Optimization of 5-Axis Milling Processes Based on the Process Models with Application to Airfoil Machining

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Abstract
5-axis milling is widely used in machining of complex surfaces such as airfoils. Improper selection of machining parameters may cause low productivity and undesired results during machining. There are several constraints such as available power and torque, chatter stability, tool breakage etc. In order to respect such constraints proper machining parameters should be determined. In this paper, methodologies for improving 5-axis milling processes are presented. Selection of machining parameters is performed using process simulations. The developed methodologies are presented on an example airfoil.

1 INTRODUCTION

Increasing need for manufacturing of parts with complex surfaces and geometries brings additional challenges such as tool accessibility and contouring. 5-axis milling provides increased accessibility and tool orientation capability satisfying these requirements. On the other hand, 5-axis milling also brings additional challenges due to complex process geometry and mechanics. The process planner should select parameters such as tool orientation, depth of cuts, spindle speed, feedrate, etc. Improper selections of these parameters result in low productivity or unacceptable part quality. Recent CAM software does not provide any assistance in selection of machining strategies and parameters. Therefore, there is need for guidelines in selection of machining parameters in 5-axis milling processes. Process models can be used as the tool to derive such guidelines.. Considering the number of parameters and constraints in 5-axis milling operations, it is very difficult, if not impossible, to develop a method for the optimization of the entire process. The objective of this paper is to demonstrate the application of the models based on the process mechanics in parameter selection for 5-axis milling.

One of the most important parameters in machining is the feedrate. In general, constant feedrate is used in free form surface machining operations. However, in most cases the tool-work engagement varies along the tool path resulting in cutting force fluctuations. Adjusting feedrate based on the cutting force can improve the quality and productivity. Most of the feedrate optimization studies are limited to 3-axis milling [1]-[7]. Wang [1], Ip et al. [2], and Li et al. [3] studied MRR based feedrate scheduling for 3-axis milling operations. Li et al. [3] integrated the feed rate optimization approach with CAD/CAM. Besides the MRR based feed rate selection, cutting forces have also been used in feedrate scheduling. Yazar et al. [4] proposed a feedrate optimization strategy for 3-axis sculptured surface milling. Ko, et al. [7] implemented feed rate scheduling in ball-end milling based on the maximum resultant force and the tool stress. Lim et al. [5]-[6] proposed an integrated approach to feedrate scheduling in 3-axis ball end milling. In their study, the local cutting directions leading to the maximum feed rate were determined, and used together with the scheduled feed rate. The method was demonstrated on machining of a turbine blade die. Budak et. al [8] applied cutting force modeling based feedrate scheduling on 3-axis rough milling of sculptured surfaces and showed that cycle time can be decreased significantly. The first attempt for feed rate scheduling in 5-axis milling was presented by Bailey, et al. [9]. In their study, the maximum chip load and cutting force constraints were used for scheduling of the feed rate resulting in 30% reduction in machining time.

Tool orientation is another important process parameter in 5-axis milling, which is usually selected based on the experience. The selection of tool orientation has mostly been investigated from kinematics perspective [10]-[15]. Conditions for smooth tool axis movement [10],[11], gouge and collision free tool positioning [12],[13] have been investigated. Radzevich [15] analyzed the conditions of proper sculptured surface machining from workpiece orientation, surface topography and tool geometry perspectives. Lim et al. [16] evaluated the tool orientation considering the process mechanics. In their study, the tool orientation and cutting directions are analyzed in finishing of single turbine blade experimentally where “horizontal inward with a tilt angle” is concluded to be the best strategy. However, this result can not be generalized for all cases. In addition to the feed rate and tool orientation, the cutting depths are important machining parameters. A method for selection of depth of cuts which maximize chatter-free material removal rate in end milling is presented in [14]. They obtained chatter free axial and radial depth pairs for a given spindle speed and the pair leading to minimum machining time is proposed to be the best pair.

