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CIRP Conference on High Performance Cutting

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Offline Force Control and Feedrate Scheduling for Complex Free Form Surfaces in 5-Axis Milling

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Abstract

An enhanced Force model based Feedrate Scheduling (FFS) technique for rough cutting of parts with complex free form surfaces in 5-axis machining is presented. In order to estimate the cutting forces in complex 5-axis machining an enhanced solid modeler kernel based model is developed to find the complicated engagement between cutter and workpiece for each cutter location. In this paper, cutter-workpiece engagement model is presented using the commercial Parasolid solid modeler kernel, and then cutting forces are estimated based on the developed model. In this approach, the resultant cutting forces are kept constant on a user defined threshold. The feedrate will be adjusted to keep the resultant cutting forces constant all along the tool path. Therefore, it is shown that this approach allows decreasing the cycling time drastically. The scheduled feedrate in each cutter location is carried out in NC blocks using an off-line postprocessor that can be used in commercial CAM software. Eventually, the proposed FFS technique is experimentally tested on rough machining of an impeller with free form surfaces and force validations are presented in this article.

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1. Introduction

5-axis machining is being used to manufacturing of complex free-form surfaces in aerospace, automotive, die/mold and biomedical industries for many years. 5-axis machining provides higher productivity and better access to all sides of the components, and eliminates the use of multiple fixtures. This advantage leads us to reducing the cycling time and labor costs and enhancing finished surface quality and better dimensional error.

As demands for parts with complex shapes are increasing, the need for enhancing the efficiency and productivity is also increasing. Although 5-axis machining is much more efficient in terms of time cycling, there are still more potentials to increase the productivity by optimization of cutting process. One of those potentials is the optimization of feedrate during the cutting process. In almost all of the 5-axis machining processes the feedrate is conservatively kept constant to avoid damage to machine tool and deteriorate the surface

quality of products. Besides, common CAM programs and feedrate scheduling methods are just based on the geometry and volumetric analysis of the process and the mechanics of the operation has not considered in feedrate scheduling of those methods.

Several investigations have been performed for 3-axis feedrate scheduling techniques. Erdim H, Lazoglu I, and Ozturk B. [1] performed feedrate scheduling using material removal rate (MRR) and cutting force based methods for 3-axis milling. They compared these two methods and inferred that the cutting force based method is more applicable and reliable rather than MRR method. Han Lee, and Dong-Woo Cho [2] developed an intelligent off-line feedrate scheduling for 3-axis end milling by dividing Original blocks of NC codes into smaller ones with the optimized feedrate values to adjust the peak value of cutting forces to a constant value. Yuwen Sun, Zhenyuan Jia, Fei Ren, and Dongming Guo [3] developed a guide spline-based feedrate scheduling method for machining along curvilinear paths with

simultaneous constraints of chord errors and ac/deceleration. Merdol D., and Altintas Y. [4] presented a solid modeler approach to simulate the cutting forces in three axis machining of dies and molds. Using this model, they introduced a constraint-based optimization scheme for feedrate to maximize the material removal rate (MRR) by calculating acceptable feedrate levels.

However, because of the complex geometry of 5-axis milling and the change of engagement region between cutter and workpiece through the toolpath, modeling of cutting forces and scheduling the feedrate is quite difficult. In this research an improved force model based feedrate scheduling (FFS) technique for rough cutting of an impeller using 5-axis ball-end mill is presented.

The aim of feedrate scheduling technique is to keep resultant cutting forces at the maximum limit all along the tool paths in order to decreasing the machining time and increasing the productivity. Using this strategy, appropriate feedrate is calculated between consecutive cutter locations in NC codes to maintain the cutting forces at a constant magnitude.

In order to perform a precise and reliable feedrate scheduling algorithm, the kinematics and mechanics of 5-axis ball-end milling process should be modeled comprehensively. In this paper, tool orientation for machining of an impeller is extracted from CL file and by sending it to a Parasolid solid modeler kernel the starting and exiting engagement angles are calculated. Then, according to instantaneous chip thickness that is calculated for each cutter location and using mechanistic approach, cutting forces are modeled. Simulated cutting forces for each position of cutter are used in force based feedrate scheduling strategy to select appropriate feedrate at each CL point in order to keep cutting forces below a predetermined threshold. Finally, it will be shown experimentally that this strategy is able to reduce the cycling time and increase the productivity.

