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Dynamic Force Model for 3-Axis Ball-End Milling of Sculptured Surfaces

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Abstract

Dynamic force model is used to estimate cutting forces of sculptured surface considering dynamic characteristics. Two programs were used for calculations, "ACIS" the 3-D geometric modeler and "VISUAL BASIC". Two programs were edited and used to preform the calculations, the scheme program to model the work piece ,tool and cutting edge and to obtain the geometric data and the VISUAL BASIC program designe to use ACIS geometric data to calculate the cutting forces. The engaged part of the cutting edge and work piece is divided into small differential oblique cutting edge segments. Friction, shear angles and shear stresses are identified from orthogonal cutting data base available in literature. The cutting force components, for each tool rotational position, are calculated by summing up the differential cutting forces. The machine tool was modeled by a two degree of freedom mass, spring and damper vibration system. Laboratory tests were conducted to verify the pridictions of the model. The work pieces were prepared from CK45 steel using an insert type ball-end cutter. No coolant was used in any of the experimental works. The cutting forces predicted have shown good agreement with experimental results.

Keywords*:* Milling, Ball-end milling tool, Geometric modeling, Dynamic force prediction, sculptured surface machining

1 Introduction

Milling is one of the most frequent types of machining processes used widely in the industry, almost 50% more than the other types. The ball-end milling process is used extensively in the machining of free form surfaces in turbine blade or die/mold manufacturing. The cutting force is one of the most important process parameters in the cutting operation, since it is related to various process features such as tool deflection, tool breakage, chipping, excess tool wear and cutter vibration. If more features are considered during the estimation of the cutting forces, the results would be more accurate, but would involve complicated calculations, hence a rough estimation with simple calculations usually suffices.

The static force model assumes that no tool, work piece, machine tool deflection exist and there is no dynamic behavior in the machining system.

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Ball-end mill was first studied by Hosoi [1], who showed experimentally that a spiral shaped cutting edge can perform highly productive machining without edge chipping. In this study no experimental test was done. Yang and Park [2] introduced a force model to predict the cutting forces in ball-end milling. In this model, an orthogonal cutting theory was applied to the plane of the cutting velocity and the chip velocity at an arbitrary point on the cutting edge. The development of the force model was based on an analysis of the cutting geometry of the ball-end mill with plane rake faces. Hence, the cutting edge geometry was simplified as a function of the normal rake angle of the plane rake face and the position of the cutting edge in the spherical coordinate system. This model was experimentally validated for light immersion only. Feng and Meng [3] introduced a two-component mechanistic force model that considered local cutting mechanics of differential cutting edges by introducing the force coefficient K_t and K_r as polynomials of the axial depth of cut. Due to the empirical nature of the model, a separate set of experiments was required to identify the numerical values of the empirical model parameters for the particular work piece cutter combination. Abrari and Elbestawi [4] have developed a closed form force model for flat and ball-end mills. In this model, a set of closed form functions are introduced for the projected areas of chip load on the reference coordinate planes. A pair of cutting forces, normal and tangential, are associated with each projected area. An average specific pressure matrix relates the projected areas to two components of cutting forces. Yucesan and Altintas [5] considered the normal and friction forces on both the rake and clearance faces of a constant lead ball-end mill. They assumed that the loads on the rake face are proportional to the uncut chip thickness area, and the loads on the flank face are concentrated on the in-cut portion of the cutting edge. They also assumed average values for chip flow angle and cutting coefficient along the cutting edge. Calibration and verification of their model was limited to simple two-dimensional cases (i.e. slotting). Lee and Altintas [6] introduced a force model using orthogonal cutting data base for a constant lead cutter. The helical flutes were divided into small differential oblique cutting edge segments. The orthogonal cutting parameters are carried to oblique milling edge geometry using the classical oblique transformation method. Model verification was limited to simple cases only (i.e. slotting).

All the force models introduced above were only applicable to ball-end milling of horizontal planes. Imani, Sadeghi and Elbestawi [7] developed a mechanistic force model that was applicable to ball-end milling of non-horizontal planes. They used a commercial solid modeler for extracting the geometric information required for the physical simulation. Cutting forces were calculated as the summation of normal and friction forces acting on the rake face and cutting edge. milling force coefficients determined from a set of experiments for each cutter geometry. By contrast the unified mechanics of cutting approach relies on an experimentally determined orthogonal cutting data base (i.e., shear angle, friction coefficient and shear stress), incorporating the tool geometrical variables, and milling model based on a generic oblique cutting analysis [8]. Haghighat and Sadeghi [9] introduced a force model using orthogonal cutting data for cutting inclined plan. The helical flutes were divided into small differential oblique cutting edge segments. The orthogonal cutting parameters are carried to oblique milling edge geometry using the classical oblique transformation method. Several

experiments were conducted to verify the model, and there was good agreement between the predicted and actual results.

The aim of the present investigation is to develop a ball-end milling force model for approximating cutting forces in different locations of die surface regardless of shape of work pieces. The machine tool was modeled by a two degree of freedom mass, spring and damper vibration system. Two programs were used for the calculations, first “ACIS” [10] the 3-D geometric modeler and latter “VISUAL BASIC”. Two separate programs were edited, the scheme program for modeling the work piece, tool, cutting edge and updated machined surface by taking cutting path, work piece sat file, machining conditions and data as input data and the VISUAL BASIC program to use the geometric data from the geometric modeler ”ACIS” program to calculate the tool tip vibration and cutting forces. The cutter used in this study is an "inset type" one flute ball-end mill. The cutting force components are calculated by summing up the differential cutting forces for each tool rotation steps. The model is verified at different cutting conditions generated by a sculptured surface shown in figure 1.

