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Abstract

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Modeling Cutting Forces for 5-Axis Machining of Sculptured Surfaces

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Abstract: 5-axis milling processes are used widely in various industries such as aerospace, die-mold and biomedical industries where surface quality and integrity is important and the production tolerances are very tight. Therefore, improving surface quality and integrity without sacrificing productivity is crucial in these industries. Improvements in CAD/CAM, cutting tool and the machine tool technologies allow the production of high precision parts in less cycle times. However, desired quality and productivity can be obtained if process parameters such as feedrate, spindle speed, axial and radial depth of cut are selected appropriately. In general, these parameters are selected conservatively based on engineering expertise or trial and error methods in order to prevent workpiece, cutter or the machine to be damaged. Therefore, virtual machining simulation for milling processes is an increasing demand before the production of the part. This paper presents a mechanistic cutting force model for 5-axis ball-end milling process simulation. Cutter/workpiece engagement is determined via newly developed solid modeler based engagement model. Two different 5-axis machining tests are conducted on Al7039 workpiece material for the validation of the proposed model. Validation tests demonstrate that presented model is computationally efficient and force predictions are in good agreement with the experimental data.

Keywords: 5-Axis Machining, Milling Force Model, Ball-End Mill, Cutter/Workpiece Engagement, Boundary Representation

1. INTRODUCTION

5-axis machining has been used in aerospace applications for many years. Recently, the die-mold, toolmaking and biomedical industries have shown similar interest. The main advantage of 5-axis machining is the ability to save time by machining complex shapes in a single set-up. Another benefit comes from allowing the use of shorter cutters that permit more accurate machining. Although, the aim of the 5-axis machining, specifically milling, stated to reduce the cycle times, dimensional and surface errors in its nature, without the physical modeling of the milling process this cannot be accomplished. Consequently, modeling of the cutting forces in these processes, gain more importance in order to prevent excessive cutter deflection, form errors and surface errors.

Most of the research on 5-axis machining focuses on the geometric aspects of this process such as toolpath generation, toolpath optimization and geometric verification of the toolpath. With the improvement in the CAM technology geometric constraints and errors can be eliminated, on the other hand, the physics of the process is not considered. Consequently, efficiency of the process and errors due to physical constraints cannot be predicted before the production of the part.

In the modeling of 5-axis machining processes noteworthy research was conducted by Zhu et al. [Zhu et al., 2001] where Z-map technique was utilized for cutter/workpiece engagement for cutting force prediction, then a process fault detection and fault diagnosis methodology was developed. Similarly, Fussell et al. [Fussell et al., 2003] developed a virtual machining environment for discrete simulation of sculptured surface machining which aimed automatic feedrate selection along the toolpath via mechanistic modeling of cutting forces. Bailey et al. [Bailey et al., 2002] proposed a generic mechanistic cutting force model for simulating multi-axis machining of complex sculptured surfaces. A process optimization tool was presented by employing a feedrate scheduling method using the maximum chip load and cutting force as constraints. Becze et al. [Becze et al., 2000] introduced an analytical chip load model for 5-axis high-speed milling of hardened tool steel. The effect of tilt angle on cutting forces, tool wear mechanisms and also surface integrity were investigated in this study.

Some of the most recent studies on modeling of 5-axis milling was carried out by Ozturk and Budak [Ozturk and Budak, 2007], Tunc and Budak [Tunc and Budak, 2009]. Analytical modeling of cut geometry of 5-axis machining was performed and obtained data was used for cutting force prediction and process optimization. Ferry and Altintas [Ferry and Altintas, 2008] developed a virtual machining simulation system for 5-axis flank milling of jet engine impellers extending the force model developed by Yucesan and Altintas [Yucesan and Altintas, 1996].

In this article, a mechanistic modeling cutting force model for 5-axis ball-end milling is presented. Boundary representation (B-rep) based exact Boolean method is preferred for extracting cutter/workpiece engagement due to its efficiency and speed over other discrete methods. Comprehensive formulation of cutting force model is given and its validation is demonstrated.

2. GEOMETRY OF 5-AXIS MILLING

5-axis milling geometry differs from 3-axis milling geometry. Hence transformation from 3-axis milling to 5-axis milling has to be defined. In this section, important concepts and parameters which define geometry of 5-axis machining are introduced. Then, these formulations are used in Section 4 in mechanistic modeling of 5-axis machining.

In 3-axis milling, tool movement is given as three translational motions along the X-Y-Z coordinate frame axes. In 5-axis milling, two additional rotary axes are present.