2. SOLID MODELER BASED CUTTER/WORKPIECE ENGAGEMENT

2.1. 5-axis Milling Geometry

In contrast to 3-axis milling that can be defined by three translational movements, 5-axis milling contains two rotational movements as well. Therefore, tool orientation vector in five axis milling is not constant. In 3-axis machining, tool coordinate frame (TCF) and workpiece coordinate frame (WCF) are coincident. However, in 5-axis milling because of two more rotational axes, a transformation matrix has to be defined to relate TCF and WCF.

Two rotational movements of 5-axis milling can be represented by lead and tilt angles. The illustration of the coordinate frames for 5-axis milling is shown in Fig. 1

where $X_f Y_f Z_f$, $X_t Y_t Z_t$, and $X_w Y_w Z_w$ are the feed, tool, and workpiece coordinate frames, respectively.

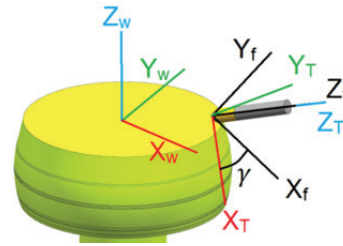


Fig. 1. Workpiece, tool and feed coordinate frame in 5-axis machining

2.2. Extracting tool orientation and transformation matrix from CL file

CL file is a text file which contains X , Y and Z coordinates of the tooltip and direction cosines of the tool vector in each cutter location [5].

Fig. 2. represents the orientation of tool for a single roughing toolpath in workpiece coordinate system that is calculated using CL file information. In this figure the red lines represents the cutter orientation and the blue line shows the tooltip position of cutter.

Because of using rotary type of dynamometer in validation tests, we need a transformation matrix to relate cutting forces in workpiece coordinate system to tool coordinate system. This transformation matrix can be found using calculated lead and tilt angles from CL file as it is shown in Eq. 1. In this equation l is lead and t is tilt angle [5].

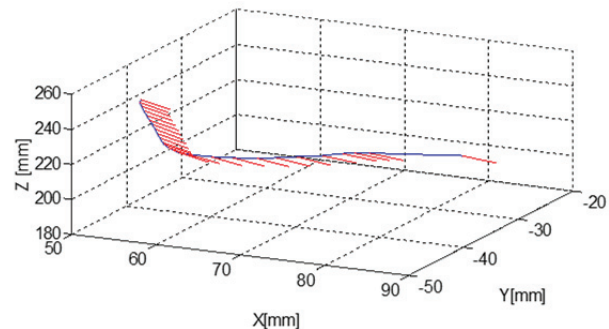


Fig. 2. Tool orientation and tooltip position in workpiece coordinate system for each cutter location point

$$T = \begin{bmatrix} \cos(l) & 0 & \sin(l) \\ \sin(t) \sin(l) & \cos(t) & -\sin(t) \cos(l) \\ -\cos(t) \sin(l) & \sin(t) & \cos(t) \cos(l) \end{bmatrix} \quad (1)$$

Eq. 2 represents the relationship between cutting forces in WCF and TCF.

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix}_{WCF} = T^{-1} \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix}_{TCF} \quad (2)$$

2.3. Cutter-Workpiece Engagement Calculation

In 5-axis machining, the cutter workpiece engagement (CWE) region does vary along the cutter path and in general, unless some specific and very simple workpiece geometry is machined, it is difficult to find an exact analytical representation. Chip load and force calculations are based on the CWE; therefore the output of the engagement model is very critical. In the literature, most of the research has been devoted to discrete simulation of NC machining processes and CWE calculation methods.

Solid-modeler based CWE calculation methods can overcome the limitations introduced by discrete methods since the cutter and the workpiece can be modeled using geometric primitives or complex geometric shapes.