Machining was done with down milling condition in varying positive and negative slope milling in x and y directions. Every freeform surface can be used in the software as the work piece. All tool situations like entering and leaving the work piece are considered and at each moment updated work piece is created.

Organization of this paper is as follow:

1- Introduction
2- Geometric modeling of ball-end milling which includes cutting edge, chip and immersion geometries
3- Modelling of cutting forces
4- Experimental verification of the force model
5- Conclusion of the developed model

2 Geometric Modelling

2.1 Tool Geometry

In the first program the following formula are used to obtain the geometric data. The cutter used in this work is an "insert type" ball-end mill (see Figure 2a) and the cutting edge (OA in Figure 2b) is generated by the intersection of an inclined plane and the ball part. The cutter radius in the x - y plane at axial location z is:

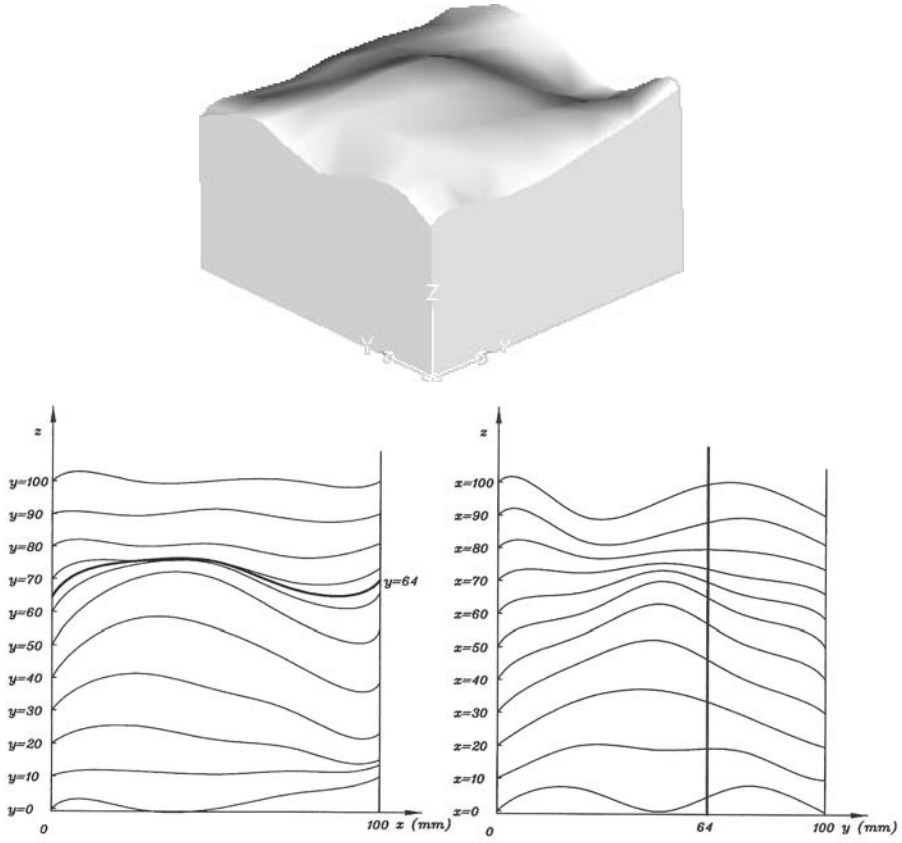

Figure 1. Sculptured surface and its contour which is considered as the test work piece.

$$R(z) = \sqrt{R^2 - (R - z)^2} \tag{1}$$

For an element at axial location z:

$$\sin\theta(z) = \frac{z\tan(i_0)}{R(z)} \tag{2}$$

Where θ(z) is the angle between the ball tip (z=0) and an element at axial location z. It is measured clockwise from the z axis (see Figure 2). Vector r (OP in Figure 2b) is drawn from the Cartesian coordinate center to a point on the cutting edge, and is defined by:

$$r = -R(z)\cos\theta(z)i + R(z)\sin\theta(z)j + zk \tag{3}$$

Using equations (2) and (3):

$$r = -\sqrt{R^2(z) - (z\tan i_0)^2}\,i + z\tan i_0\, j + zk \tag{4}$$

Thus:

$$dr = \left(-\frac{R(z)\dfrac{dR(z)}{dz} - z\tan^2 i_0}{\sqrt{R^2(z) - (z\tan i_0)^2}}i + \tan i_0\, j + k\right)dz \tag{5}$$

The length of infinitesimal curved cutting edge segment ds is computed from:

$$ds = \|dr\| = dz\sqrt{\frac{(R(z)\dfrac{dR(z)}{dz} - z\tan^2 i_0)^2}{R^2(z) - (z\tan i_0)^2} + \tan^2 i_0 + 1} \tag{6}$$