Consequently, tool motion is defined as a combination of three translational motions and two rotational motions. Contrary to 3-axis milling, tool orientation vector in 5-axis milling is not constant. Therefore, tool coordinate frame (TCF) has to be mapped on to the workpiece coordinate frame (WCF).

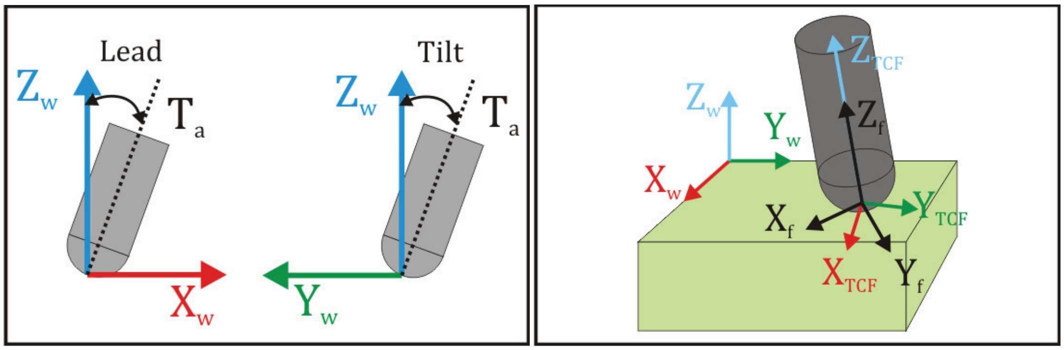

Figure 1; Lead and Tilt angles, and the illustration of coordinate frames.

Rotational motion in 5-axis milling is represented by lead and tilt angles. Lead angle is defined as the rotation angle about Y_w which is Y axis of workpiece coordinate frame. Tilt angle is the rotation angle about X_w which is X axis of the workpiece coordinate frame. Definition of the lead and tilt angles and the illustration of the coordinate frames are shown in Figure 1 where $(X_f - Y_f - Z_f)$ is the feed coordinate frame, and is explained in Section 4.

In order to extract lead and tilt angles from toolpath data Cutter Location (CL) output of Siemens NX6 is used. CL file is parsed via a pre-processor, and then CL points and tool orientation vectors in the form of direction cosines are obtained. A CL block consists of X, Y and Z coordinates of the tooltip and the orientation vectors *i, j, k* respectively. Lead and tilt angles can be calculated as follows:

$$lead = atan2(i, \sqrt{j^2 + k^2}) \tag{1}$$

$$tilt = atan2(-j, k) \tag{2}$$

Since, transformation from the workpiece coordinate frame to the tool coordinate frame is necessary for inverse transforming the calculated cutting forces in cutting force model; the rotation matrix from workpiece coordinate frame to tool coordinate frame has to be calculated. Transformation matrix from workpiece coordinate frame to tool coordinate frame is given as:

$$T = \begin{bmatrix} \cos(lead) & 0 & \sin(lead) \\ \sin(tilt)\sin(lead) & \cos(tilt) & -\sin(tilt)\cos(lead) \\ -\cos(tilt)\sin(lead) & \sin(tilt) & \cos(tilt)\cos(lead) \end{bmatrix} \tag{3}$$

Cutting forces calculated in TCF can be transformed to WCF as follows:

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix}_{WCF} = T^{-1} \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix}_{TCF} \tag{4}$$

3. SOLID MODELER BASED CUTTER/WORKPIECE ENGAGEMENT

In sculpture surface machining, the cutter/workpiece engagement 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 for the engagement region. Chip load and force calculations are based on the cutter/workpiece engagements; therefore the output of the engagement model is very critical. Mathematically, the swept volume is the set of all points in space encompassed within the object envelope during its motion. The basic idea in NC verification and simulation is to remove the cutter swept volume from the workpiece stock and thus to obtain the final machined surfaces.

In literature, NC machining simulation can be mainly categorized into three major approaches. The first approach is the exact Boolean, the second approach is the spatial partitioning, and the third approach is the discrete vectors. The direct Boolean subtraction approach is an exact and analytical approach. It directly performs the Boolean subtraction operation between a solid model and the volume swept by a cutter between two adjacent tool positions. Although this approach can provide accurate verification and error assessment, the computation cost is known to grow too much for a large number of tool-paths. The second approach uses spatial partitioning representation to define a cutter and the workpiece. In this approach, a solid object is decomposed into a collection of basic geometric elements, for example Z-map (Z-buffer), voxel, and ray representation, thus simplifying the processes of regularized Boolean set operations. However, its computation time and memory consumption are increased drastically to get better accuracy. One of the other widely used NC simulation methods is based on the vector-clipping approach.