One of the first steps in CWE calculation is to generate the solid volume removed by the tool cutting the workpiece. Schematic illustration of a ball-end mill sweep along is shown in Fig. 3 .

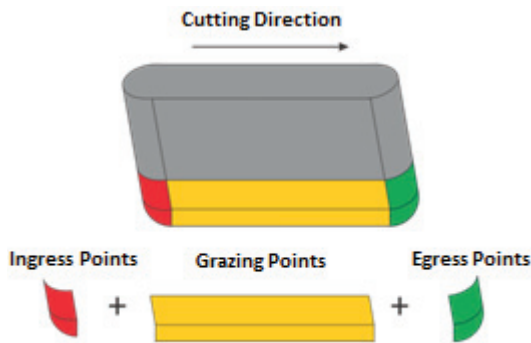


Fig. 3 Tool swept volume of a ball-end mill.

As shown in Fig. 3 tool swept volume of a ball-end cutter comprises three regions which are egress, ingress and grazing points. While obtaining the swept volume most important parameter is cutting direction since it determines the grazing points together with the geometric properties of the cutter. Possible engagement domain of the cutter lies in the egress points region meaning that front side of the tool swept volume.

In the B-rep methodology an object is represented by both its boundaries defined by faces, edges, vertices and the connectivity information. As the simulation continues, the in-process workpiece is obtained for each CL point and the contact patch surface between the tool and workpiece can be extracted. Once contact region is obtained they are transformed from the workpiece coordinate frame to the tool tip of the cutter.

The resulting 3D contact surface is illustrated for CL point #2895 in Fig. 4.(a) for the same example given in Section 5. Since engagement domain is simply the combination of start and exit angles of each discrete disc located on the cutter, the next step is to assign the start and exit angles as show in Fig. 4. (b) to each respective projected discs by intersecting the 2D discs with the boundaries of the contact patch in plane. The procedure described above is implemented in Visual Studio.NET using the Parasolid solid modeling Kernel and Parasolid Workshop on a Windows Core2Duo, 1.8 GHz/4GB Laptop.

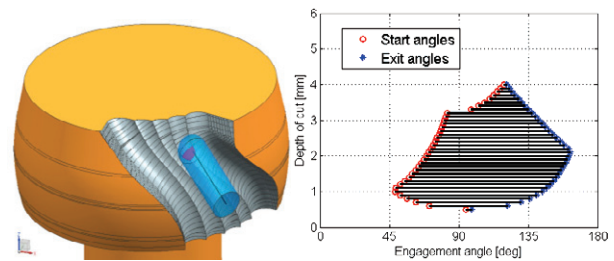


Fig. 4. The engagement domain for CL point #2895: (a) 3D contact patch, (b) Start and exit angles for the discs along the cutter axis.

3. CUTTING FORCE MODEL

After calculating the start and exit angles for each disk element along the cutter axis in section 2, the next step is estimation of instantaneous chip thickness.

In free-form surface machining the distance and the rotation angle between two CL points are relatively small, therefore the effect of rotational velocities of the tool is negligible. Considering this fact, the instantaneous chip thickness for ball-end mill tool can be obtained as follows [6];

$$(t_c)_k = t_x \times \sin(\theta) \times \sin(\psi) \times \cos(\alpha) \mp \cos(\psi) \times \sin(\alpha) \quad (3)$$

Where $(t_c)_k$ is the chip thickness, t_x is the feed per tooth, θ is the immersion angle of the cutting point, ψ is the cutting element position angle, and α is the feed inclination angle measured with respect to horizontal feed direction. The immersion angle of a discrete cutting point on the flute of the cutter is given as:

$$\theta = \Omega + 2\pi(n - 1)/N_f - \beta_k \quad (4)$$

Where θ is the immersion angle for flute n , k represents the number of discrete point on a cutting edge, Ω is the cutting edge rotation angle, N_f is the total number of flutes and β_k is the lag angle due to helix angle of the cutter in the respective k^{th} disk.