Where:

$$\frac{dR(z)}{dz} = \frac{R - z}{R(z)} \tag{7}$$

Where: $\alpha_n = 20^o, i_0 = 10^o \; and \; R = 8mm$

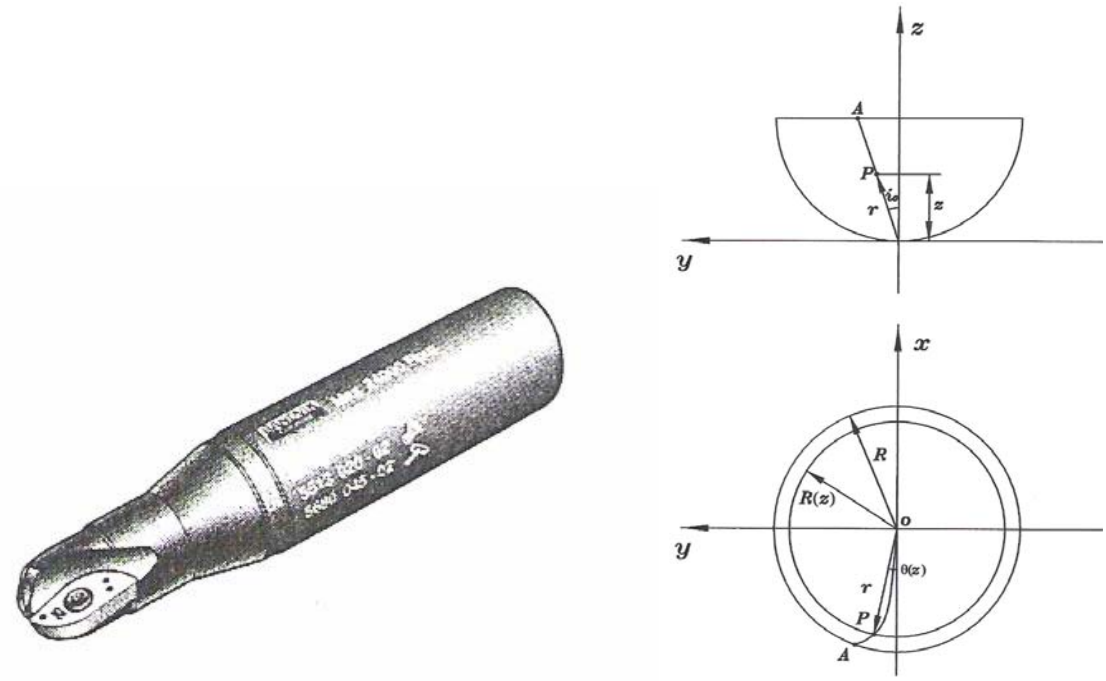

Figure 2. (a) Insert type ball end-mill (b) geometric model of the insert type ball-end mill

A point on the flute j at height z is defined by its angular position $\Psi(\theta, z)$ on the global coordinate system:

$$\psi(\theta, z) = \theta + (j-1)\frac{2\pi}{N} - (\theta_0 - \theta(z)) \tag{8}$$

Where θ is the tool rotation angle about z axis and θ_0 is maximum angle between ball tip (z = 0) and an element at axial location R and from equation (2):

$$\theta_0 = \arcsin(\tan i_o) \tag{9}$$

2.2 Dynamic undeformed radial chip thickness

Tooth path and radial chip thickness for milling process with horizontal feed directions have been studied by Martellotti [11, 12]. For the case of 3-axis ball-end milling Lim et al. [13] considered the effect of vertical component of feed on chip thickness using the following relation:

$$t(\theta, z) = R_2(z) - R_1(z) + f_h \sin \psi(\theta, z) \tag{10}$$

Where f_h is horizontal component of the feed along the tool path. $R_1(z)$ and $R_2(z)$ are the ball-nose radii at two successive positions in the same z value (See Figure 3).

The difference between $R_1(z)$ and $R_2(z)$ is due to the vertical height difference f_v. Therefore this difference can be approximated by:

$$R_2(z) - R_1(z) = \frac{dR(z)}{dz} f_V \tag{11}$$

From equations (1), (7), and (10):

$$\begin{aligned} t(\theta,z) &= -\frac{R-z}{\sqrt{R^2-(R-z)^2}} f_V - f_h \cos\Psi(\theta,z) \Rightarrow if \gamma \geq 0 \\ t(\theta,z) &= -\frac{R-z}{\sqrt{R^2-(R-z)^2}} f_V + f_h \cos\Psi(\theta,z) \Rightarrow if \gamma < 0 \end{aligned} \tag{12}$$

$$f_V = f\sin\gamma, f_h = f\cos\gamma \tag{13}$$

Where γ is the slope angle of the tool path between two successive point of NCcode (See Figure 3).

