A Simulation of Kinematic Deviations of Boring Processes on CNC Machining Centers

Wiroj THASANA¹, Atsushi TAKAHASHI¹, Arata YOSHIDA¹, Nobuhiro SUGIMURA¹, Yoshitaka TANIMIZU¹ and Koji IWAMURA¹
¹ Graduate School of Engineering, Osaka Prefecture University, Japan, wiroj@tni.ac.th

Abstract:
A simulation model is proposed in the paper to estimate and to verify the geometry deviations of the machined surfaces in the machining processes of CNC machining centers and single point tools. The model proposed here represents the boring processes based on both the shape generation motions and the cutting tool geometries. The individual motions are mathematically described by 4 by 4 transformation matrices including the kinematic motion deviations. Emphasis is given to the modeling and analysis of the machining process of the single point tools.

Keywords: Kinematic motion deviations, Geometric deviations, CNC Machining process simulations, Shape generation motions, Boring processes

1. Introduction
In present global competitions, machine industries are constantly exploring systematic methods to increase the quality and the reliability of their products and to decrease the annual expenditures on the machining operations. Machining processes are inherently complex, and lead to use empirical methods for process developments. In particular, process parameters such as machining speeds, feed rates and tooling are usually selected based on handbooks and trial-and-error prototyping. However, these methods do not guarantee the process parameters which satisfy the required quality.

Since the early 1990s, a paradigm shift in manufacturing from ‘real’ to ‘virtual’ production has resulted in a build-up of research interests in the simulation techniques. With the aid of computers, it becomes possible to simulate some of the activities of physical manufacturing systems. The main objective of the virtual productions is to understand and to emulate the behavior of the manufacturing systems on the computers prior to the physical productions, aiming at reducing the amount of testing and experiments on the shop floors. They are so called as virtual manufacturing, virtual machine tools, virtual machining, virtual assembly, virtual tooling and virtual prototyping [1]. Some simulation models for the machining processes have recently been purposed to predict the dimensions, geometries and geometric deviations of the machined parts, aiming at investigating the suitable machining process parameters [2-3]. However, the proposed models have been applied only to the limited areas of the machining processes.

The objective of the present research is to propose a simulation model of the machine tools and the machining processes, in order to estimate and to verify the geometric deviations of the machined faces in the machining processes of CNC machining centers and single point tools. The model proposed here represents the boring processes based on both the shape generation motions and the cutting tool geometries. The individual motions are mathematically described by 4 by 4 transformation matrices including the kinematic motion deviations. Emphasis is given to the modeling and analysis of the boring process of the single point tools.

2. Present Status of Shape Generation Process and Simulation Models
One of the most important revolutions in the later part of the last century is introduction of CNC machine tools, which are able to carry out various complicated machining processes without human interaction. Various types of CNC machine tools are now being designed and applied to machining processes of complicated machine products. The machining accuracy is one of the most important characteristics of the CNC machine tools for generating the products with the high accuracy and the complicated geometries. Some researchers have been carried out for the investigation of the machining processes based on the kinematic motion deviations between the tools and workpieces [4]. However, the research did not consider the rotational deviations of the spindles.

J.G. Li et al. [5] conducted a survey of the off-line optimization on CNC machining based on the virtual machining and also discussed about the machining error compensation. This research did not consider the machining process analysis, and did not discuss about the geometries of the inserted tools in accordance with the international tool geometry standards.

Recently, some models have been proposed for both the machine tools and the machining processes and applied to the analysis of such characteristics as geometric deviations, kinematics and dynamics of the machine tools and the machining processes. F.Atabey et al. [6] have proposed a model for the analysis of boring process mechanics, which provide a method to estimate the chip thickness distributions along the cutting edges, based on the tool inclination angles, nose radius, depth of cut and feed rate. The three dimensional cutting forces are also
estimated for the cases of the insert boring heads with run-out. M. Kaymakci et al. [7] has proposed a unified cutting force model for turning, boring, drilling and milling operations with the inserted tools. The inserted tips and their orientations to the reference tool coordinates are mathematically represented by following ISO tool definition standards. The friction forces acting on the rake faces are transformed into reference tool coordinates using the general transformation matrix. However, the proposed model did not deal with how the individual models are combined to obtain the final geometries of the machined parts, the geometric deviations in the boring process on CNC machining centers, and the surface generation in the virtual machining processes.