The instantaneous infinitesimal chip load can be written as follows:

$$dA_c = (t_c)_k \times (dz)_k \quad (5)$$

For a differential chip load dA_c in the engagement domain, the differential cutting forces in radial, axial, and tangential directions (r, ψ, t) is written as follows;

$$\begin{aligned} dF_r &= K_{rc} \times dA_c + K_{re} \times dz \\ dF_\psi &= K_{\psi c} \times dA_c + K_{\psi e} \times dz \\ dF_t &= K_{tc} \times dA_c + K_{te} \times dz \end{aligned} \quad (6)$$

Where K_{rc} , $K_{\psi c}$ and K_{tc} are radial, axial and tangential cutting force coefficients and K_{re} , $K_{\psi e}$ and K_{te} are cutting edge coefficients, respectively. Cutting force and edge coefficients are determined by the calibration procedure where these coefficients vary along tool axis direction [6].

Transformation matrix A transforms the cutting forces into feed coordinate frame which is initially coincident with tool coordinate frame (TCF). If the angle between feed direction and X_{TCF} is not zero, B matrix transforms the cutting forces into tool coordinate frame.

$$A = \begin{bmatrix} -\sin(\psi) \times \sin(\theta) & -\cos(\psi) \times \sin(\theta) & -\cos(\theta) \\ \sin(\psi) \times \cos(\theta) & \cos(\psi) \cos(\theta) & -\sin(\theta) \\ \cos(\psi) & -\sin(\psi) & 0 \end{bmatrix} \quad (7)$$

$$B = \begin{bmatrix} \cos \gamma & -\sin \gamma & 0 \\ \sin \gamma & \cos \gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (8)$$

By using transformation matrix T given in Eq. 1, cutting forces in WCF can be written as:

$$\begin{bmatrix} dF_x \\ dF_y \\ dF_z \end{bmatrix} = [T]^{-1} [B] [A] \times \begin{bmatrix} dF_r \\ dF_\psi \\ dF_t \end{bmatrix} \quad (9)$$

4. FEEDRATE SCHEDULING

Because of the complex geometry of the 3D free-form surfaces, CAM processors and CNC operators tend to select conservative cutting parameters to avoid tool breakage, low surface quality, tool deflections, machine tool damages, etc. On the other hand, process planning engineers wish to increase the productivity by reducing the cycling time. One of the cutting parameters that affect the productivity in a direct manner is feedrate. Conservative constant feedrate values have been widely used in industry for 5-axis free-form surface machining due to lack of a comprehensive model that is able to take

into account the physics of the process. Besides, currently used CAM programs are only based on the geometry of the process and volumetric analysis. Therefore, the next step in developing smart CAM packages is introducing effective algorithms to update the cutting parameters according to different cutting conditions during free form surface machining.

Typically, there are two methods for scheduling feedrate value namely the volumetric and force based strategies. According to previous studies, volumetric based feedrate strategy is insufficient for determining the optimum feedrate values [1].

The offline feedrate scheduling model that is introduced in this study is able to adjust the feedrate values for each NC block based on reference cutting forces that are determined in previous section. In 3D free-form surface milling because of permeate fluctuation in depth of cut and engagement angles, the resultant cutting force is not fixed. By anticipating the cutting forces using above mentioned force model, appropriate feedrate values can be selected to keep the cutting forces below a threshold which is determined by user.

According to Eq. (5) and (6) there is a linear relation between cutting forces and feedrate values. This provides to derive a linear relation depending on feedrate as follows:

$$dF_i = A \cdot f + B \quad (10)$$

Where dF_i is differential cutting force, f is feedrate value, and A , B are constant values. The model is processed to keep the resultant force at the desired constant limit level along the tool path for the CL points. The model uses the contact region defined for each CL point from the solid modeler kernel. The limiting feedrate formula for the i^{th} CL point is given as follows;

$$f_{lim,i} = (F_{lim,i} - F_{1,i}) \cdot \frac{f_2 - f_1}{F_{2,i} - F_{1,i}} + f_1 \quad (11)$$

Where $1, 2 \dots i$, is the number of CL points in the tool path, f_1 [mm/min] is the original constant feedrate for the tool path; f_2 [mm/min] is twice of f_1 in order to obtain the linear relation for the i^{th} CL point. $F_{1,i}$ [Newton] is the maximum resultant force value for the i^{th} CL point for f_1 feedrate value, $F_{2,i}$ [Newton] is the maximum resultant force value for i^{th} CL point for f_2 feedrate value, $F_{lim,i}$ is the limiting constant resultant force threshold value and $f_{lim,i}$ is obtained as scheduled feed in [mm/min] for the i^{th} CL point.