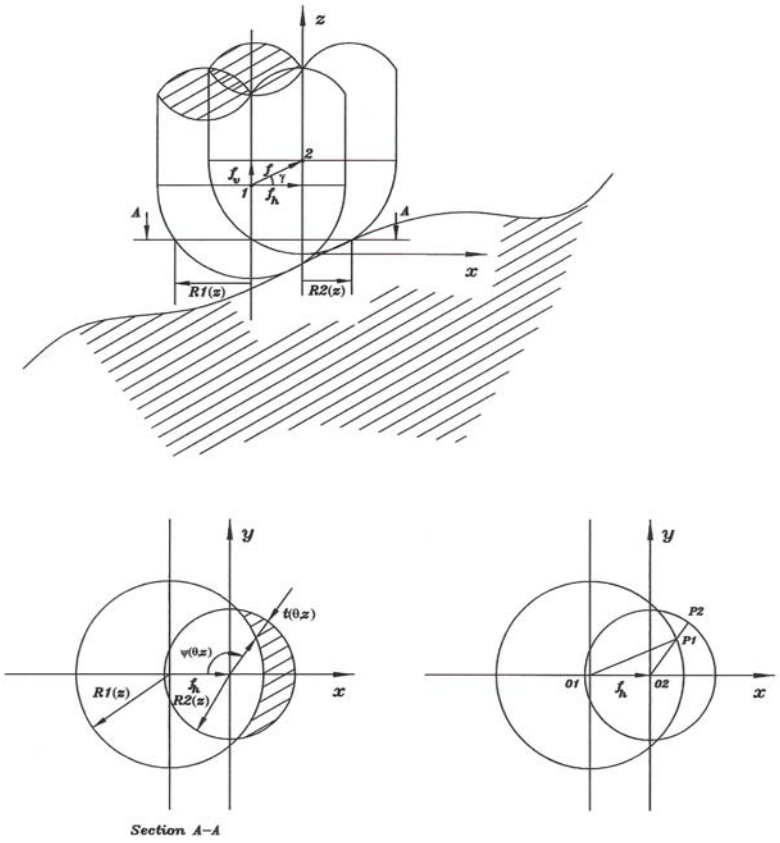

Figure 3. Chip thickness in three-dimensional ball-end milling process

Equation (12) states undeformed chip thickness regardless of machine tool vibration. To calculate the dynamic undeformed chip thickness a dynamic model of machine tool which is shown in Figure 4 is considered.

By solving the equation (14) with forth order Rung-Kutta numeric method displacement of tool tip in x & y direction was extracted.

$$\begin{cases} m_x\ddot{x} + C_x\dot{x} + k_x x = F_{cx} + F_{px} \\ m_y\ddot{y} + c_y\dot{y} + k_y\ y = F_{cy} + F_{py} \end{cases} \tag{14}$$

With respect to the Figure 5 the following equation is generated:

$t_{dynamic}(\theta, z)=t(\theta,z)+u(\theta,z)-u_{old}(\theta,z)$ (15)

Where:

$$\begin{cases} u = y\sin\Psi(\theta,z) - x\cos\Psi(\theta,z) & if \ \ \gamma \geq 0 \\ u = x\cos\Psi(\theta,z) - y\sin\Psi(\theta,z) & if \ \ \gamma < 0 \end{cases} \quad (16)$$

$$\begin{cases} u_{old} = y_{old}\sin\Psi(\theta,z) - x_{old}\cos\Psi(\theta,z) & if \ \gamma \geq 0 \\ u_{old} = x_{old}\cos\Psi(\theta,z) - y_{old}\sin\Psi(\theta,z) & if \ \gamma < 0 \end{cases} \quad (17)$$

"Old" subscript means the previous cut data at the same angle.
In the situation that $t_{dynamic}$ <0 we should consider $t_{dynamic}$ =0 because in this occasion, the tool jumps out of cut. Ploughing force is considered too [14].

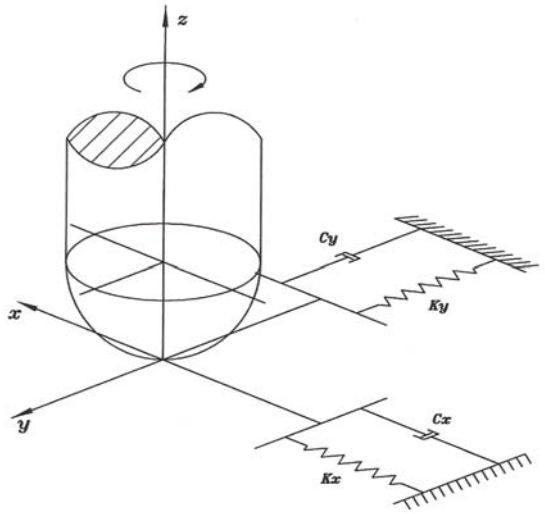

Figure 4. Machine tool dynamic model

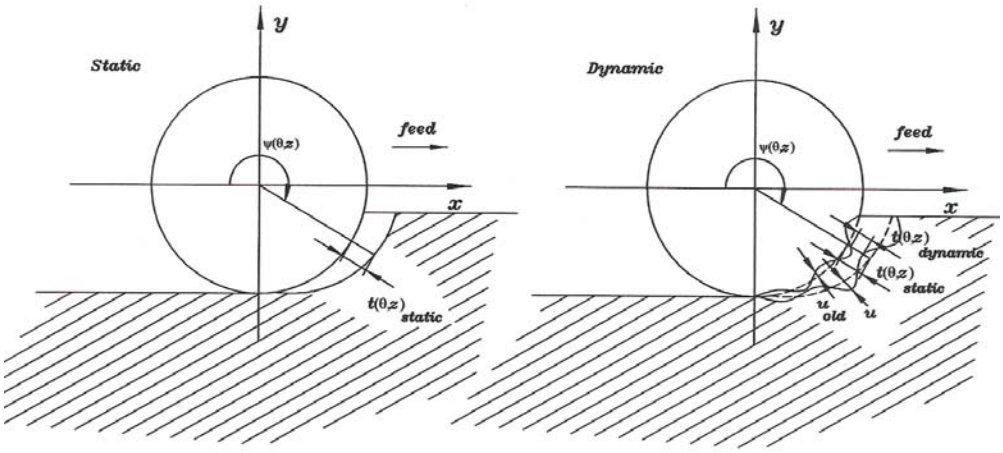

Figure 5. Dynamic & static undeformed chip thickness comparison

3 Prediction of Milling Forces

The unified mechanics of cutting approach introduced by Budak et al. [8] is extended to the ball end milling process. It is assumed that the cutting edge is sharp and therefore the edge forces are not considered. The elemental tangential, dF_t , radial, dF_r and axial, dF_a forces acting on an element at axial location z are given by (see Figure 6):

