

Modeling and Analysis for Five-Axis High Speed Milling Process Based on Cutter Optimal Kinematics Performance

Liqiang Zhang, Dazhong Wang and Keyong Wang
College of Mechanical Engineering, Shanghai University of Engineering Science,
Shanghai 201620, China

Abstract: The overall goal of the research is the integration of geometric and mechanistic models for cutting process simulation and feedrate optimization. Five-axis milling methods are used in industries such as aerospace, automotive and mold for free-form surface machining. In these process, surface quality and material removal rate are of very important. Conservative cutting parameters have been mostly used since there was a lack of physical models and optimization tools. Part and tool deflections under high cutting forces may result in unacceptable part quality. The extracted cutter workpiece engagements are used as input to a force prediction model. The model predictions for cutting forces and feedrate optimization are compared and verified by experimental results.

Keywords: Feedrate scheduling, five-axis, geometric simulation, mechanistic model

INTRODUCTION

Free-form machining is one of the most commonly manufacturing processes used in various industries such as aerospace and die mould industries. In planning process operations, the CAM program has to be conservative most of the time in selecting machining conditions in order to avoid undesirable results such as cutter breakage or over-cut due to excessive cutter deflection. The production time and cost are the key factors in today competitive market. However, conservative constant feedrate values have been mostly used to now since there was a lack of physical models and optimization tools for the machining process. Currently the NC code generators are based on only the geometric analysis, but not on the physics of the free-form machining process (Zhang, 2011). It is often difficult to select applicable cutting conditions to achieve high productivity due to the complicated surface geometry.

Feedrate scheduling for free-form surfaces has become popular recently. Two methods exist for conducting feedrate scheduling: one is based on the Material Removal Rate (MRR) and the other is based on the cutting force (Makhanov, 2010). The goal of the research is the integration of geometric and mechanistic models for force prediction and feedrate scheduling. Figure 1 shows the framework of the proposed feedrate scheduling system. Objective of the study can provide effective physical models and tools for cutting process simulation and improve machining accuracy and productivity.

THE CUTTING PROCESS SIMULATION

The geometric model performs two important functions in the feedrate selection process. It is used to determine the location and size of the contact area between the cutting tool and the workpiece. It also serves as a dynamic geometric record of the in-process workpiece. The method selected for geometric stock modeling is the dixel (depth element) approach (Fig. 2).

The advantage of dixel model is its smaller memory requirement and fewer processing volume elements. Figure 3 shows the screenshot of impeller machining simulation interface developed by the author (Zhang *et al.*, 2009). The Cutter Workpiece Engagements geometry defines the instantaneous intersection boundary between the cutting tool and the in-process workpiece at each location. Figure 4 summarizes the steps involved in CWE extraction. Inputs from CAD/CAM include the tool paths based CL Data file, geometric description of the cutting tool and geometric representation of the initial workpiece. The key steps which are the swept volume generation and the in-process workpiece update.

The CWE geometry is a key input to force calculation and feed rate scheduling in milling. From the CWE, the cutter entry-exit angles and depth of cuts are found and used to calculate the instantaneous cutting forces in the radial, tangential and feed directions. These can be converted to forces with respect to the machine coordinate system. This step provides critical inputs to the simulation and optimization for 5-axis machining process (Guo *et al.*, 2010; Lasemi *et al.*, 2010).