5. SIMULATION AND EXPERIMENTAL RESULTS

Some experimental validation tests were conducted to check the performance of force model and feedrate scheduling strategy in five axis machining of complex free form surfaces. In Fig. 5, the CAD/CAM model and toolpaths for an impeller that was used as experimental setup is presented.

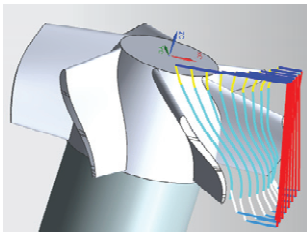


Fig. 5. CAD/CAM model of the experimental workpiece

The experimental tests were performed on Mori Seiki NMV 5000 DCG 5-axis CNC machine using AL7075 workpiece material. A Sandvik two fluted 12 mm ball end mill with helix angle of 30 degree was used to machine the impeller. Kistler rotary type of dynamometer (model 9123) was used to measure the cutting forces. All of the experiments were performed with the spindle speed of the 4000 rpm. In all the simulations, ball part of the cutter was discretized into disks with 0.1 mm height. Fig. 6 shows the experimental setup that has been used in this study.



Fig. 6. : Five-axis machining center and data acquisition system used in the experimental setup to validate the feedrate scheduling strategies.

In order to validate the force model a test with constant cutting feed were performed on the impeller. Simulated and experimentally measured resultant cutting forces are shown in Fig. 7. In this test spindle speed, feedrate and tool diameter are 4000 [rpm], 450[mm/min], and 12[mm], respectively. The main

source of discrepancy between measured and estimated model is tool runout and noncutting effects like ploughing effect. It will be shown that this amount of discrepancy does not have a significant effect on feedrate scheduling model.

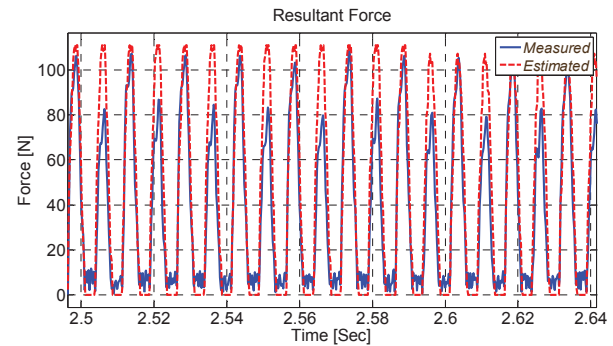


Fig. 7. Force model validation test for impeller

As it was mentioned in the introduction section, resultant cutting forces are not constant during 5-axis machining of free form surfaces. This fact is shown in Fig. 8. In this case, cutting parameters are as same as cutting parameters in Fig. 7. The resultant cutting force is simulated and measured for one single toolpath that is represented in Fig. 5. As it is clear in Fig. 8, the cutting force is maximum at the beginning of the engagement and as the tool moves through the toolpath, cutting forces are gradually decreasing.

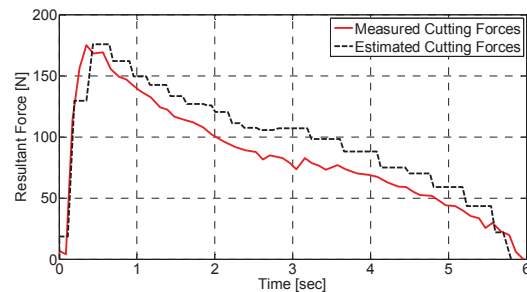


Fig. 8. Variation of resultant cutting force through toolpath

It was mentioned in Section 4, the threshold cutting force, which is represented by $F_{lim,i}$ in Eq. (11), is the limitation defined by user for resultant cutting forces. The feedrate scheduling algorithm regulates feedrate value in each cutter location to keep resultant cutting forces close to this threshold.