$dF_t = K_t\, t_{ndynamic}(\theta,z)db$, $dF_r = K_r\, t_{ndynamic}(\theta,z)db$, $dF_a = K_a\, t_{ndynamic}(\theta,z)db$ (18)

Where $db = \dfrac{dz}{\sin\kappa}$, $\kappa = \arcsin\dfrac{R(z)}{R}$ and $t_{ndynamic}(\theta,z) = t_{dynamic}(\theta,z)\sin\kappa$

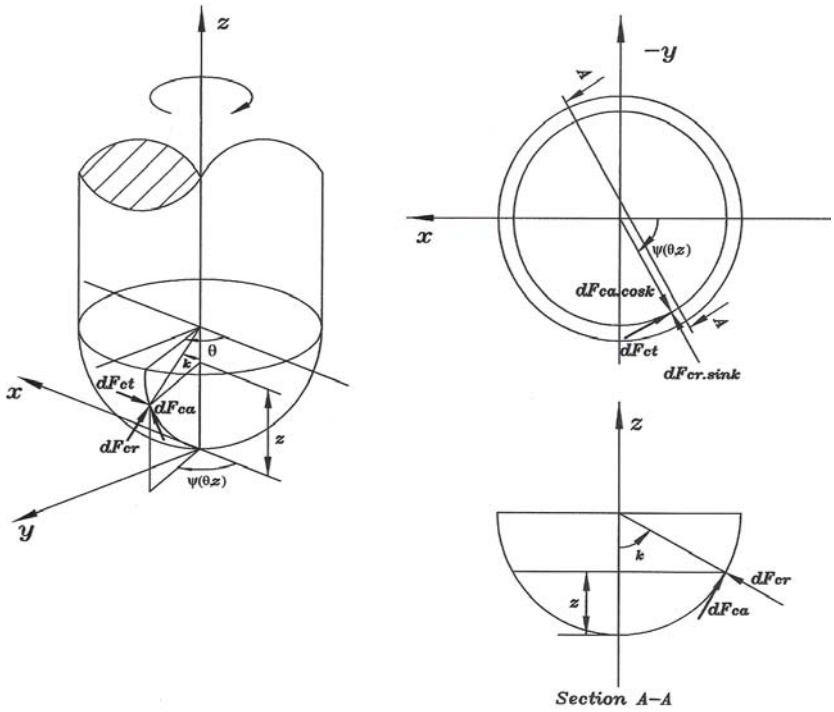

Figure 6. Element cutting force components acting on the cutting edge

Cutting coefficients k_r, k_t and k_a are identified from a set of orthogonal cutting tests using an oblique transformation method [5].The shear stress (τ), friction angle (β) and shear angle (ϕ) are modeled using the yang [2] predictions:

The differential cutting forces calculated using equation (18) transformed to Cartesian coordinates as follows:

$$if\gamma \geq 0\begin{cases} dF_x = \sin k\cos\Psi(\theta,z)dF_r - \sin\Psi(\theta,z)dF_t - \cos k\cos\Psi(\theta,z)dF_a \\ dF_y = -\sin k\sin\Psi(\theta,z)dF_r - \cos\Psi(\theta,z)dF_t + \cos k\sin\Psi(\theta,z)dF_a \\ dF_z = \cos kdF_r + \sin kdF_a \end{cases}$$

$$if\gamma < 0\begin{cases} dF_x = -\sin k\cos\Psi(\theta,z)dF_r + \sin\Psi(\theta,z)dF_t + \cos k\cos\Psi(\theta,z)dF_a \\ dF_y = \sin k\sin\Psi(\theta,z)dF_r + \cos\Psi(\theta,z)dF_t - \cos k\sin\Psi(\theta,z)dF_a \\ dF_z = \cos kdF_r + \sin kdF_a \end{cases} \quad (19)$$

Finally, the instantaneous cutting forces acting on the cutting edge can be expressed as:

$$\{F_x, F_y, F_z\} = \int_{z_l}^{z_u} dF_x, dF_y, dF_z \qquad (20)$$

The integration limits (z_l and z_u) are the lower and upper boundaries of the in-cut segment and are provided by geometric simulation which are stored in the related file. The above formulation is used in the VISUAL BASIC program and the cutting force for each point of cutting in the three directions are stored in a file which can be plotted verses time of machining.

4 Experiments and Results

In this research a sculptured surface is considered and the cutting forces for different rows of cutting are calculated. Experimentally a 3-D-axis CNC milling machine was used to perform some tests in order to verify the calculated results. The preload of the CNC ball screws were high enough (maximum force with no back lash were 3.55 KN) that no backlash affected the machining system because in down milling direction of cutting forces sometimes change. The dynamic characteristics of the machine tool were extracted from modal tests. A 16 mm diameter, 20° rake angle, one flute ball-end mill was used in the experiments. The work piece material was CK45 carbon steel. Feed direction was along x axis and down milling operation was used. Instantaneous cutting forces were measured using a Kistler type 9255A, 3-D force component table dynamometer with 1000 Hz sample rate data acquisition board. The natural frequency of the dynamometer (approximately 3 KHz in each axis) was high enough so as not to cause any interference in the vibratory system. The work piece surface was an sculpture one. The cutter-part immersion geometry for different point was varying depending on the sculpture contour (See Figure 1). To cut totally the work piece surface 26 path along the x axis were selected. As an example the tenth cutting path calculated and measured forces verses time and its tool deflection are presented. The calculated and measured cutting forces are shown in Figures 7 and 8. Tool tip displacement and its calculated vibration are shown in Figure 9 to Figure 11. The experimental results show that there was good agreement between predicted and actual forces with an error of approximately 15%.

