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This paper represents a comprehensive strategy for estimation of tool deflection in five-axis ball-end milling operation. The cutter-work piece contact zone is computed using a solid modeler kernel and based on that, instantaneous cutting forces are estimated using a mechanistic model. Finite Element Method (FEM) method is employed to simulate the deflection of tool during the cutting process. The proposed model is evaluated by conducting some experiments. Effectiveness of the proposed strategy is considering cutting force as a distributed load along cutting edge, simplicity and less computation time.

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Tool Deflection in Five-Axis Milling

S. Ehsan Layegh K.[1], Ismail Lazoglu[1], Huseyin Erdim[2]
[1] Manufacturing and Automation Research Center,
Koc University, Department of Mechanical Engineering, Sariyer, Istanbul 34450, Turkey
[2]Mitsubishi Electric Research Laboratories, 201 Broadway, Cambridge, MA, USA

Abstract

This paper represents a comprehensive strategy for estimation of tool deflection in five-axis ball-end milling operation. The cutter-work piece contact zone is computed using a solid modeler kernel and based on that, instantaneous cutting forces are estimated using a mechanistic model. Finite Element Method (FEM) method is employed to simulate the deflection of tool during the cutting process. The proposed model is evaluated by conducting some experiments. Effectiveness of the proposed strategy is considering cutting force as a distributed load along cutting edge, simplicity and less computation time.

Keyword:

Milling, Cutting Tool, Deformation, Finite element method (FEM)

1 INTRODUCTION

Five-axis ball-end milling turns out to be one of the most extensively common methods in manufacturing of complex free form surfaces in high-tech industries like dies/molds, automotive, aerospace, biomedical and so on. In order to meet demands of those industries for manufacturing of high precision parts, five-axis ball-end milling process should be investigated and optimized in many respects. One of the main sources of unwanted dimensional error in ball-end milling process is the tool deflection resulting from the periodic cutting forces. Until now, few tool deflection models have been developed for simulation of dimensional error in a complex machining process like five-axis ball-end milling. Most of the models developed in the literatures consider three-axis ball-end milling. Besides, cutting force has been considered as a vector that is applied on tip of the tool rather than take it as distributed load acting on cutting edge.

One of the earliest studies on estimation of tool deflection and machining error in ball-end milling process was conducted by Lim and Menq [1]. They used moment area method to calculate the stiffness of the cutter/tool holder system at each point. In their model the instantaneous cutting force is considered as a vector that is applying on the tip of the tool.

Ikua et al. [2] developed a force model and tool deflection system for ball-end milling of cylindrical parts. They suggested the optimum machining strategy to end up with the highest machining precision. The main drawback to their model is that the formulation for chip thickness and deflection error is just for cylindrical parts.

G.M. Kim, B.H. Kim and C.N. Chu [3] suggested a method to calculate the cutting forces based on an empirical approach and using Z-map methodology to determine cutter contact area. Using estimated cutting forces and considering the tool as a cantilever beam, they came up with estimation of tool deflection and dimensional error. The disadvantage of their model is considering the cutting force as a vector that is applying on a point.

M. Kaymakci and I. Lazoglu [4] developed a mathematical model of cutting forces that was integrated with a CAM package to simulate tool contact region. They used the modeled cutting forces as an input for their deflection model to simulate the tool deformation. However, they considered the cutting force as concentrated load acting on cutting edge.

Hiroyasu Iwabe [5] et al. introduced a model of surface generation mechanism based on tool deflection and FEM analysis. They used ANSYS to simulate the tool deflection due to cutting forces; nevertheless, cutting forces are changing complicatedly and updating the cutting forces for each CL point as an input for ANSYS is really difficult and time consuming.

This paper presents an approach for estimation of tool deflection in five-axis ball end milling process using FEM method. This approach offers the following advantages:

- The ability of considering cutting forces as a distributed load acting on cutting edge;
- Embedding the deflection code into force model code that leads to lower computation time and no need for employing CAE packages;

- The ability of being implemented in CAM packages for future generations to taking into account the deflection of the tool and dimensional error;

2 CUTTING PROCESS MODEL

One of the most critical issues in five-axis freeform ball-end milling is computation of the cutter-workpiece engagement region and estimation of instantaneous cutting forces. Due to permanent change of tool orientation and contact region, simulation of engagement area and instantaneous cutting forces are extremely complicated. Using a Parasolid kernel, a solid modeler based cutter-workpiece engagement (CWE) model is developed to calculate the instantaneous engagement map at each CL point. Besides, a cutting force model is developed to estimate the cutting forces based on the results of engagement modeler algorithm. The details of engagement modeling and cutting force estimation are not going to explained in this paper and can be found in author's previous publications [6].

