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Research of Information Flow for Multi-axis Surface Machining Based on Cutter Motion Simulation

Liqiang Zhang, Shoujun Zhang

***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 processes, 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.**

***Index Terms*—Five-axis, geometric simulation, mechanistic model, feedrate scheduling**

I. 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's 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 [1]. 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 became 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 [2]. The goal of the research is the integration of geometric and mechanistic models for force prediction and feedrate scheduling. Fig.1 shows the framework of the cutter workpiece engagements extraction. Objective of the study can provide effective physical models and tools for cutting process simulation and improve machining accuracy and productivity.

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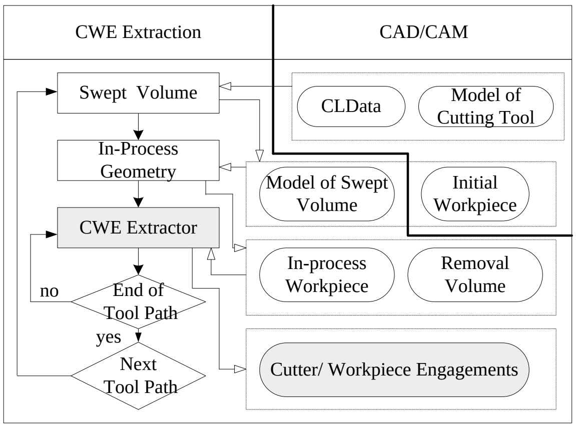

Fig.1 The Cutter Workpiece Engagements Extraction

II. 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 dexel (depth element) approach (Fig.2).

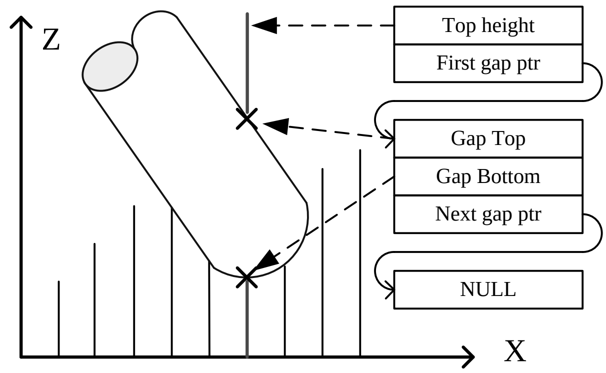

Fig.2 The linked list data structure of dexel model

The advantage of dexel model is its smaller memory requirement and fewer processing volume elements. Fig.3 shows the screenshot of propeller machining simulation interface developed by the author [3]. The Cutter Workpiece Engagements geometry defines the instantaneous intersection boundary between the cutting tool and the in-process workpiece at each location. 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.

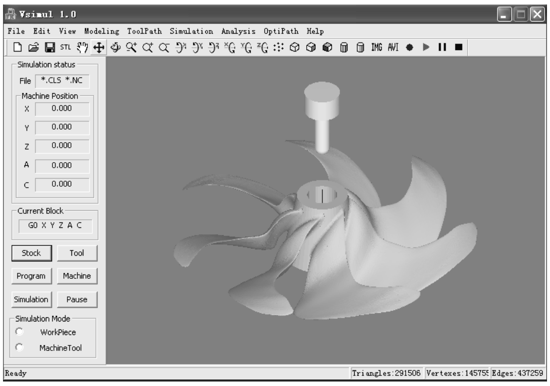

Fig.3 Five-axis simulator interface and screenshot of propeller machining simulation

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 instaneous 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 [4-5].

III. THE KENEMATICS AND MECHANISTIC MODEL

The Fig.4 shows the approximate chip thickness distribution along the cutting edge given by the 2D general end mill model.

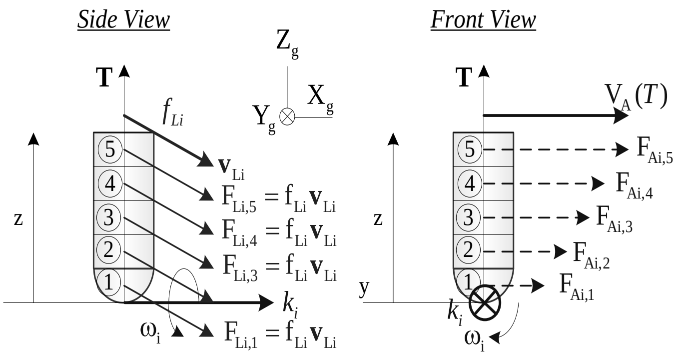

Fig. 4 The illustration of cutter motion in five-axis flank milling

A five-axis tool path for free-form surface machining is composed of a number of small segments connected together in series. In each tool path segment, the translational and angular velocities can be assumed to be constant, with changes occurring at the segment connection nodes. To calculate cutting forces along each segment, the depth of cut is divided into a number of differential elements along the axis of the cutter (Fig.5).