In this work, B-rep based method is developed to find the cutter/workpiece engagement (CWE). Currently the most popular schemes used in solid modelers are the Boundary representation and Constructive Solid Geometry (CSG). In the B-rep methodology an object is represented by both its boundaries defined by faces, edges, vertices and the connectivity information. The prototype program is implemented using the commercial Parasolid solid modeler kernel. The tool movements are subtracted from the workpiece model by using Parasolid ‘PK_BODY_sweep’ and ‘PK_BODY_boolean_2’ function in order to find the in-process machined surface. Figure 2 shows the resultant machined surfaces for the corresponding examples used in Section 5.

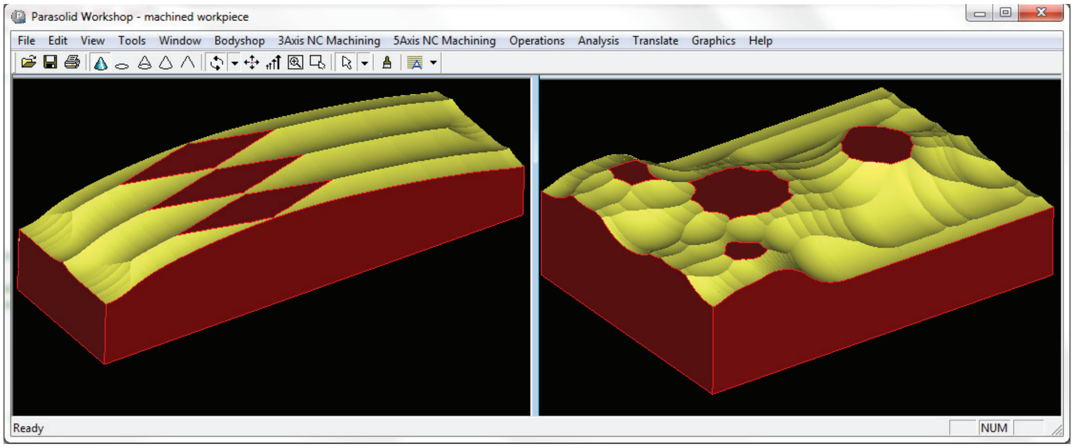

Figure 2; The user interface of the program and the simulated machined surfaces.

Once the in-process workpiece is obtained for each CL point, the contact patch surface between the tool and workpiece can be extracted by using Parasolid 'PK_BODY_boolean_2' function. Then, the resulting 3D contact surface, as illustrated in Figure 3, is projected to the plane perpendicular to the cutter axis by using parasolid 'PK_BODY_make_curves_outline' function. This step finds the enclosing boundaries and curves of the contact patch. Since the force model discretizes the cutter into slices perpendicular to the tool axis and to perform force calculation for each slice, the discs at each level are projected to the plane perpendicular to the cutter axis. The discs are shown by circles in view AA in Figure 3.