In this paper, some methodologies are presented to derive guidelines for selection of machining parameters in 5-axis milling. Cutting force simulations are performed for offline feedrate scheduling and parameter selection. The developed methods are applied to blade machining. In comparison with the previous studies, this paper considers both process mechanics and geometry in selection of process parameters. The paper is organized as follows. First, the process geometry is presented briefly. Then, the cutting force simulations, and feedrate scheduling approach are given in section 3. Afterwards, the selection of depth of cut and tool orientation is presented. Finally, the applications of the methods are presented and conclusions are derived.

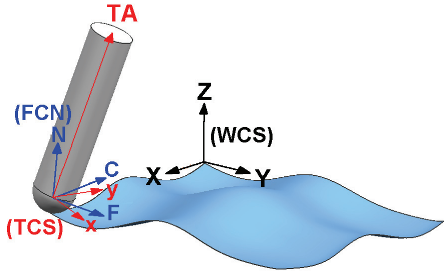


Figure 1: Coordinate systems.

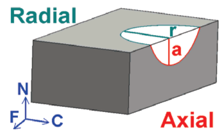
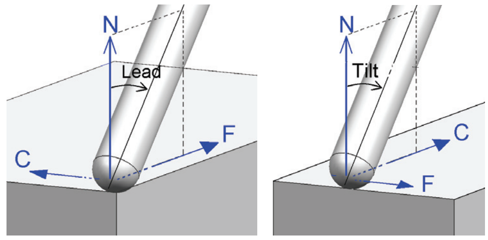


Figure 2: Depths of cut axial (a) and radial (r).



(a) (b)

Figure 3: Lead (a) and Tilt (b) Angles.

2 5-AXIS PROCESS GEOMETRY AND FEEDRATE SCHEDULING

In the analysis 3 coordinate systems are used: workpiece coordinate system (WCS), the process coordinate system (FCN) and the tool coordinate system (TCS) as shown in Figure 1. FCN consists of the feed axis of the tool (*F*), the cross-feed axis (*C*), and the surface normal axis (*N*). TCS consists of the tool axis (TA), and the two perpendicular transversal axis (*x*) and (*y*), which are in F-N and C-N plane respectively. The geometrical parameters are the axial depth of cut, radial depth of cut, lead and tilt angles, which are shown in Figure 2 and Figure 3, respectively.

As the tool immerses into the workpiece, the flutes of the cutter engage with the workpiece. The engagement boundaries between the cutting flutes and the work material, which are needed in the force calculations, depend on the depth of cuts, lead and tilt angles, and the tool geometry. In 5-axis milling, lead and tilt angles are measured with respect to the surface normal. The lead angle is the rotation of the tool about the cross-feed axis (*C*), where tilt angle is the rotation about the feed axis (*F*).

2.1 Cutting force simulation

In this study, the cutting force simulations are performed to serve two purposes. The first one is to predict the variation of the cutting forces throughout a toolpath for feedrate scheduling. The second purpose is the selection of depth of cuts, spindle speed, and tool orientation, i.e. lead and tilt angles.

Cutting force simulation for a given toolpath is performed in the following manner; first, the process information i.e., tool geometry, cutter location (CL) and cutter axis vector, is parsed directly from the CL file [17]. Then, the axial and radial depths of cut, lead and tilt angles are calculated by applying coordinate transformations and by use of analytical methods [17]. Cutting force simulation [18] is performed at specific CL points and then, the maximum value of cutting forces per one revolution is recorded. The force model [18] uses the orthogonal cutting database of the workpiece material. Then, cutting forces are calculated by applying orthogonal to oblique transformation. This structure enables easy integration to CAM software, which is an ongoing research in our laboratory. The details of the process model and geometrical calculation procedure can be found in [17]-[18].

2.2 Feedrate scheduling

Offline feedrate scheduling is performed in order to maintain the forces at a constant or near constant level in a cycle. In this section, first, the constraints are described, and then the method for feedrate adjustment is presented.

