry accuracy for any cut direction. [7, 6, 8]

In the current model, geometric software which applies the tri-Dexel model is used to determine TWE data for every cutter location (CL) point of a part program (see Figure 1).

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This TWE data determines which elements of a discretized tool mesh are engaged in the cut during that move. The cutting force contribution of each engaged element are then combined to determine the global cutting force for that move.

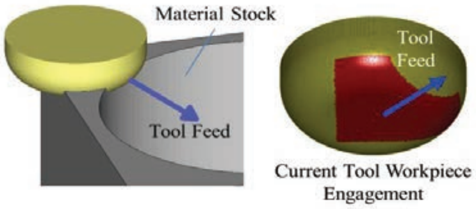

Figure 1: Example tool/workpiece engagement determined through simulation of material removal from stock material.

## 2. Discretized Force Model

In order to predict cutting forces for arbitrary feed direction with arbitrary TWE, a discrete cutting force model is used. The model concept is shown in Figure 2A, where cutting forces on a bull nose end mill act in different directions based on the cutter position and orientation. An example of the local cutting forces are shown at one section of the cutting edge, where there is a local radial force $F_r$, acting normal to the cut surface, tangent force, $F_t$, acting in the opposite direction of the cutting speed, and axial force, $F_a$, tangent to the cut surface along to the tool profile

The complex cut area from Figure 2B is discretized into multiple elements in Figure 2C. Each element has an effective cut width, $b_{el}$, and thickness, $h_{el}$, which represents the cut dimension normal to the cutting edge, **r**. The global tool force is determined by combining the effects of all active cutting elements.

This section outlines the processes to determine the effects each tool element have on global cutting force. Ultimately, the force effects of each element are defined by a constant edge force vector, $F_{e,XYZ,el}$, and a cutting force matrix giving, $F_{c,XYZ,el}$, as a function of tool feed, $f_{XYZ}$, in Equation (1).

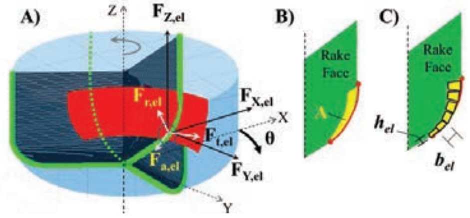

Figure 2: Cutting forces in local radial, tangent, and axial directions for discretized tool elements.

$$\begin{Bmatrix} F_{X,el} \\ F_{Y,el} \\ F_{Z,el} \end{Bmatrix} = \begin{Bmatrix} F_{e,X,el} \\ F_{e,Y,el} \\ F_{e,Z,el} \end{Bmatrix} + \begin{bmatrix} \frac{F_{c,X,el}}{f_X} & \frac{F_{c,X,el}}{f_Y} & \frac{F_{c,X,el}}{f_Z} \\ \frac{F_{c,Y,el}}{f_X} & \frac{F_{c,Y,el}}{f_Y} & \frac{F_{c,Y,el}}{f_Z} \\ \frac{F_{c,Z,el}}{f_X} & \frac{F_{c,Z,el}}{f_Y} & \frac{F_{c,Z,el}}{f_Z} \end{bmatrix} \begin{Bmatrix} f_X \\ f_Y \\ f_Z \end{Bmatrix} \quad (1)$$

$$\{F_{XYZ,el}\} = \{F_{e,XYZ,el}\} + [Q_{XYZ,el}]\{f_{XYZ}\}$$

### 2.1. Tool Discretization

The tool is discretized circumferentially, and along the tool profile, $L$, allowing the TWE of the tool to be defined by a single 2D matrix (i.e. it combines radial and axial components into a single vector along the tool profile). In addition, the elements along $L$ are created with equal length, $b_{el}$, regardless of the orientation of the elements. While other tool geometries can be configured using the current meshing approach, the mesh is illustrated in Figure 3A for a bullnose end mill with tool diameter, $D$, corner radius, $R$, and a maximum axial length of $Z_{max}$.

The mesh is created to follow the helical curve to match the shape of the cutting edge. In Figure 3B, two meshes are shown, one with zero helix angle, and one with λ=30°.

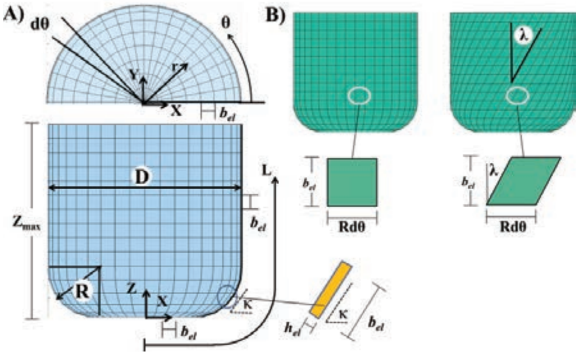

Figure 3: Tool discretisation along the tool profile, L, with increments, $b_{el}$, at angle, θ, in increments of dθ.

The tool is discretized along the tool profile, $L$, into $N_L$ elements of dimension $b_{el}$, and circumferentially into $N_c$ elements with dimensions, dθ. The mesh structure is shown in Figure 4. The $L$ mesh indices represent the concentric circles radiating from the tool tip center and extending up the side of the tool. The element cut width, $b_{el}$, is the distance between two adjacent $L$ indices. The Θ indices represent the tool elements in the circumferential direction. The circumferential elements are positioned with lag angles to follow the helical curve of the cutting edge, as shown in Figure 4. By creating the mesh along the helical curve, the indices of the TWE Map always correspond directly to the cutting edge, and each Θ index corresponds directly to the elements of one flute at one rotational position.

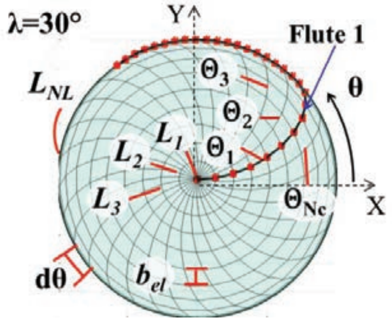

Figure 4: Tool mesh indices following the tool profile, L, and flute position angle, Θ.