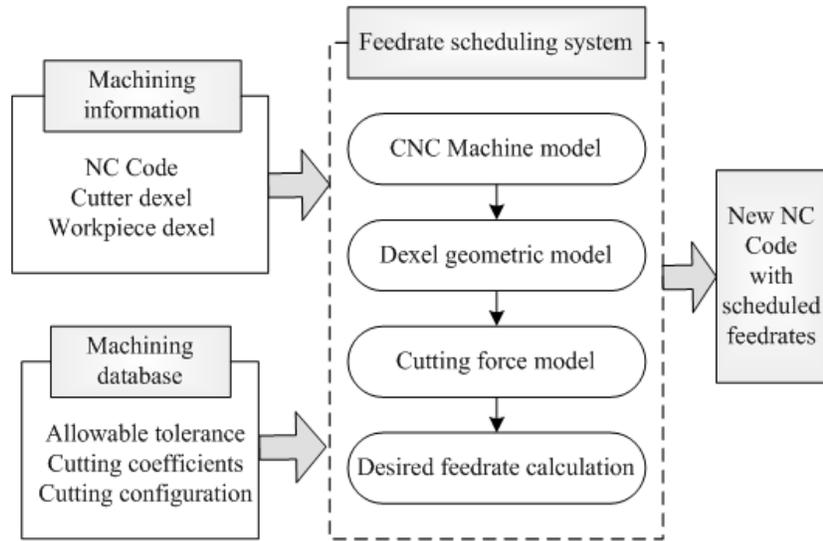


Fig. 1: Flowchart of the integrated modeling approach for feedrate scheduling

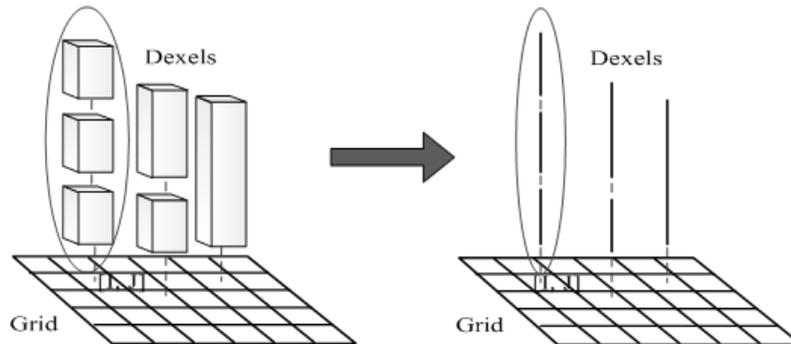


Fig. 2: The linked list data structure of dixel model

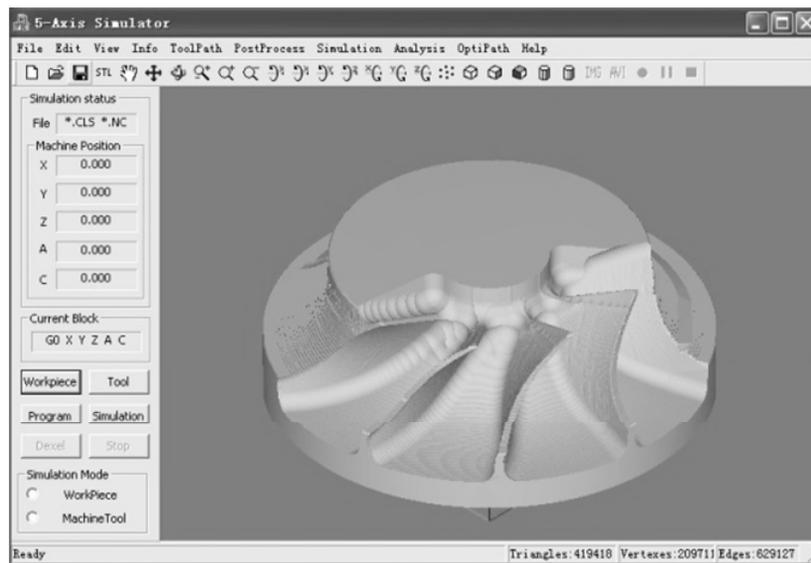


Fig. 3: Five-axis simulator interface and screenshot of impeller machining simulation