Description of constraints

Similar to the approaches used in the previous studies, the tool stress and deformation are taken as the constraints. Based on these, the cutting force becomes the derived constraint. However, in some cases the spindle torque, tool deflection or spindle power may be the limitation. The following four equations define the constraints mathematically.

$$FOS \cdot CP \leq SP \quad (1)$$

$$FOS \cdot CT \leq ST \quad (2)$$

$$FOS \cdot BS \leq TRS \quad (3)$$

$$TD \leq MAD \quad (4)$$

CP, CT, BS, and *TD* denote cutting power, torque, bending stress and tool deflection in the process, respectively. *FOS, SP, ST, TRS* and *MAD* stand for factor of safety, spindle power, spindle torque, transverse rupture strength of the tool material, and maximum allowable tool deflection. BS is calculated as follows;

$$BS = \frac{F_{xy}^{\max} \cdot L \cdot c}{I} \quad (5)$$

L and *I* stand for the distance from the fixed end of the tool to the force application point, and the moment of inertia of the tool cross section, respectively. F_{xy} is the resultant transversal force acting on the tool as depicted in Figure 4. F_{xy}^{max} is the maximum of F_{xy} per one revolution of the cutter.

Calculation of the optimized feedrate

The feedrate scheduling is applied in order to maintain the cutting forces at a desired level, which is performed in the following manner. Initially, the process simulation is performed along the toolpath by use of the approach described in the previous section. Since the feedrate does not affect the edge forces on the tool [18] , the cutting component of the force due to chip load, $F_{cut,xy}^{max}$ is calculated separately in the simulations. The maximum value of the total cutting force F_{xy}^{max} is then determined by adding the edge force component. If the determined force level violates the constraints, it is adjusted accordingly. The geometrical parameters needed in the simulations are determined as explained in section 2.1. The feed per tooth, *fpt*, is adjusted according to $(\text{limit} F_{xy,max}^{cut}) / {}^{i}F_{xy,max}^{cut}$ ratio. "${}^{i}F^{cut}_{xy,max}$" is the cutting force due to the chip load at the ith simulation point. The "${}^{i}F^{cut}_{xy,max}$" is updated using the new *fpt* until "${}^{i}F^{cut}_{xy,max}$" converges to "limit $F^{cut}_{xy,max}$". The *fpt* value obtained from the CL file is used as the initial value. MRR maximization is applied in the following manner. The *fpt* is set to fpt^{max}, which is the maximum available *fpt* value. The process simulation is performed using the calculated geometrical parameters, and the limiting constraint is identified. Finally, the *fpt* is adjusted using the procedure given in Figure 5.

3 SELECTION OF PARAMETERS

This section details the selection procedure for the tool orientation and the depth of cuts. The process parameters have nonlinear effects on MRR, cutting forces, torque and power. Thus, overall optimization requires consideration of all parameters. However, this study is limited to depths of cut, spindle speed and tool orientation. Chatter stability must be considered in selection of depths of cut and spindle speed. 5-axis chatter stability model development is currently an ongoing study in our laboratory. Thus, the stability limits are determined by semi-experimental methods.

3.1 Determination of best tool orientation

Tool orientation directly affects the cutting forces since it has major effect on the engagement boundaries. In most of the 5-axis milling applications, improper selection of lead and tilt angles causes tool-workpiece collisions. Thus, the applicable combinations of lead and tilt angles are determined by trial and error in the CAM software for the given workpiece and tool. Among the feasible combinations, the one which minimizes the F_{xy}^{max} is selected.

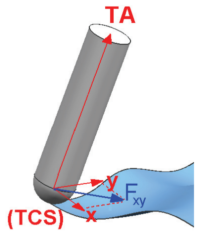


Figure 4: Resultant transversal cutting force, Fxy.