Figure 1 illustraties the elemental cutting force vectors and geometry of the ball-end mill tool. Force components in radial, tangential and zenith direction can be estimated using mechanistic cutting force model as follow [7]:

$$
\begin{aligned}
dF_r &= K_{rc} \times dA_c + K_{re} \times dz \\
dF_\psi &= K_{\psi c} \times dA_c + K_{\psi e} \times dz \qquad (1) \\
F_t &= K_{tc} \times dA_c + K_{te} \times dz
\end{aligned}
$$

Above, K_{rc}, $K_{\psi c}$, and K_{tc} are radial, zenith and tangential cutting force coefficients, K_{re}, $K_{\psi e}$ and K_{te} are cutting edge coefficients, respectively. dA_c and dz indicate chip load and integration thickness element along the tool axis.

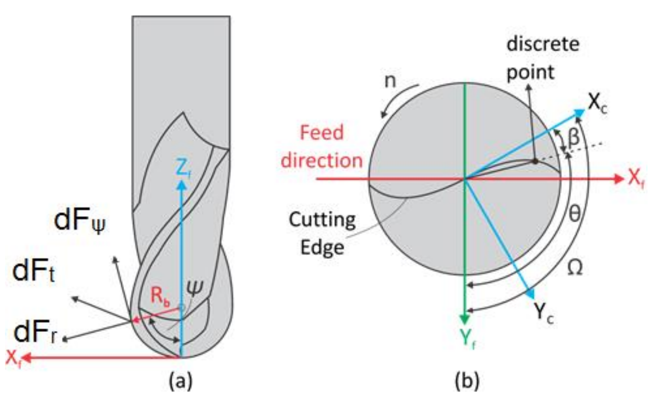

Figure 1: Illustration of cutting force vectors and cutting edge geometry

In order to estimate the cutting forces, elemental force components in Equation (1) should be integrated along cutting edge. This integral should be taken over the engagement zone that is calculated by the solid modeler kernel of the force model.

Figure 2 shows the cutter-workpiece set-up which is used in this research. Tool is cutting a freeform airfoil geometry with variable lead and tilt angle. Figure 3 represents the modeled engagement area and cutting flute for one of the cutter location points (CL). The entry and exit angle of engagement zone along tool axis can be found by projection of 3D yellow engagement surface in Figure 3 into XY plane.