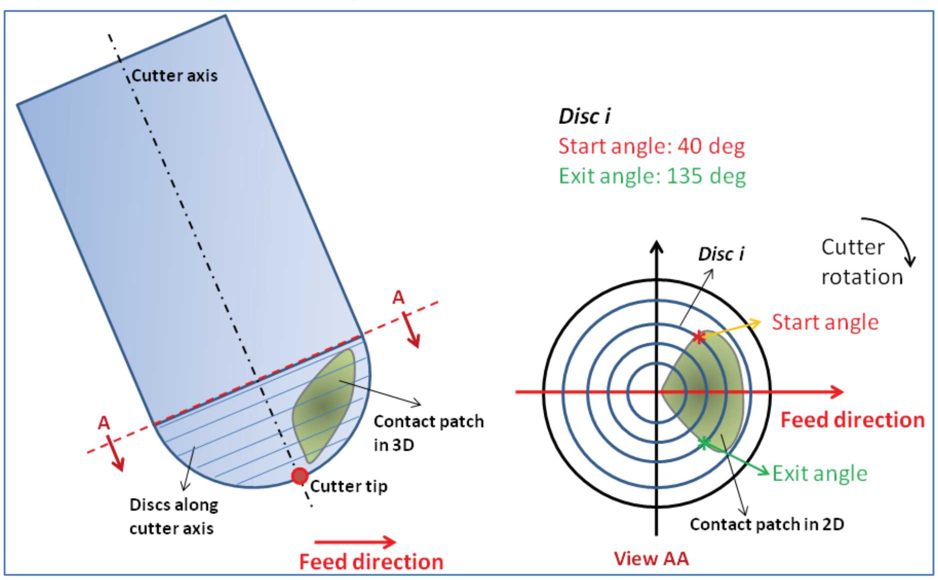

Figure 3; Cutter engagement geometry for ball-end mill

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 to each respective projected disc by intersecting the 2D discs with the boundaries of the contact patch in plane by using Parasolid 'PK_CURVE_intersect_curve' function. A final step is required to convert the intersection points into start and exit angles that are required for the force prediction model. For example, the start and exit angles are found as 40 and 135 degrees respectively for the *disc i* shown in Figure 3.

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 Personal Laptop. The output of the program is processed in Matlab and the engagement angles are shown together with the contact patch for CL point #25 in Figure 4 for the airfoil geometry test. The computation time for the engagement domain for the corresponding examples are 21 sec and 48 sec for airfoil (137 CL points) and penguin (415 CL points) surfaces respectively.

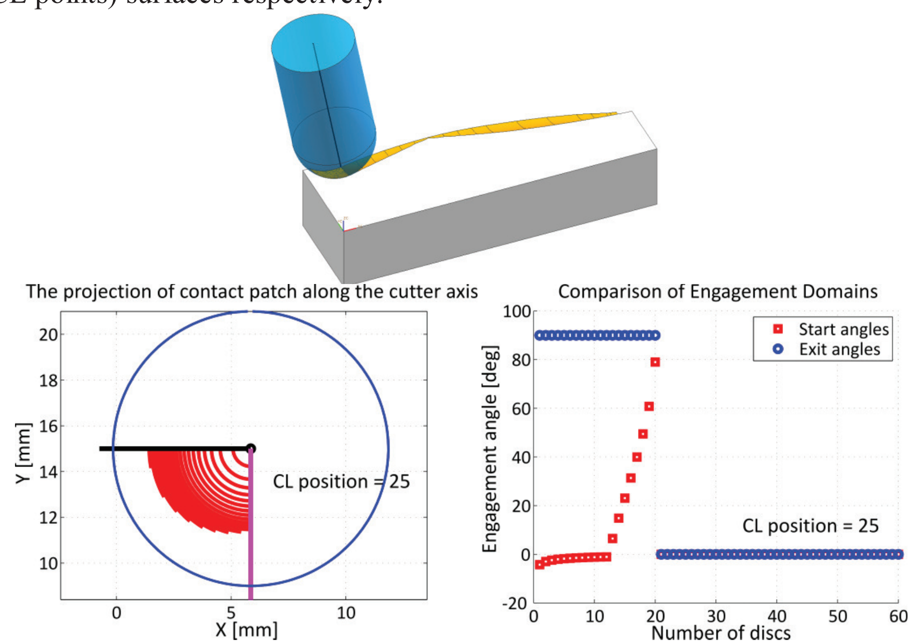

Figure 4 ;The engagement domain for CL point #25 for airfoil geometry test : (a)The previously machined surface with the tool instance, (b) Projected view of contact patch along cutter axis, (c) Start and exit angles for the discs along the cutter axis,

4. CUTTING FORCE MODEL

In milling, cutting forces depend on instantaneous chip thickness; the uncut chip thickness should be calculated precisely to improve the accuracy of force model that is used in force prediction. For ball-end mill tool instantaneous undeformed chip thickness is obtained as follows [Erdim et al., 2006];

$$(t_c)_{kn_{new}} = t_x \times \sin(\theta) \times \sin(\psi) \times \cos(\alpha) \pm t_x \times \cos(\psi) \times \sin(\alpha) \quad (5)$$

where $(t_c)_{kn_{new}}$ is the improved chip load, 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 which is shown in Figure 5. The immersion angle of a discrete cutting point on the flute of the cutter is given as:

$$\theta = \Omega + 2\pi(n-1)/N_f - \beta_k \quad (6)$$

where θ is the immersion angle for flute n, k represents the total number of discrete points 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.