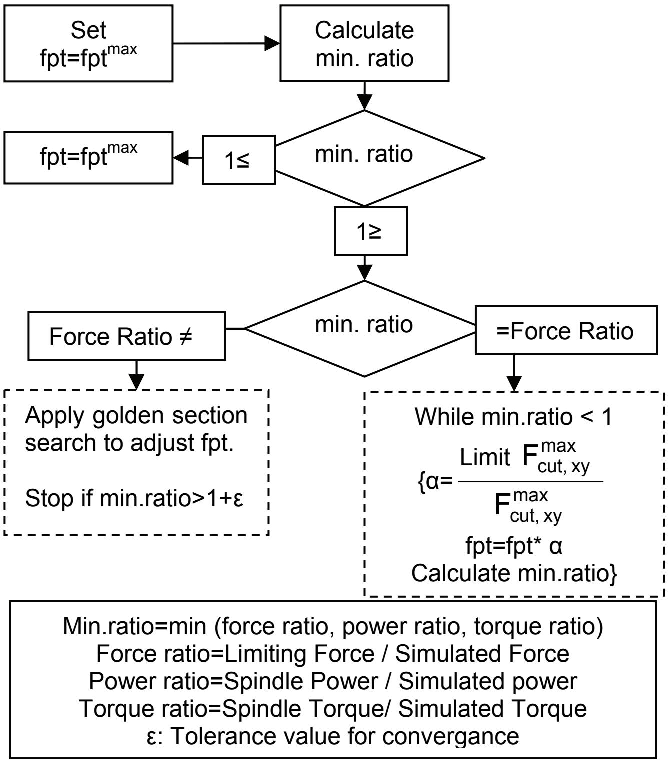


Figure 5: Algorithm for fpt adjustment.

The naive approach for finding the best lead and tilt combination is running process simulations for every applicable combinations of lead and tilt angles. However, such an approach compromises the number of calculations and accuracy. Instead, single objective gradient based method, steepest descent, is applied [19]. Since the result depends on the initial guess, generation of the initial guess is an important issue. Instead of trying various initial guesses blindly, the initial guesses are generated in the following manner; firstly, the range of applicable lead and tilt combinations is divided into large grids and F_{xy}^{max} is calculated at those grid points. Then, the initial guess is selected according to the minimum F_{xy}^{max}. If there are multiple combinations leading to approximately same minimum value of F_{xy}^{max}, those are chosen to be candidate initial guesses. Starting with the selected initial guess, steepest descent algorithm is applied. The procedure is applied for the other candidate initial guesses. The gradient of F_{xy}^{max} with respect to the lead and tilt angles is calculated by central finite difference. The main steps of this approach are given in Figure 6.

The best combination of the lead and tilt angles is affected by the radial depth of cut. Thus, the described procedure is repeated for the relevant range of radial depths of cut if it is not predefined. The other process parameters Selection of depths of cut and spindle speed
Selection of the depth of cuts is of great importance to achieve high MRR, dimensional accuracy and surface quality. In finishing, radial depth, i.e. step over, is limited with surface roughness. However, the axial depth can be adjusted to improve the quality of the machined surface. In the selection of depth of cuts for roughing and semi-finishing, the applicable values are identified for the chosen operation and tooling. The radial depth of cut is chosen according to F_{xy}^{max}/MRR ratio. Then, the maximum axial depth value satisfying the constraints is selected. The axial depth is chosen with respect to the minimum F_{xy}^{max} in finishing. In ball-end milling, local radius of the tool changes with the axial depth and tool orientation, thus cutting speed varies. Spindle speed is adjusted according to the cutting speed limitations and chatter stability. Although the stable depths can not be determined without a complete 5-axis chatter model, the appropriate spindle speeds can be determined through impact or cutting tests. After presenting the methodologies for force simulation, feedrate scheduling and parameter selection, the following section presents the application of those to blade machining.