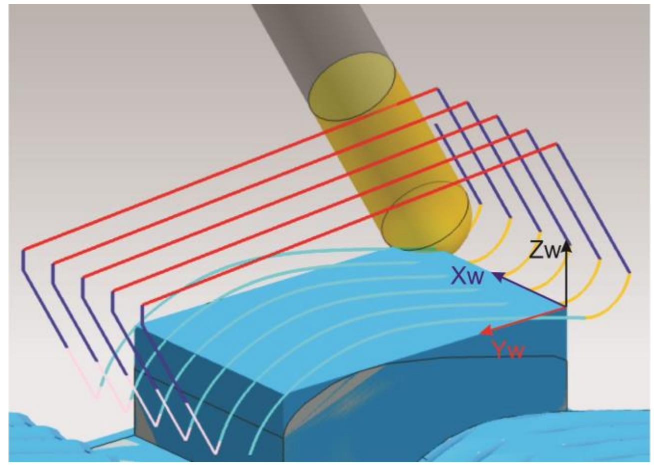

Figure 2: Cutter and workpiece geometry

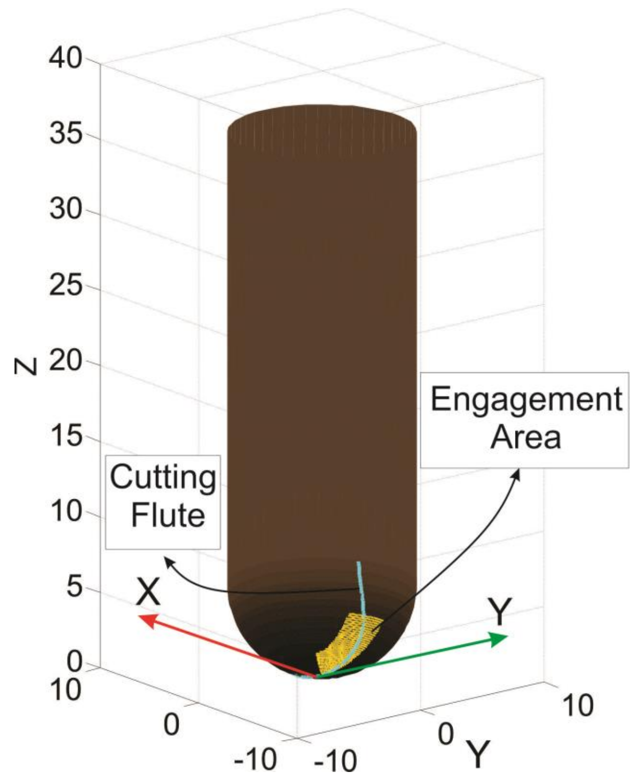

Figure 3: Modeled engagement for five-axis ball-end milling of airfoil geometry

3 DEFLECTION MODEL

So far, the deflection of flat-end mill and ball-end mill tools is calculated by considering the cutting force as concentrated load applying on a point of the tool tip. This methodology can be feasible, if the depth of cut is low and the contact area between tool and workpiece is close to a point. However, in roughing process the contact area is a line across the cutting flute and the cutting force should be considered as a distributed load applying on contact line. Figure 4 is showing the modeled cutting forces as distributed load acting on each cutting flute.

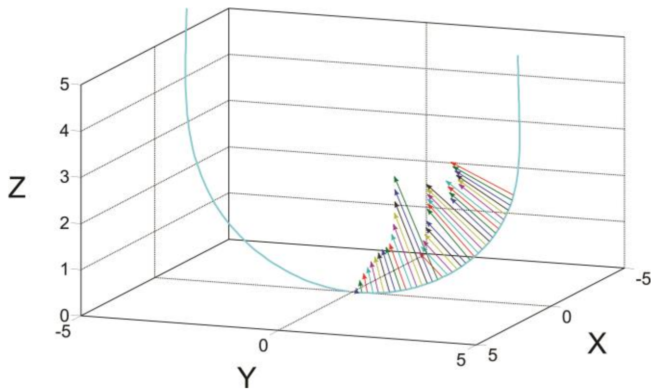

Figure 4: Distributed cutting force along cutting flute

In contrast to flat end mill, Helix angle and cutting coefficients change considerably along the cutting flute by changing the diameter in ball part of the tool [8]. Due to this reason, the disk thickness for force modeling should be thinner close to the tip of the tool to calculate the cutting forces precisely. On the other hand, the thickness of elements for calculation of tool deflection is constant along the tool axis. Figure 5 is representing the schematic view of tool which is considered as a cantilever beam with circular section. For the sake of simplicity, the ball part of the tool is sketched in flat form. However, in the deflection model the ball part of the tool is taken into account.

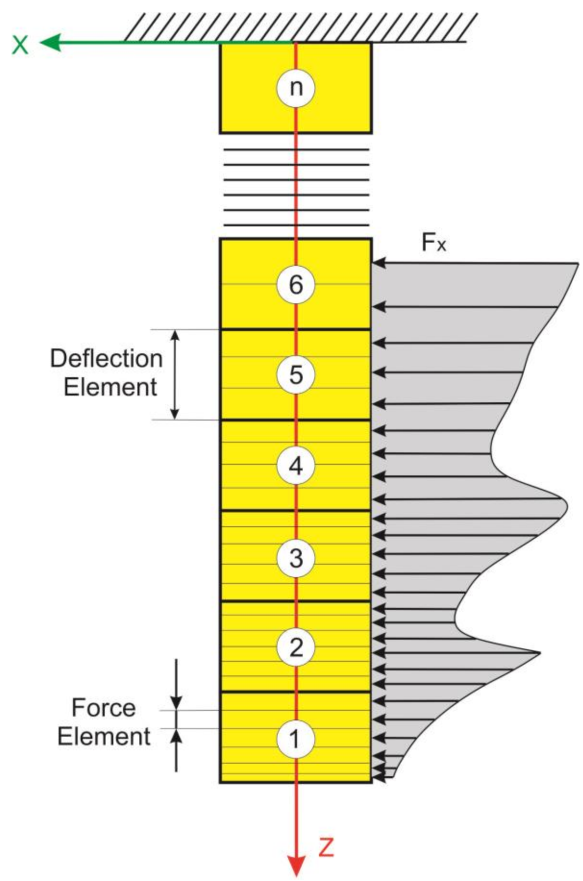

Figure 5: FEM model of tool deflection

Due to the flute-groove design of the tool, it is not accurate to consider the radius of the cutter as the radius of the tool section in deflection model. In order to overcome with this problem, the equivalent diameter of the tool is determined based on its compliance [9].