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.

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.

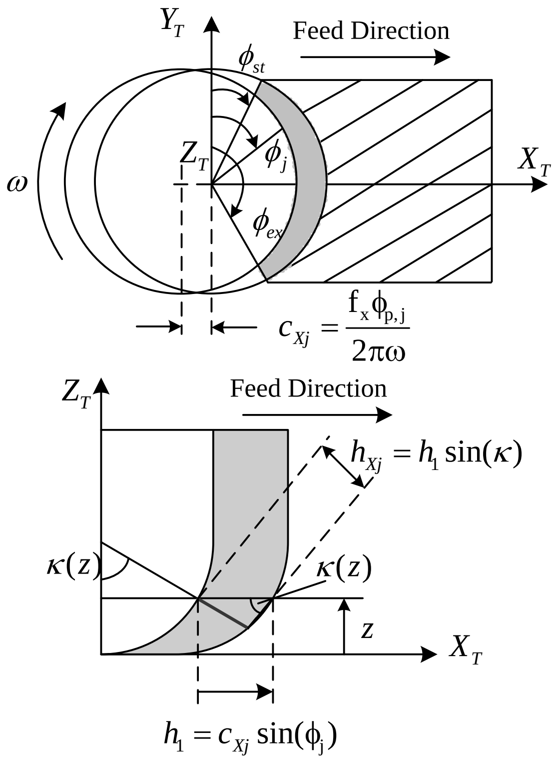

Fig.5 The Chip thickness distribution due to horizontal feed

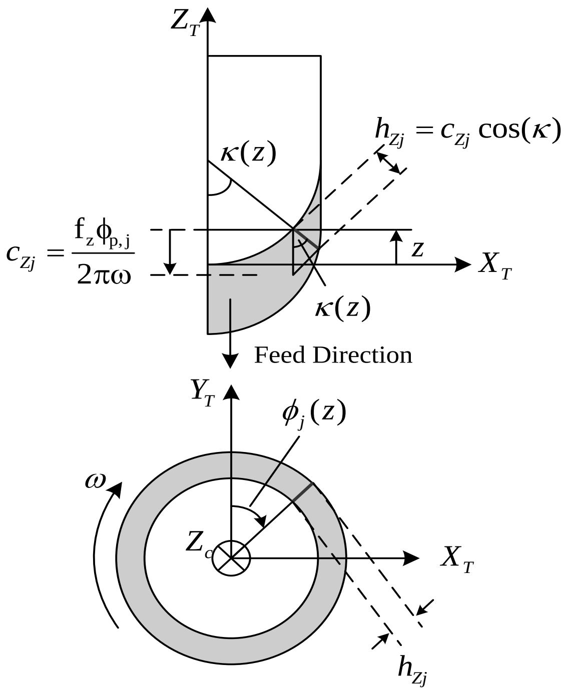

Fig.6 The Chip thickness distribution due to vertical feed

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:

$$
\begin{aligned}
dF_t &= K_{tc}(h_a)^{-p_1}\, h(\phi, z)dz \\
dF_r &= K_{rc}(h_a)^{-p_2}\, h(\phi, z)dz \\
dF_a &= K_{ac}(h_a)^{-p_3}\, h(\phi, z)dz
\end{aligned} \qquad (1)
$$

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.

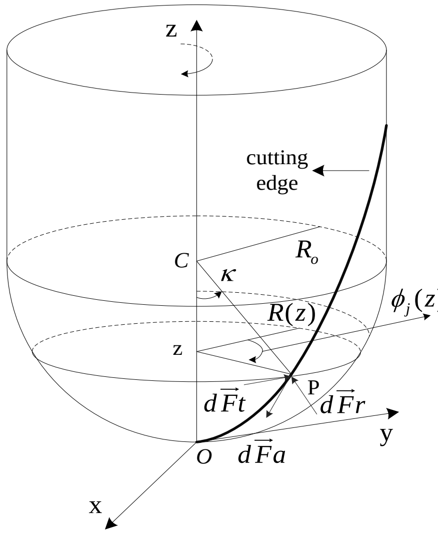

Fig.7 The Geometry of Ball-end Mill

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

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

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 dexel 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. 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 acceptable milling force values to be calculated while producing unacceptable chip thickness values [6].

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.