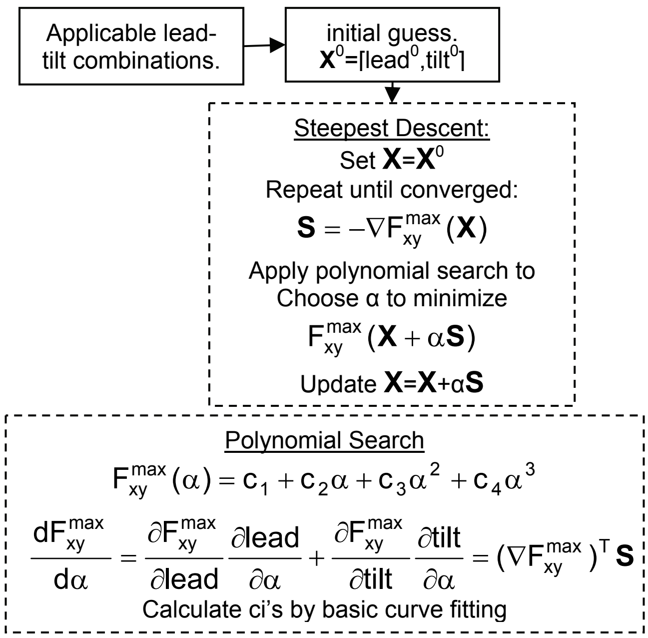


Figure 6: Selection of lead and tilt angles.

4 APPLICATIONS

The proposed methodologies are applied to machining of a compressor blade. First, the application of the cutting force simulation and selection of process parameters is demonstrated on semi-finishing. Feedrate scheduling is applied to the same airfoil in order to demonstrate the benefits. For roughing, simulated and measured cutting torque are compared and shown that the values are below the spindle torque. In addition, the benefit of applying G93 feedrate mode over the G94 is presented by machining time study. Machining is performed on a 5-Axis vertical milling machine, which has 2 rotary axes on the table side. The forces are measured using a rotary type of dynamometer. The workpiece material is Ti6Al4V. The cutting coefficients of the machined material are obtained through orthogonal cutting experiments [20]. The tool is 16 mm carbide ball-end mill, having 4 flutes with 30° helix angle.

4.1 Force simulation for airfoil machining

The radial depth is fixed (slotting) in roughing; therefore, the selection procedure of the radial depth can not be demonstrated. In finishing, the radial depth is subject to the required scallop height. However, both axial and radial depths can be controlled in semi-finishing. Therefore, the semi-finishing is considered in this study. Cutting forces are simulated for semi-finish machining of the airfoil given in Figure 7. Also, the selection of process parameters are demonstrated, which are given in Table 1. Figure 8 shows that F_{xy}^{max}/MRR ratio decreases steeply up to 2 mm of radial depth of cut, and then varies linearly up to 4 mm. Based on this observation, the radial depth of cut is chosen to be 2 mm. The axial chatter stability limit is identified as 1 mm for 2 mm of radial depth of cut for one of the low speed stability lobes around 1750 rpm. This is due to the low machinability of the titanium alloys forcing slow cutting speeds to be used. Therefore, the toolpath is generated to achieve axial depth around 1 mm. However, it can not be selected as constant due to the blade geometry. The axial depth of cut is calculated along the toolpath using the CL file. The variation of the axial depth is given in Figure 9, which varies between 0.8 mm and 1.1 mm.

For this part, the applicable range of lead and tilt angles are 0 to 15 deg and -15 to 0 degrees, respectively. The applied method offers lead=2 and tilt=-12 deg combination for radial depth of 2 mm, which leads to minimum F_{xy}^{max} as shown in the contour plot of F_{xy}^{max} (Figure 10). However, lead and tilt angles are selected as 10 deg. and -10 deg., respectively. The lead angle is selected a bit larger than the proposed one to prevent the tool tip contact, where cutting speed decreases to zero. In addition, the CAM software applies tool axis smoothing for lead angles greater or equal to 10 deg. For simulation, constant fpt is selected according to the tool manufacturer recommendations.