Timoshenko beam element is used for computation of element matrices and element forces. Figure 6 is showing a schematic view of the Timoshenko beam and its 6 degrees of freedom. In this figure *E, G, A*, *I* and K_s are modulus of elasticity, shear modulus, cross section, moment of area and shear correction factor, respectively.

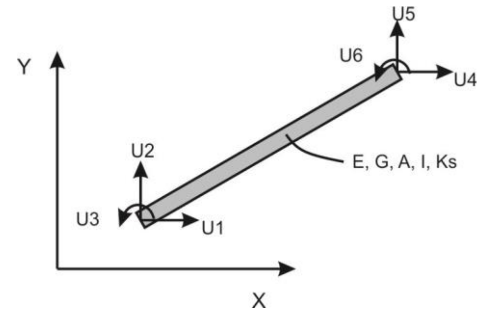

Figure 6: Timoshenko element beam

The element stiffness matrix K^e is computed according to

$$K^e = G^T \bar{K}^e G \tag{2}$$

Where, G is transformation matrix and can be calculated as:

$$G = \begin{bmatrix} n_{x\bar{x}} & n_{y\bar{x}} & 0 & 0 & 0 & 0 \\ n_{x\bar{y}} & n_{y\bar{y}} & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & n_{x\bar{x}} & n_{y\bar{x}} & 0 \\ 0 & 0 & 0 & n_{x\bar{y}} & n_{y\bar{y}} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$n_{i\bar{i}}$ in matrix G are the direction cosines and can be calculated as:

$$n_{x\bar{x}} = n_{y\bar{y}} = \frac{x_2 - x_1}{L}, \quad n_{y\bar{x}} = -n_{x\bar{y}} = \frac{y_2 - y_1}{L}$$

Above, L is the element length.

In equation (2), $\bar{K}^e$ is given by:

$$\bar{K}^e = \begin{bmatrix} \frac{EA}{L} & 0 & 0 & -\frac{EA}{L} & 0 & 0 \\ 0 & A & B & 0 & -A & B \\ 0 & B & C & 0 & -B & D \\ -\frac{EA}{L} & 0 & 0 & \frac{EA}{L} & 0 & 0 \\ 0 & -A & -B & 0 & A & -B \\ 0 & B & D & 0 & -B & C \end{bmatrix} \tag{4}$$

above;

$$\mu = \frac{12EI}{L^2 GAK_s}, A = \frac{12EI}{L^3(1+\mu)}, B = \frac{6EI}{L^2(1+\mu)},$$

$$C = \frac{4EI(1+\frac{\mu}{4})}{L(1+\mu)}, D = \frac{2EI(1-\frac{\mu}{2})}{L(1+\mu)}$$

K^e matrices are going to be assembled in the following form to generate the structure stiffness matrix K:

$$K=\begin{bmatrix} k_{11} & k_{12} & \vdots & & & \\ k_{21} & & \vdots & & & \\ \cdots & \dots & k_{ii}+k_{ii}^{e} & k_{ij}+k_{ij}^{e} & \cdots & \dots \\ \cdots & \cdots & k_{ji}+k_{ji}^{e} & k_{jj}+k_{jj}^{e} & \cdots & \cdots \\ & & \vdots & \vdots & & \\ & & \vdots & \vdots & & k_{nn} \end{bmatrix} \quad (5)$$

where, n is the number of discrete elements on the tool.

After finding the elemental cutting forces for each node in Figure 5, the deflection of each node in x and y direction can be found using the following equation:

$$\begin{cases} K \times X_x = F_x \\ K \times X_y = F_y \end{cases} \quad (6)$$

Figure 7 is representing the modeled deflection for the cutting conditions mentioned in Table 1.