The effect of rotational velocities of the tool axis is not considered in this approach because for free-form surface machining the distance and the rotation angle between two CL points are relatively small and can be neglected. The instantaneous infinitesimal chip load is written as follows:

$$dA_c = (t_c)_{kn_{new}} \times (dz)_{kn} \quad (7)$$

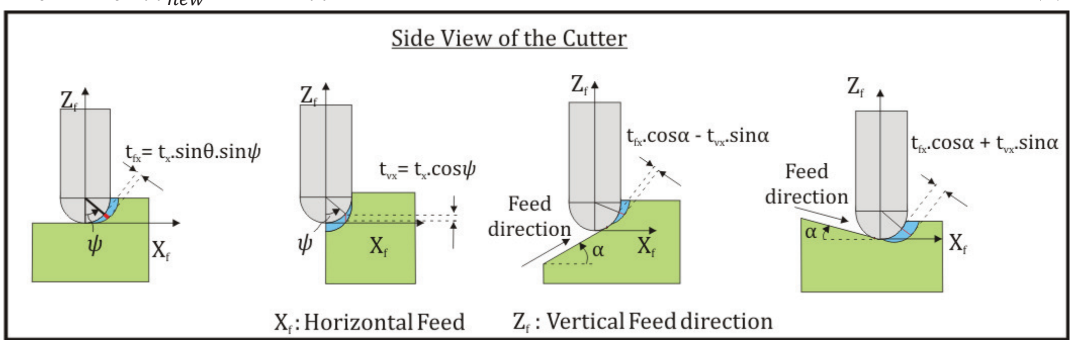

Figure 5; Chip thickness due to horizontal and vertical feed.

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;

$$\begin{aligned} dF_r &= K_{rc} \times dA_c + K_{re} \times dz \\ dF_\psi &= K_{\psi c} \times dA_c + K_{\psi e} \times dz \\ dF_t &= K_{tc} \times dA_c + K_{te} \times dz \end{aligned} \quad (8)$$

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 mechanistic calibration procedure where these coefficients vary along tool axis direction.

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

$$A = \begin{bmatrix} -\sin(\psi) \times \sin(\theta) & -\cos(\psi) \times \sin(\theta) & -\cos(\theta) \\ \sin(\psi) \times \cos(\theta) & \cos(\psi)\cos(\theta) & -\sin(\theta) \\ \cos(\psi) & -\sin(\psi) & 0 \end{bmatrix} \quad (9)$$

$$B = \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (10)$$

In this study, a table type dynamometer is used. Therefore, cutting forces in feed coordinate frame are transformed into workpiece coordinate frame which is also dynamometer coordinate frame. By using transformation matrix T^{-1} given in Section 2, cutting forces in workpiece coordinate frame is written as:

$$\begin{bmatrix} dF_X \\ dF_Y \\ dF_Z \end{bmatrix} = [T^{-1}][B][A] \times \begin{bmatrix} dF_r \\ dF_\psi \\ dF_t \end{bmatrix} \tag{11}$$

5. SIMULATION AND EXPERIMENTAL RESULTS

Two different validation tests are presented for the modeling of 5-axis milling. First one is airfoil geometry and the other one is the penguin free-form surface. For airfoil geometry test nominal 10° lead angle with smoothing, for penguin free-form surface constant 15° lead and 5° tilt angle is simulated. Details of toolpaths are shown in Figure 6.

A table type dynamometer is used for measuring forces which is attached to the rotary table of the machine. Although the cutting forces for whole toolpaths are measured and simulated, one passes of both toolpath simulations are compared against experiments for better illustration of the comparison. The spindle speed and the feedrate for these toolpaths are kept constant at 600 rpm and 48 mm/min respectively. A two fluted ball-end mill with a diameter of 12 mm, nominal helix angle of 30°, and projection length of 37 mm is used as the cutting tool and Al7039 as workpiece material. Depths of cut during two toolpaths vary approximately between 0 – 5 mm along tool axis.

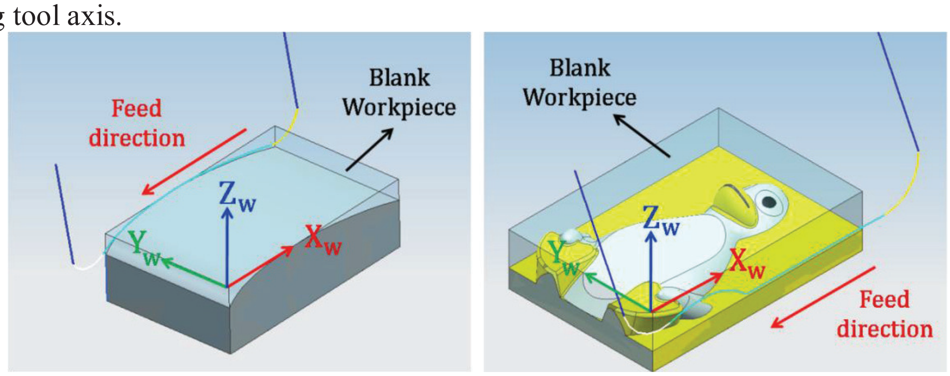

Figure 6; Airfoil geometry and Penguin free-form surface toolpaths.