There are approximately 250 CL points in each cut step, and the force simulations are performed at 50 points. The toolpath consists of parallel passes with the same parameters, thus simulation is performed for one pass. Having said that, the dynamics of the blade varies from top to the root; therefore this should be considered when the chatter due to part dynamics is imposed in the model. The comparison of measured and simulated F_{xy}^{max} for pressure and suction side cut step is given in Figure 11 and Figure 12, respectively.

Fpt (rev/tooth)	Axial Depth	Radial Depth	Spindle Speed	Lead/Tilt
0.16 mm	0.8–1.1mm	2 mm	1750 rpm	10/-10 deg.

Table 1: Machining parameters for semi-finishing.

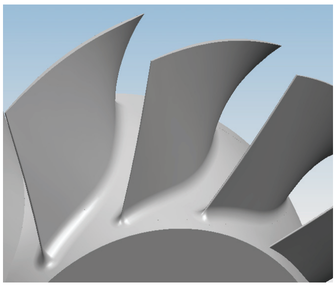


Figure 7: Machined airfoil.

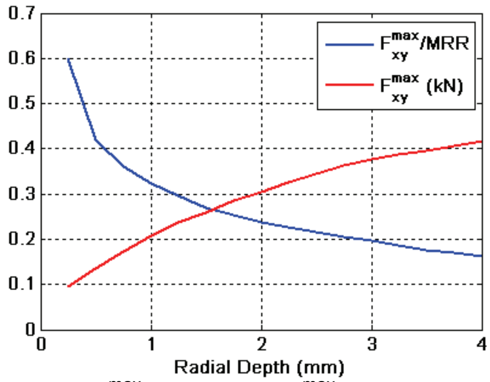


Figure 8: F_{xy}^{max}/MRR and F_{xy}^{max} vs radial depth.

For roughing (slotting) the stable axial depth is determined to be 0.7 mm. The variation of cutting torque for this case is given in Figure 13. The maximum cutting torque is about 2 Nm, which is much below the spindle torque at 1750 rpm (80 Nm). Thus, it can be concluded that, chatter limits the selection of axial depth.

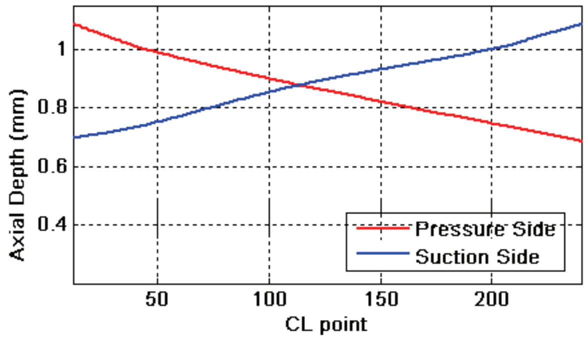


Figure 9: Variation of axial depth of cut.

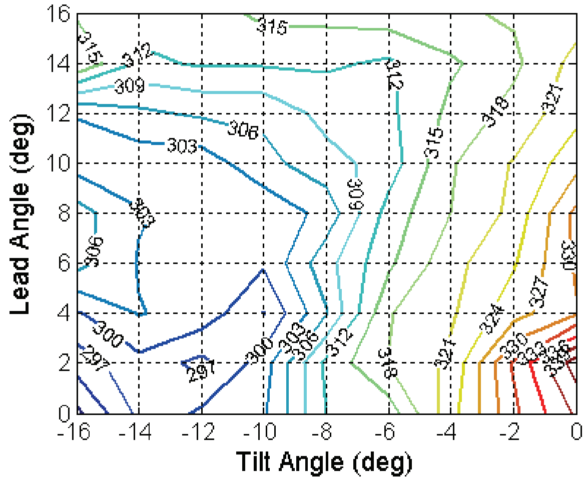


Figure 10: Contour plot of F_{xy}^{max}.