5 Conclusion

This paper represents a dynamic force model for prediction the cutting forces and tool tip displacement during machining of sculptured surfaces with ball-end mills. The cutting edge and updated part geometry are modeled using a commercial available geometric modeler “ACIS” and “VISUAL BASIC”. Machine tool was modeled by a two degree of freedom vibration system. Displacements in the x & y directions was calculated with the fourth order Rung-Kutta numerical method. Dynamic undeformed chip thickness was calculated and cutting edge is generated by intersecting an inclined plane with the cutter ball nose. The in cut segments are extracted and are used by the force model. The cutting forces generated by each element on the portion of the engaged cutting edge are evaluated by applying classical oblique cutting

transformation to orthogonal cutting data which allows the model to be extended to any cutter geometry without milling calibration tests.
The total cutting force components for each tool rotation step are calculated by summing up the infinitesimal cutting forces.
A sculptured surface at any point was engaged to the tool and contact area was simulated exactly. Therefore for each block of NCcode, a separate force was calculated.

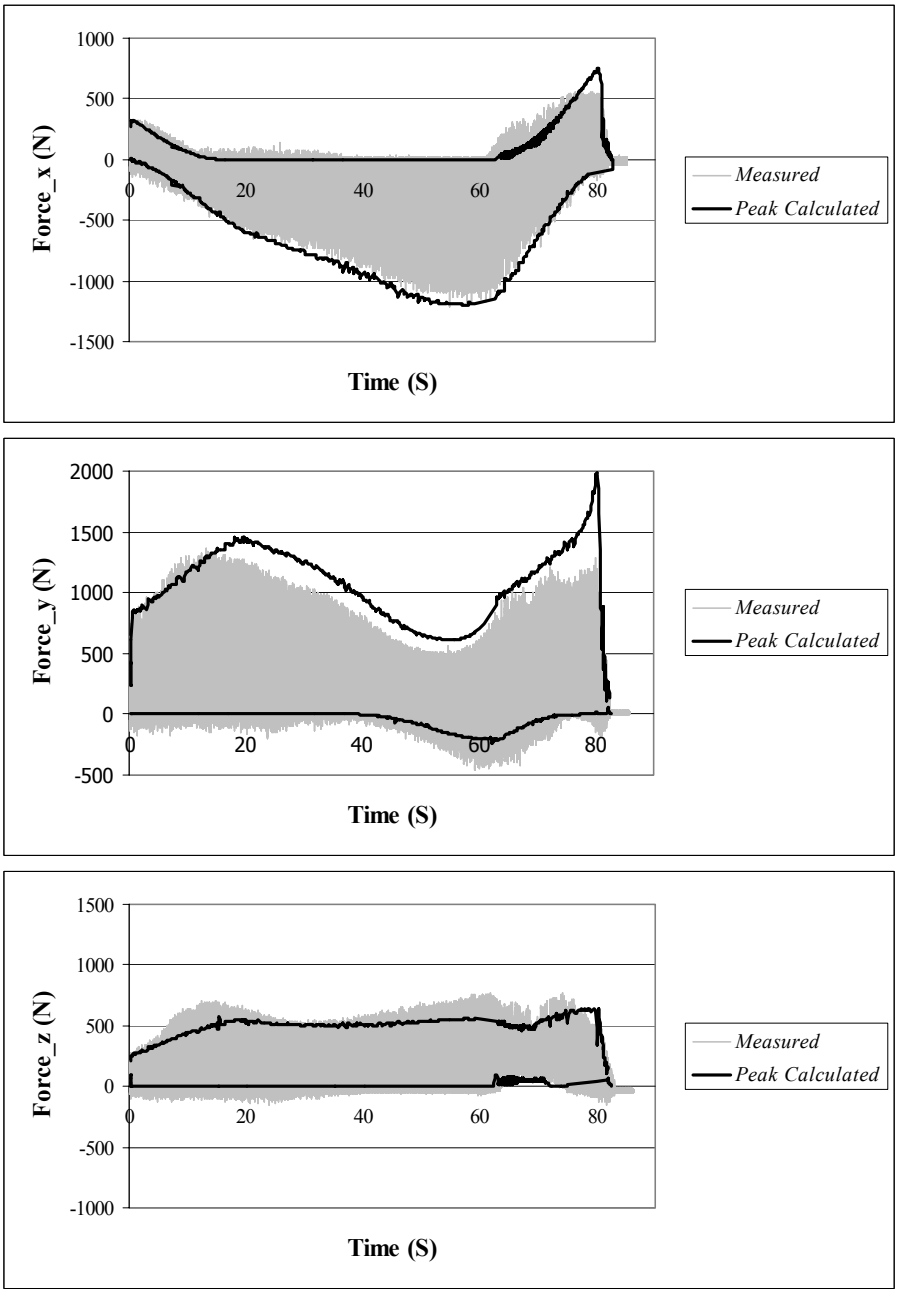

Figure 7. Measured & calculated dynamic force spectrum for sculptured cutting for y=64 (tenth path) Cutting conditions: spindle speed=600 rpm, Feed=72mm / min, Depth of cut=2 mm and Δy =4 mm