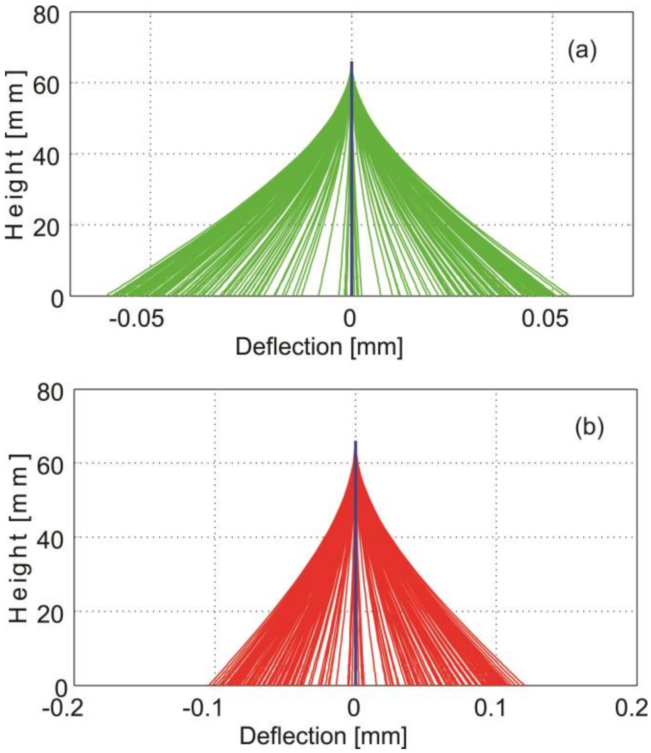

Figure 7: Modeled deflection, (a): Deflection in X-direction, (b): Deflection in Y-direction

Tool Diameter [mm]	Spindle Speed [rpm]	Feedrate [mm/min]	Tool Length [mm]	Maximum Depth of Cut [mm]
12	4000	500	66	5.5

Table 1: Cutting conditions for simulation of tool deflection

4 EXPERIMENTAL RESULTS AND VALIDATION

This section presents the series of experiments performed to validate the proposed cutting force and deflection model algorithm. All of the tests were conducted on five-axis Mori Seiki NMV5000DCG milling machine. A rotary type of Kistler dynamometer was used to measure the forces during the cutting process. Two Keyence laser sensor head with precision of 1 micron and sampling rate of 50 kHz were utilized to measure the tool deflection. Figure 8 is showing the experimental setup which is used to validate the force and deflection model.

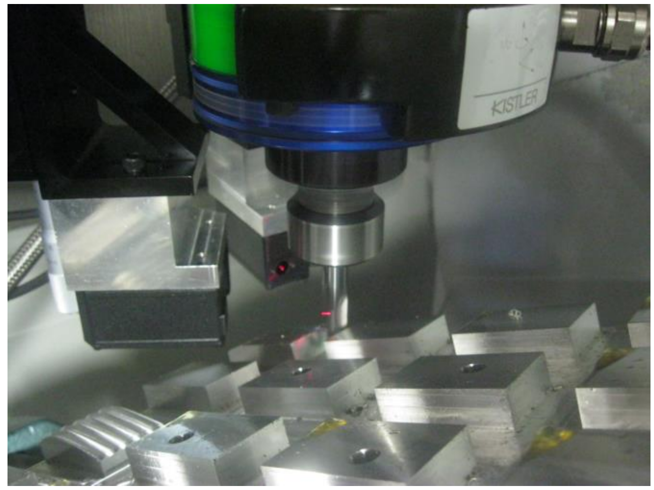

Figure 8: Experimental setup for measuring force and tool deflection

Figure 9 is representing the simulated and measured cutting forces for the conditions mentioned in Table 1. As it is obvious from the figure there is a good agreement between the simulated and measure cutting forces. Since the tool and spindle system is highly rigid in Z direction, the z component of cutting force and deflection has not considered.

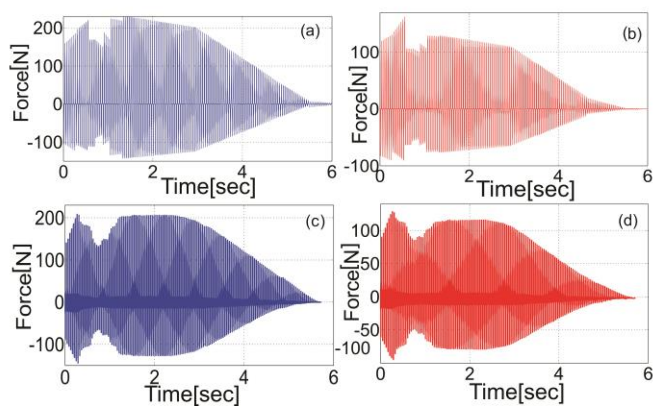

Figure 9: Simulated and measured cutting forces. (a) simulated cutting forces in y direction, (b) simulated cutting forces in x direction, (c) measured cutting forces in y direction and (d) measured cutting forces in x direction.