Figures 7 and 8 show the comparison for the simulation and the experimental cutting forces. As it is demonstrated in the figures simulated and experimental cutting forces match quite well not only in their trends but also in their amplitudes. In most of the regions, the error between simulation and the experimental force amplitudes is below 15 % which can be considered as acceptable for 5-axis milling process simulations.

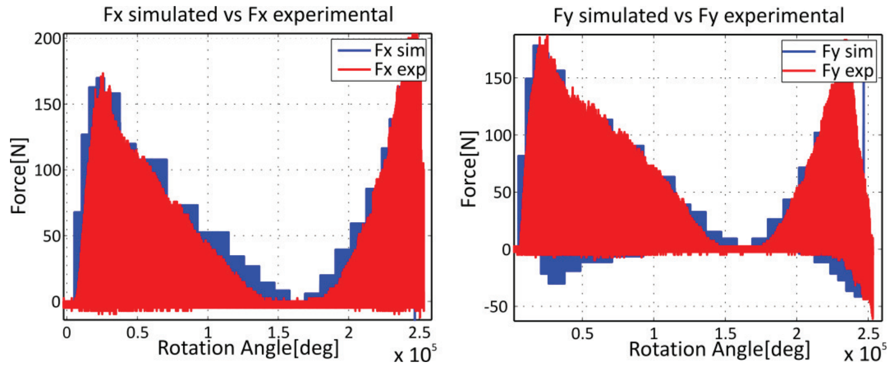

Figure 7; Airfoil geometry simulation and experimental cutting force comparison.

The main differences in cutting force predictions can be attributed to the unequal cutter radius of the flutes which may change the force amplitudes with a phase difference in peak forces. This phenomenon is observed in the cutting tool, although a set of the same tool is used. Another reason can be stated as; penguin surface has free-form geometry, in some regions tooltip contact with the workpiece occurs. Therefore, cutting edge of the tool may be rubbing the workpiece material rather than cutting due to zero cutting velocity at the tooltip.

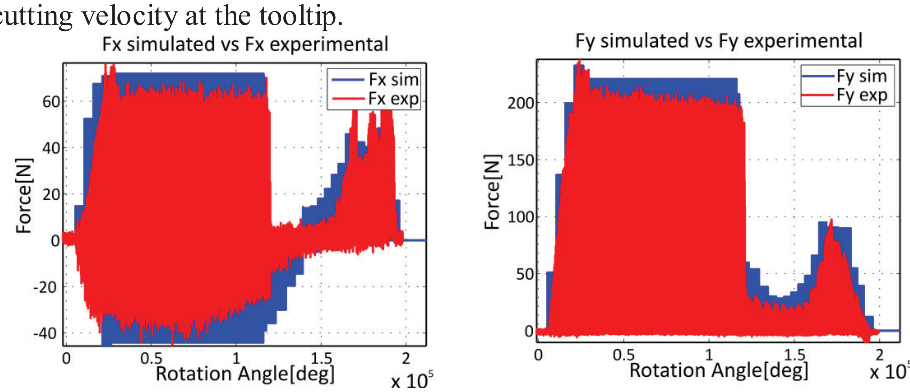

Figure 8; Penguin surface simulation and experimental cutting force comparison.

6. CONCLUSION

In this paper, solid modeler based engagement model and a model for the prediction of cutting force system in 5-axis ball-end milling process are presented. The approach developed based on this model is modular. Therefore, different cutter and workpiece geometries, etc. can be incorporated into the model very easily. The model has the ability to calculate the workpiece/cutter intersection domain automatically for a given CL file, cutter and workpiece geometry.

The presented model can be used in industry, for process simulation and process optimization and it can be integrated into CAD/CAM programs. Cutting parameters of an existing 5-axis ball-end milling process can be used in the model to simulate the cutting forces and optimize the feedrate and other cutting parameters in the process.

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