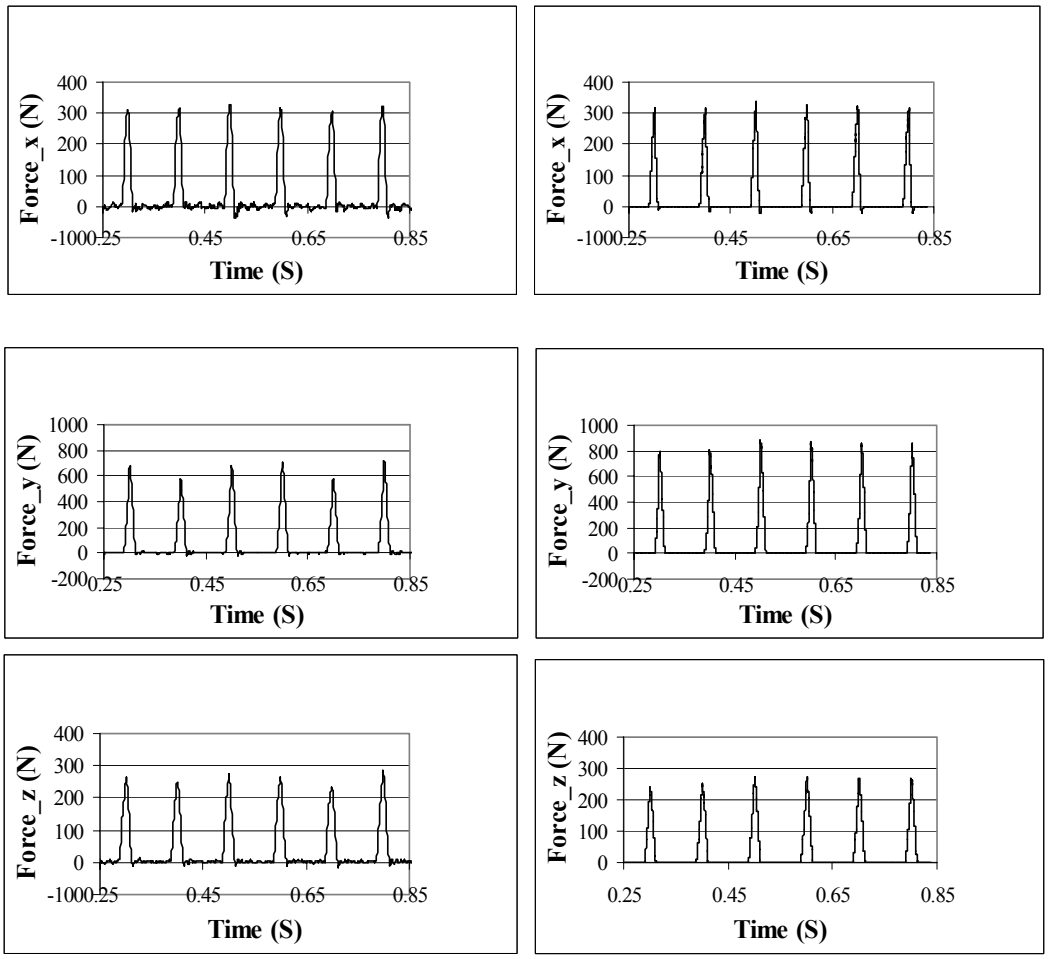

Figure 8. Detailed measured & predicted force shown in Figure 7 for tenth path. a) Measured b) calculated