Figure 10 presents the simulated and measured deflection at the tip of the tool. In order to avoid of any collusion during the machining, laser heads set to be 20 mm upper that the tool tip. An extrapolation algorithm found the measured deflection at the tool tip. As it can be seen from Figure 10, there is a good agreement between experimental and simulated results. The maximum error in the deflection model is 20% which is acceptable.

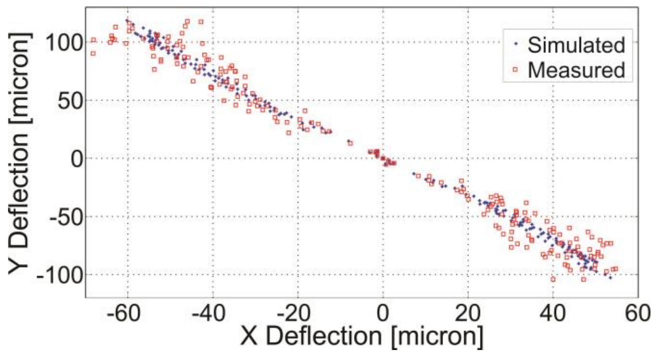

Figure 10: Simulated and measured deflection during the cutting process at the tip of the tool

5 SUMMARY

This paper has presented a deflection model for five-axis ball end milling process based on FEM analysis. The cutting forces were modeled and verified using the previous works of the authors and were used in deflection model to simulate deformation of cutter during the cutting process. The advantage of this model was considering the cutting forces as distributed load along the cutting flute. Moreover, the cutting force model and deflection model were combined into one code that leads to faster analysis and no need for using any CAE packages. At the end, the validity of the model was examined through conducting a series of experimental tests.

6 ACKNOWLEDGEMENTS

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7 REFRENCES

[1] Lim, EE Meng and Menq, Chia-Hsiang, 1995, *The Prediction of Dimensional Erroe for Sculptured Surface Production Uing the Ball-End Milling Process. Part 2: Surface Generation Model and Experimental Verification,* International Journal of Machine Tools and Manufacture, 35/8:1171-1185.

[2] Bernard W. Ikua, Hisataka Tanakara, Fumio Obata, Satoshi Sakamoto, 2001, *Prediction of cutting forces and machining error in ball end milling of curved surfaces -I theoretical analysis,* Precision Engineering, 25/4:266-273.

[3] Kim, G. M., Kim, B. H., and Chu, C. N., 2003, *Estimation of cutter deflection and form error in ball-end milling processes,* International Journal of Machine Tools and Manufacture, 43/9:917-924.

[4] Kaymakci, M. and Lazoglu, Ismail, 2008, *Tool Path Selection Strategies for Complex Sculptured Surface Machining,* Machining Science and Technology, 12/1:119-132.

[5] H. Iwabe, S. Natori, M. Masuda, T. Miyaguchi, 2004, *Analysis of Surface Generating Mechanism of Ball End Mill Based on Deflection by FEM,* JSME International Journal Series C, Mechanical Systems, Machine Elements and Manufacturing, 47/1:8-13.

[6] Yaman Boz, Seyed Ehsan Layegh K., Huseyin Erdim, Ismail Lazoglu, 2010, *High performance of five axis milling of complex scluptured surfaces*, in *Machining of Complex Sculptured Surfaces*, J.P. Davim, Editor. Springer: London. p. 67-125.

[7] Altintas, Yusuf, 2012 *Manufacturing automation: metal cutting mechanics, machine tool vibrations, and CNC design*. Cambridge university press.

[8] Gradišek, Janez, Kalveram, Martin, and Weinert, Klaus, 2004, *Mechanistic identification of specific force coefficients for a general end mill,* International Journal of Machine Tools and Manufacture, 44/4:401-414.

[9] L. Kops, D.T. Vo, 1990, *Determination of the equivalent diameter of an End Mill based on its compliance,* CIRP Annals - Manufacturing Technology.