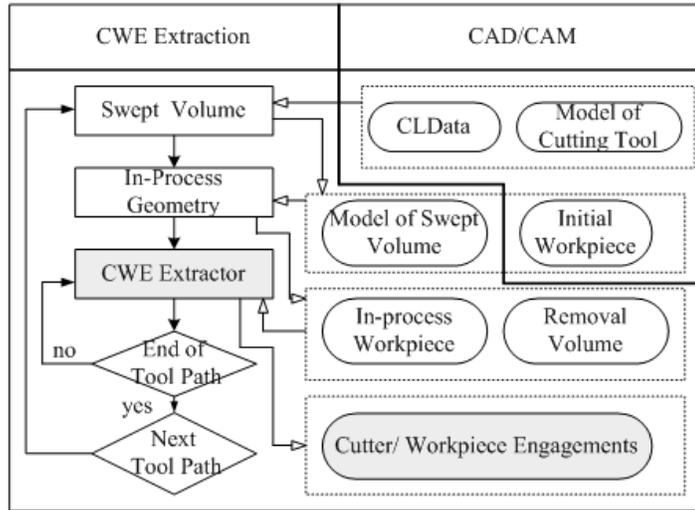


Fig. 4: The cutter workpiece engagements extraction

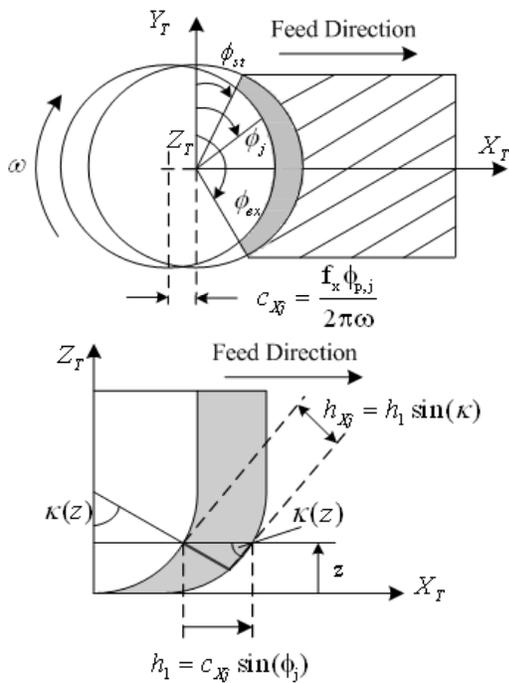


Fig. 5: The chip thickness distribution due to horizontal feed

The kinematics and mechanistic model: The Fig. 5 shows the approximate chip thickness distribution along the cutting edge given by the 2D general end mill model.

The feed-per-tooth along the feed direction for flute j is denoted by c_{Xj} and the immersion angle of flute j , is given by $\phi_j(z)$. The immersion angle is defined as the angle of the cutting edge form the y -axis of the feed coordinate system at the tool tip.

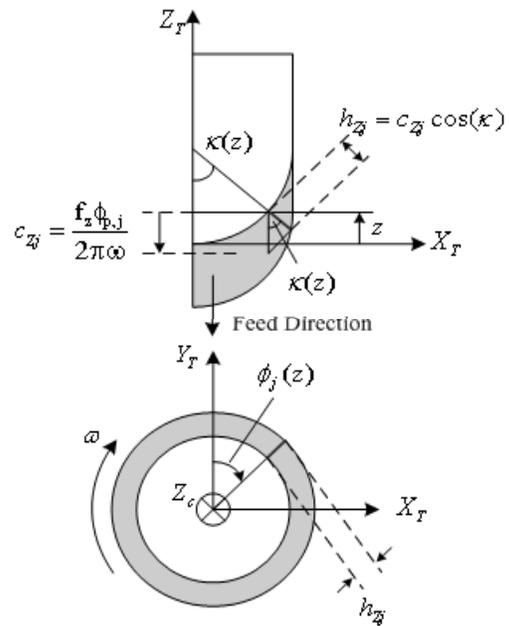


Fig. 6: The chip thickness distribution due to vertical feed

The effects of vertical feed on the chip thickness are shown in Fig. 6, which describes two discrete positions and the chip cut during movement from one to the other.

The discrete mechanistic milling model can be used to estimate instantaneous force magnitude and direction (Fig. 7). The discrete mechanistic milling model can be used to estimate instantaneous force magnitude and direction. It used a numerical technique which slices the cutter into a series of discs and sums the force contribution from each flute segment in the disc that is in contact with the workpiece.

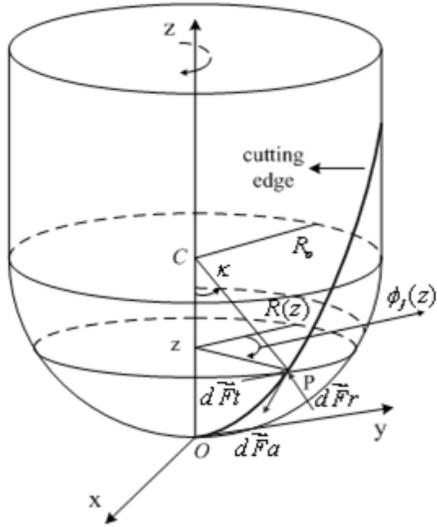


Fig. 7: The geometry of ball-end mill

At the tool tip, the local radius $R(z)$ is zero and it increases along the z -axis in the ball part. The different tangential (dF_t), radial (dF_r) and axial (dF_a) cutting forces are:

$$\begin{aligned} dF_t &= K_{tc} (h_a)^{-P_1} h(\phi, z) dz \\ dF_r &= K_{rc} (h_a)^{-P_2} h(\phi, z) dz \\ dF_a &= K_{ac} (h_a)^{-P_3} h(\phi, z) dz \end{aligned} \quad (1)$$