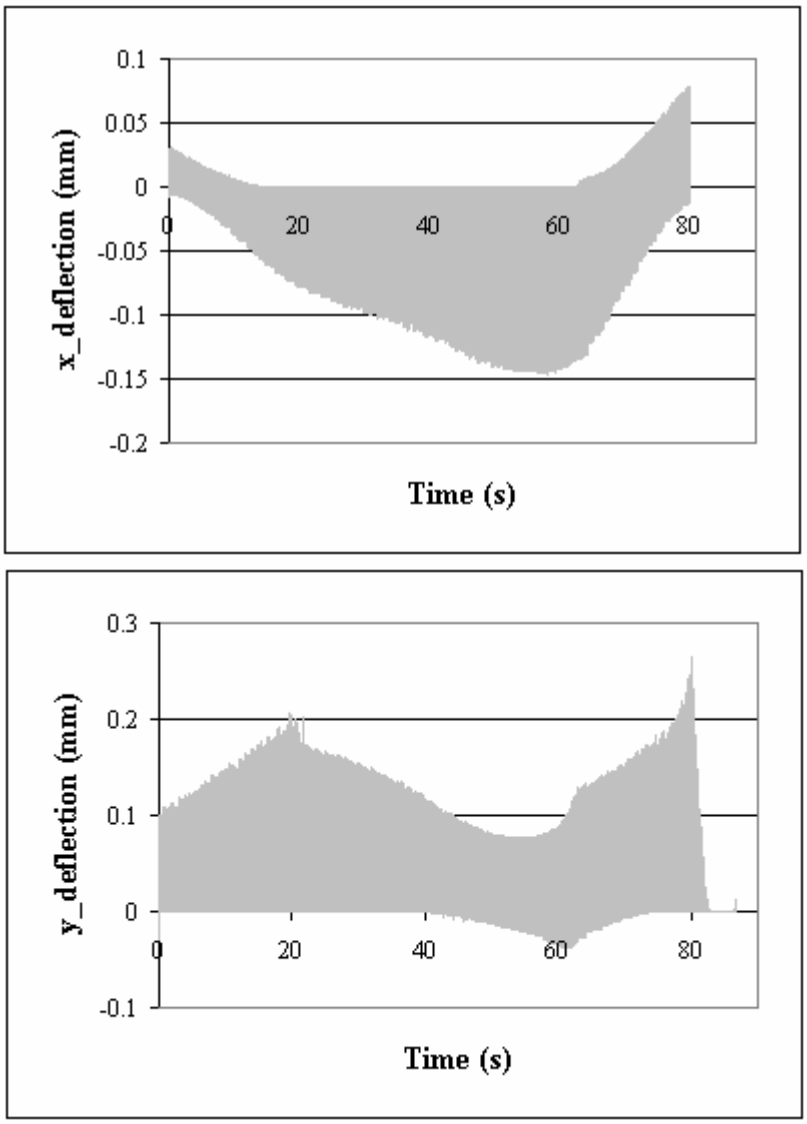

Figure 9. Calculated tool tip displacement spectrum for sculptured cutting for y=64 (tenth path) Cutting conditions: spindle speed=600 rpm, feed=72mm / min, Depth of cut=2 mm and Δy =4 mm

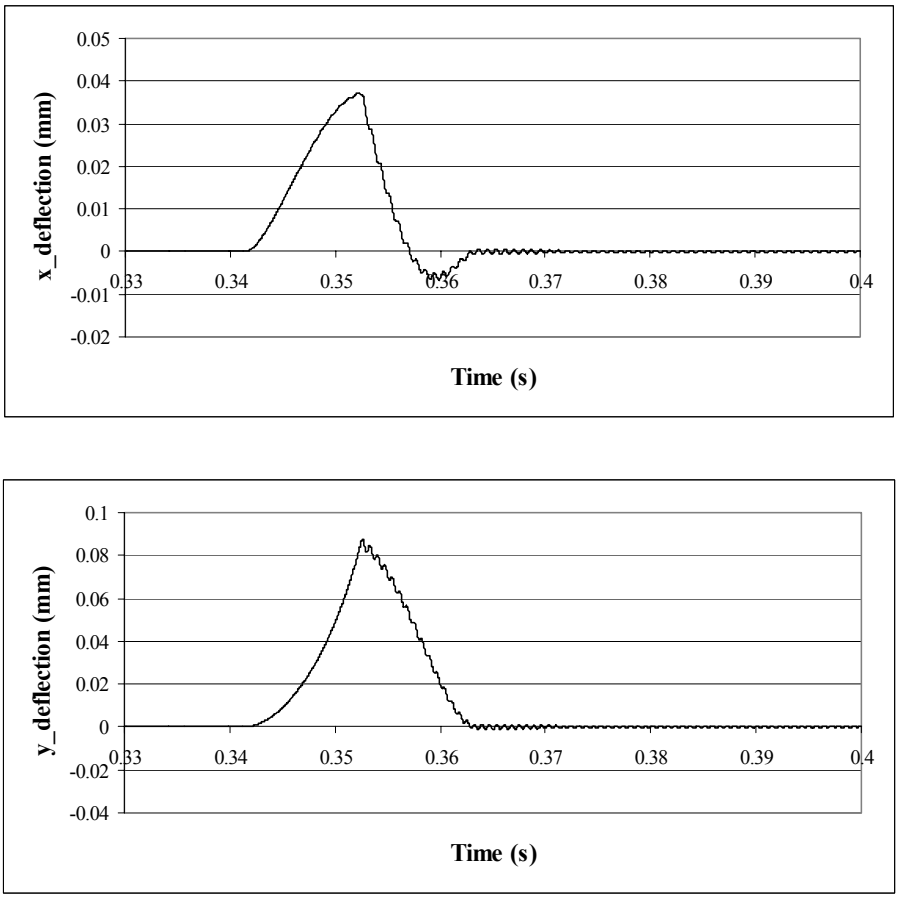

Figure 10. Detailed tool tip displacement calculated shown in Figure 9 for tenth path

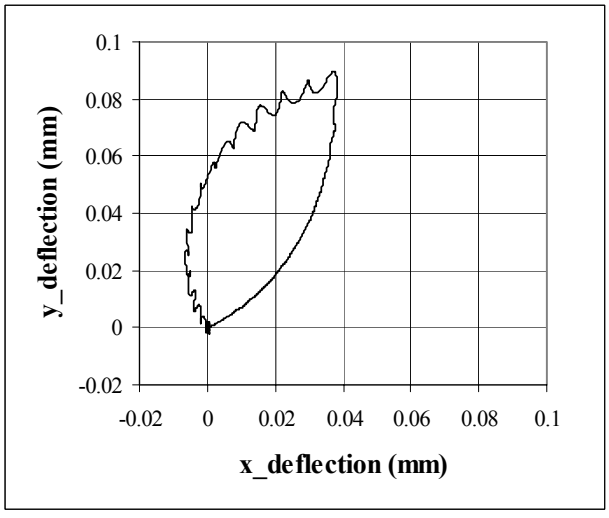

Figure 11. Detailed tool tip displacement in the forth cutter rotation from start of cutting on tenth path

Acknowledgments

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