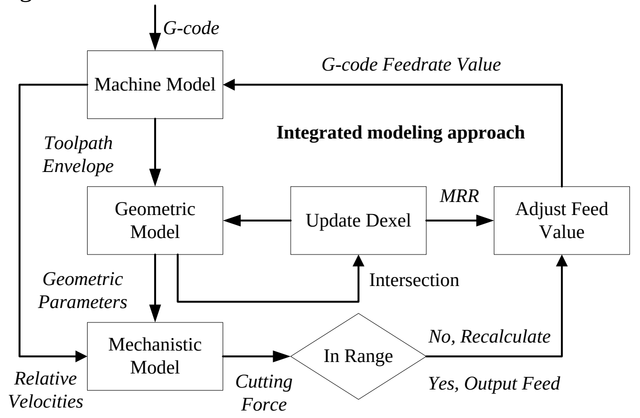

Fig.8 Flowchart of the integrated modeling approach for feedrate scheduling

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. Fig.8 summarizes the steps of the integrated modeling approach for feedrate scheduling.

The procedure for selecting optimum cutting conditions is quite different than the table based approach. For each tool move, the toolpath envelope is checked for intersections with the dexel model, and the geometric model is updated accordingly. The entrance and exit angles, contact areas, are then calculated for each intersected axial disc. The mechanistic model is then used to estimate the feedrates. The primary focus of this system is using models to set the best feedrates for sculptured surface machining subject to constraints. These constraints can be divided into three categories: part quality, tool life and machine tool limitations.

Off-line feedrate scheduling model is derived from mechanistic cutting force model, which is used to predict maximum resultant cutting force. The envelope of the cutter is used in identifying the intersection of cutter and workpiece geometry, which is required in simulating the material removal process and in dynamically updating the blank geometry for graphical NC tool path verification. The cutting edge model can be broken into small increments, where the cutting constant may be different at each location. The geometric model must be integrated with a mechanistic model for accurately estimating cutting forces and calculating acceptable feedrates. These models are the key parts of an optimization program which automatically calculates feedrates.

IV. CASE STUDY

Cutting experiments were conducted to verify the proposed computational models. A propeller part machining test was performed on 5-axis dual rotating table machine as shown in Fig. 9 and Fig.10. Cutting force was measured with a Kistler dynamometer and a PC data acquisition board. Based on the extended dexel model of workpiece and kinematics model, a prototype system of force prediction and toolpath optimization was developed with Visual C++ and OpenGL library.

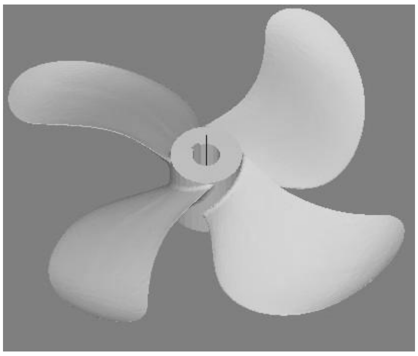

Fig.9 Part geometry of propeller model

A four fluted 20mm cylindrical ball mill was used to cut aluminum Al7050. The simulated and measured peak force for a constant feedrate is shown in Fig.11 and Fig.12.

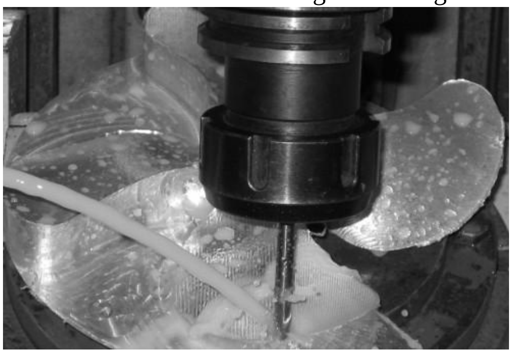

Fig.10 Machining tests of propeller part

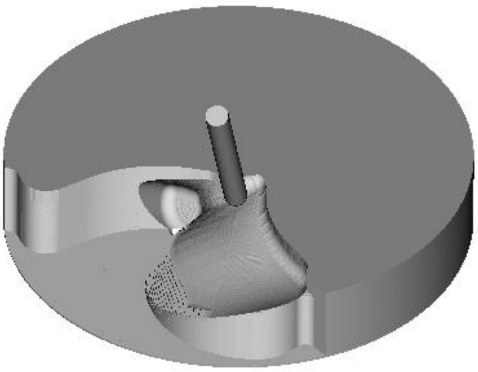

Fig.11 The machining simulation process

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.

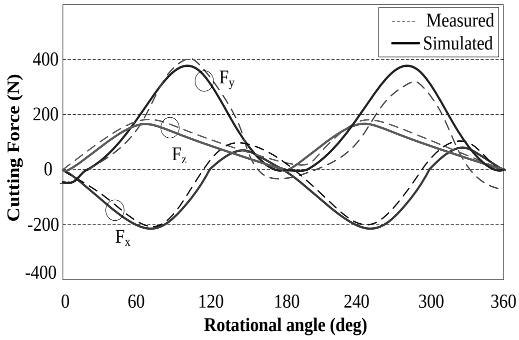

Fig.12 The comparison of simulation and experiment results for cutting forces

V. CONCLUSION

This work 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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