K_{tc} , K_{rc} , K_{ac} , P_1 , P_2 and P_3 are constants that depend on the workpiece material properties, tooth geometry, tool wear and material temperature and h_a is the average chip thickness of the cut at some tool angle θ :

$$\begin{bmatrix} dF_x \\ dF_y \\ dF_z \end{bmatrix} = \begin{bmatrix} -\sin\phi \sin\kappa & -\cos\phi & -\sin\phi \cos\kappa \\ -\cos\phi \sin\kappa & \sin\phi & -\cos\phi \sin\kappa \\ -\cos\kappa & 0 & -\sin\kappa \end{bmatrix} \begin{bmatrix} dF_r \\ dF_t \\ dF_a \end{bmatrix} \quad (2)$$

$$\begin{aligned} F_x(0) &= \sum_{i=1}^N \int_{z_1}^{z_2} [-dF_{ti} \sin\phi_i \sin\kappa_i - dF_{ri} \cos\phi_i - dF_{ai} \sin\phi_i \cos\kappa_i] dz \\ F_y(0) &= \sum_{i=1}^N \int_{z_1}^{z_2} [-dF_{ti} \cos\phi_i \sin\kappa_i + dF_{ri} \sin\phi_i - dF_{ai} \cos\phi_i \cos\kappa_i] dz \\ F_z(0) &= \sum_{i=1}^N \int_{z_1}^{z_2} [-dF_{ri} \cos\phi_i - dF_{ti} \sin\kappa_i] dz \end{aligned} \quad (3)$$

N is the number of flutes on the cutter. z_1 and z_2 are the contact boundaries of the flute within the cut and can be found from the geometric model of each zone.

In this research, the geometric and mechanistic models are executed in an integrated manner for feedrate scheduling. For each tool move the toolpath envelope is checked for intersections with the dixel model and the geometric model is updated accordingly. The mechanistic model is then used to estimate the feedrate necessary to maintain a desired force.

The summary chart of the proposed model was also given in Fig. 8. As it is seen from this chart, the force model consists of three modules which are Calibration, Cutter workpiece Engagement and force calculation modules. The calibration module is completely an important part, since the material is characterized and certain values such as cutting and edge coefficients are obtained. The cutting coefficients are assumed to be constant for a tool-work material pair and they can be evaluated either mechanistically or oblique cutting transformations.

While the milling forces estimated by the mechanistic model are a function of chip thickness, it is possible for