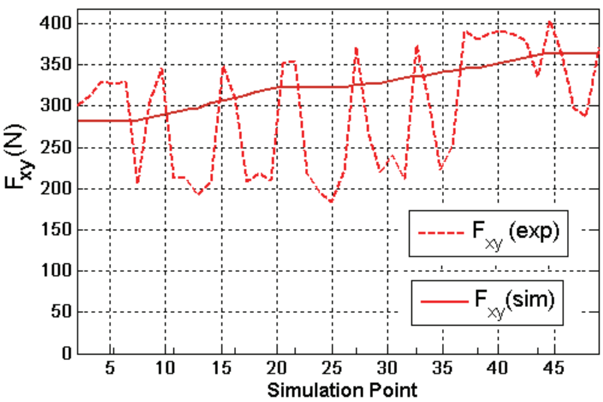


Figure 11: F_{xy} at the suction side.

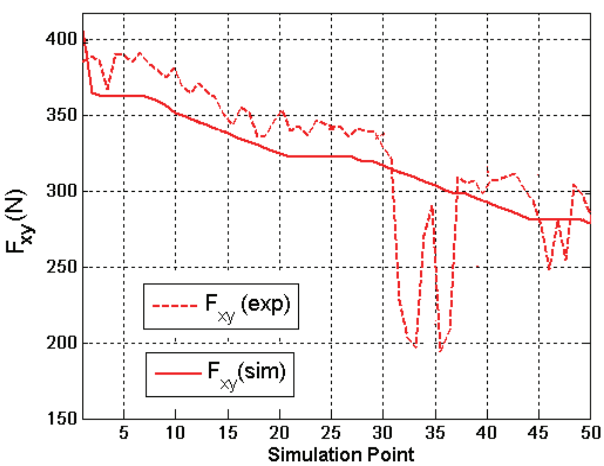


Figure 12: F_{xy} at the pressure side.

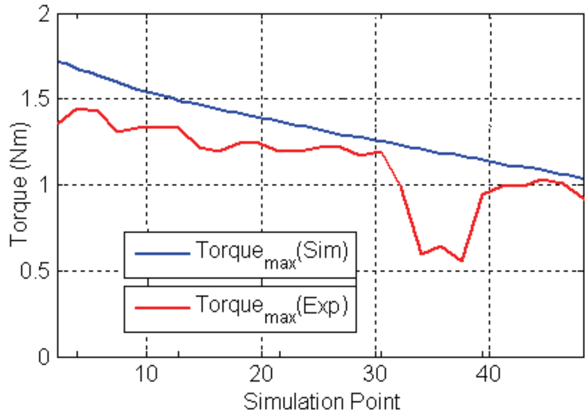


Figure 13: Cutting torque for roughing.

4.2 Demonstration of feedrate scheduling

The feedrate scheduling approach is applied on semi-finishing of the airfoil. The forces are leveled to the maximum of simulated F_{xy}^{max} value. The scheduled feed values are plotted in Figure 14, which are fitted to a basic quadratic function in order to achieve smooth variation. The simulated F_{xy}^{max} with the scheduled feedrate is given in Figure 15.

Comparison of G93 and G94 feedrate modes

In continuous 5-axis machining operations rotary axes move together with the linear axes. Depending on how the cutting length is calculated in the post processor. This may result in incorrect actual feedrate, i.e. the relative motion between the work and the tool. This also causes significant deviations between the actual and the predicted machining times in 5-axis operations. This deviation can be reduced by applying G93, i.e. inverse time feed mode in the NC Code. In this method of feed calculation, the completion time of each line is calculated using the part geometry and the cutting motion. For this purpose, CL file is parsed and the actual distance between each CL point is calculated to determine the execution time of each line. This section compares G94 and G93 modes by use of a time study. The roughing process is performed using both G93 and G94. The actual and calculated machining times for both modes are compared in Table 2.