As it can be found from Fig. 8, the cutting forces are not constant through the toolpath and by decreasing depth of cut and engagement area the cutting forces decrease. Therefore, by scheduling the feedrate value, it is possible to keep the cutting forces constant and increase the productivity. In this case, the threshold resultant cutting force in Eq. (11) was set to 176 (N) which is the maximum resultant cutting force at the

beginning of cutting in Fig. 8. Fig. 9 illustrates the result of feedrate scheduling validation test. In this figure the red line represents measured cutting forces during running scheduled feedrate values and the blue line represents measured cutting forces during constant feedrate, which is equal to 450 [mm/min]. According to Fig. 9, machining time for one single path using constant feed is 5.9 (sec) and using scheduled feed is 2.6 (sec) that means 60% reducing in cycling time. Roughing milling process consists of several level of machining. This test was conducted for second level of machining.

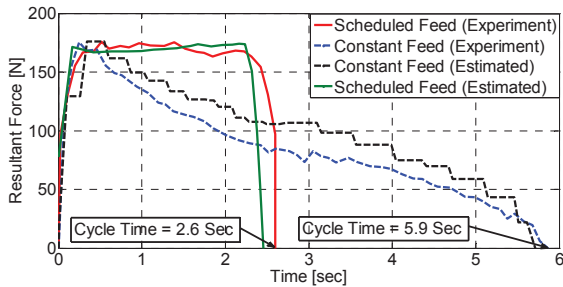


Fig. 9. Measured and simulated cutting forces during constant feedrate and scheduled feedrate cases for the second level of rough milling

Fig. 10. illustrates the change of feedrate values in each cutter locations to keep the resultant cutting force constant. It should be mentioned that because of safety, the maximum feedrate was set to be 2500 [mm/min]. This value can be adjusted by the process engineer.

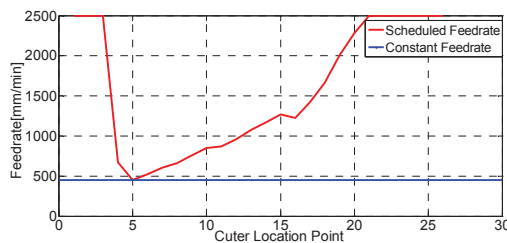


Fig. 10. Scheduled feedrate values for each cutter location

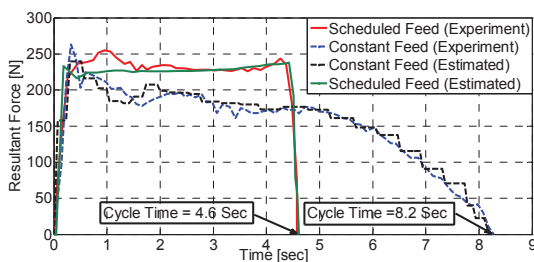


Fig. 11. Measured and simulated cutting forces during constant feedrate and scheduled feedrate cases for the third level of rough milling

In order to check the performance of proposed feedrate scheduling algorithm, several test were done in different levels and toolpaths. Fig. 11 represents the

result of feedrate scheduling technique for third level of rough milling. It can be found from this figure that the optimization in feedrate value ended up to 44% reducing in cycling time.

6. Conclusion

In this paper, an enhanced Force model based Feedrate Scheduling (FFS) technique in 5-axis machining of parts with complex free form surfaces was introduced. The cutter/workpiece engagement was modeled using a commercial solid modeler kernel and cutting forces were simulated based on the developed model. Finally, the feedrate scheduling for five axis machining was introduced. The validation of the model was shown by conducting experimental tests on the five-axis machining center. It was shown that using this model the cycle time could be decreased dramatically for machining of an impeller with complex free form surfaces.

The presented model can be used in new generation of CAM software to schedule the feedrate in order to decrease the cycle time and increase the productivity.

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