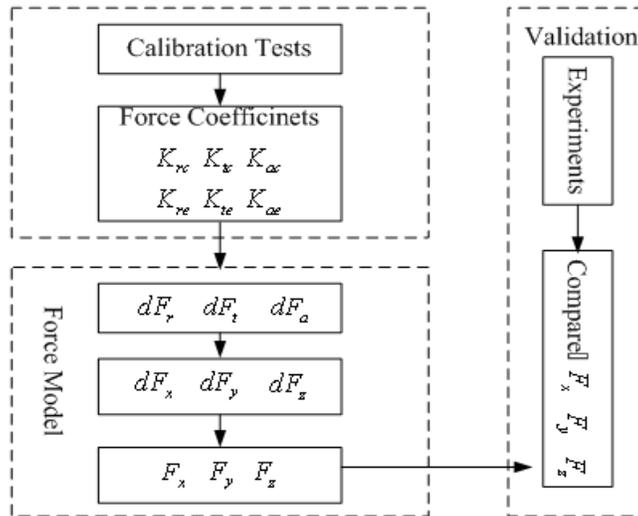


Fig. 8: The chart of the proposed mechanistic approach

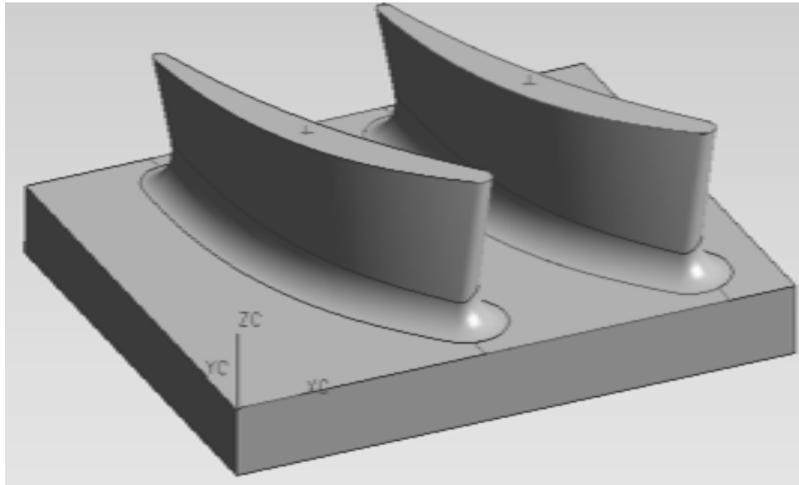


Fig. 9: Part geometry of dual blades

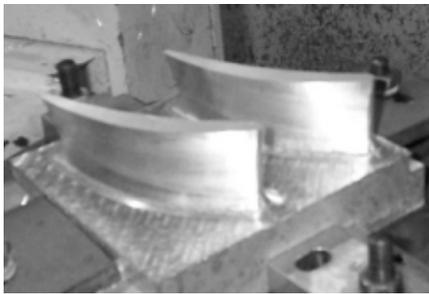


Fig. 10: Machining tests of dual blades part

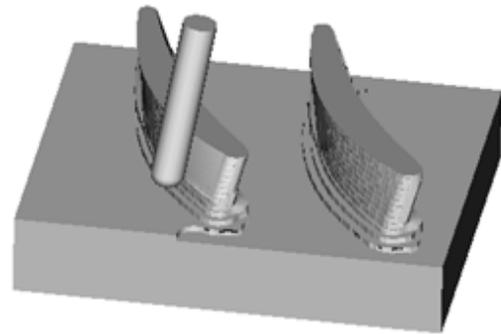


Fig. 11: The machining simulation process

acceptable milling force values to be calculated while producing unacceptable chip thickness values (Zhang and Wang, 2011).

Another important module is cutter workpiece engagement module which finds the intersection domain between the workpiece and tool. The engagement domain briefly finds the start and exit angles of discs through the spherical part of the cutter. Then they are used to calculate differential cutting forces in three orthogonal directions. These differential forces are integrated and cutting forces for each cutting edge rotation angle are obtained.

Off-line feedrate scheduling regulates the maximum resultant cutting force during one revolution of a cutter at a reference value. The combined models of the software system are tied together in an integrated modeling approach, where the overall system is integrated such that the only links between components are passing data.

CASE STUDY

Cutting experiments were conducted to verify the proposed computational models. A dual blades part machining test was performed on 5-axis dual rotating table machine as shown in Fig. 9 and 10. Cutting forces

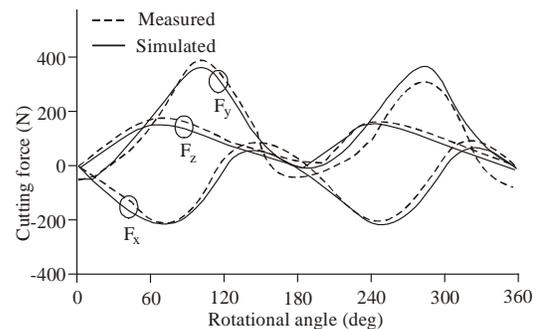


Fig. 12: The comparison of simulation and experiment results for cutting forces

were measured with a Kistler dynamometer and a PC data acquisition board. Based on the extended dixel model of workpiece and kinematics model, a prototype system of force prediction and toolpath optimization was developed with Visual C++ and OpenGL library.

A four fluted 20 mm cylindrical ball mill was used to cut aluminum A17050. The simulated and measured peak force for a constant feedrate is shown in Fig. 11 and 12.

The magnitudes and trends of the forces are very similar between the estimated and measured force. The discrepancy in cutting force magnitudes between simulation and experiment is due to the difference between the simulated feedrate and actual feedrate of contour machining, which requires trajectory generation.

CONCLUSION

This study demonstrates the feasibility of combining a geometric model with a discrete mechanistic model for force prediction. The proposed strategy provides effective physical models and tools for cutting process simulation and feedrate optimization.

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