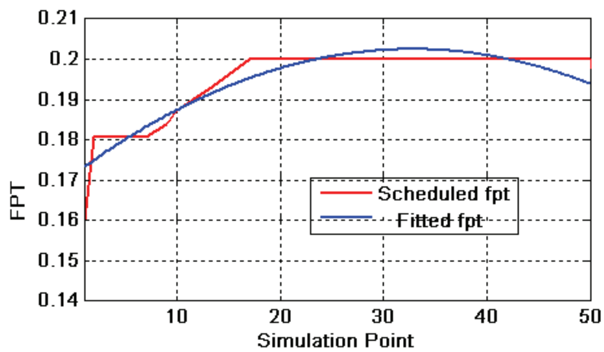


Figure 14: Scheduled fpt for leveled cutting forces.

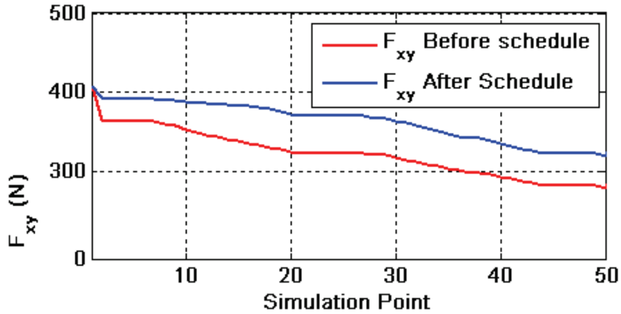


Figure 15: Leveled cutting forces.

	G93 time (min)		G94 time (min)	
	Actual	Predicted	Actual	Predicted
Rough	13.06	12.08	16.06	12.08

Table 2: Comparison of G93 and G94 feed modes.

5 DISCUSSION

In cutting force simulations F_{xy}^{max} predictions agree well with the measurements. However, some discrepancy and unexpected changes are observed in the measured forces. This is believed to be caused by the rotary motions of the table. Due to rotary motion on the table the actual feedrate slightly decreases, then increases at some tool positions resulting in force variations. In addition, at some positions the maximum angular velocity of the rotary axis can not meet the desired angular velocity, which decreases the actual feedrate.

For roughing (slotting), it is experimentally found that the stable axial depth of cut is 0.7 mm. The simulated cutting torque agrees well with the measured cutting torque. Under these conditions the cutting torque is around 2Nm which is much lower than the spindle torque at 1750 rpm (80Nm). Therefore, it is concluded that the chatter stability limits the roughing process.

In application of feedrate scheduling, after a certain fpt value the process becomes feed limited. This results in constant feedrate after the 15th simulation point. Thus, the forces can not be leveled to the desired value at each simulation point. Though, the application of feedrate scheduling yields about 20% saving in machining time.

As another feedrate issue, G93 and G94 feedrate modes are compared. It is observed that G93 mode lets the tool to achieve the actual feedrate as the angular velocity limit of the rotary axis permits. Machining time can be used as one of the indicators of achieving the actual feedrate. As seen in Table 2 applying G93 feed mode leads closer machining time to the predicted value. G94 mode yields approximately 25% longer machining time with respect to the G93 Mode.

6 CONCLUSIONS

In this paper, methodologies to derive guidelines in parameter selection for 5-axis milling processes are studied based on process simulations. Feedrate scheduling is also applied based on cutting force simulations. The best combination of lead and tilt angles is selected according to the cutting forces. Single objective gradient based method, steepest descent is applied in selection of lead and tilt angles. Chatter stability is considered experimentally in selection of depth of cuts. Besides, application of constant feedrate (G94) and inverse-time feedrate (G93) modes in machining are compared.

Cutting force simulation approach is applied on semi-finish milling of an airfoil. Based on the simulated F_{xy}^{max}, feedrate scheduling is applied to keep the forces at the maximum value of F_{xy}^{max}. Approximately 20% of the machining time saving is achieved by applying feedrate scheduling. Also, the selection of process parameters is demonstrated on the semi-finishing operation. It is also shown that the actual feedrate can be achieved by applying G93 feedrate mode. Integration of the cutting force simulation and feedrate scheduling techniques to CAM software are under development.

7 ACKNOWLEDGEMENTS

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