3. Kinematic Motions in Boring Processes

The boring processes on CNC machining centers are carried out by both the spindle rotations and the linear feed motion along Z-axis, therefore, the motion deviations of the spindle rotation is an important issue for evaluating the geometric deviations of bored holes.

Five Cartesian coordinate systems shown in Fig. 1 are set to represent the kinematic motion deviations. They are, $O_R$, $O_S$, $O_B$, $O_T$ and $O_E$ which represent the coordinate systems of the reference, spindles, boring bars, tool tips and cutting edges, respectively.

\[
X_R = A_{RS}A_{SB}A_{BT}A_{TE}X_E
\]  

(1)

where,

- $X_E$ : Position vector of a point on the cutting edge in the cutting edge coordinate system.
- $X_R$ : Position vector of the point on the cutting edge in the reference coordinate system.
- $A_{ij}$ : 4 by 4 homogeneous transformation matrices representing the relative positions and motions between pairs of rigid bodies.

The individual matrices include some kinematic and position deviations due to both the motion errors and the set-up errors, therefore, the kinematic motion deviations in the boring processes are discussed in the following section.

4. Kinematic Deviations in Boring Processes

4.1 Coordinate Systems and Deviation Parameters

The reference coordinate system $O_R$ is set according to ISO 230-1 [9-10], and the other coordinate systems are set as shown in Fig. 2.

![Coordinate systems for boring processes](image)

(1) The coordinate system $O_S$ of the spindle is fixed on the spindle and has four deviation parameters representing the position and orientation deviations of the average rotational axis of the spindle. They are, $\delta_x(C)$, $\delta_y(C)$, $\varepsilon_x$, and $\varepsilon_y$ which represent the positioning deviations in X- and Y-axis and the rotational deviations around X- and Y-axis.

(2) The coordinate system $O_B$ of the boring bar is fixed on the boring bar and the parameter $z_B$ gives the distance between $O_S$ and $O_B$ representing the length of the boring bar.

(3) The coordinate system $O_T$ of the tool tip is fixed on the tool tip and the parameter $R_T$ gives the distance between $O_B$ and $O_T$ representing the radial position of the tool tip against the boring bar axis.

(4) The coordinate system $O_E$ of the cutting edge is fixed on the cutting edge and the parameters $R_E$ and $Z_E$ gives the distance between $O_T$ and $O_E$ representing the shapes and the dimensions of the tool tip.
The following equation is obtained from Eq. (1) by applying the parameters mentioned above.

$$X_R = \mathbf{E}_{RS} \mathbf{A}^6( \theta ) \mathbf{A}^5(-z_B) \mathbf{A}^4( R_T ) \mathbf{A}^3(-z_E) \mathbf{A}^2( R_E ) \mathbf{X}_E$$

(2)

where,

$\mathbf{E}_{RS}$ : Geometric deviations of spindle against reference coordinate system

4.2 Formulation of Kinematic Motion Deviations in Boring Processes

(1) Spindle motion

The spindle motion is represented by the following equation.

$$\mathbf{A}_{RS\_actual} = \mathbf{E}_{RS} \mathbf{A}^6( \theta_z )$$

$$= \begin{bmatrix}
1 & 0 & \varepsilon_y & -\sin \theta_z & \cos \theta_z & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\cos \theta_z & -\sin \theta_z & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
0 & 1 & -\varepsilon_y & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
-\varepsilon_y & 1 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
0 & 0 & 0 & 1 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\cos \varepsilon_x & \cos \varepsilon_z & \varepsilon_x & \cos \theta_z & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\delta_{c_{21}} & \delta_{c_{22}} & \delta_{c_{31}} & \delta_{c_{32}} & \delta_{c_{33}} & \delta_{c_{34}} & \delta_{c_{35}}
\end{bmatrix}
$$

(3)

where,

$\varepsilon_x$ : Positioning deviation in X-axis

$\varepsilon_y$ : Positioning deviation in Y-axis

$\delta_z(C)$ : Rotational deviation around X-axis

$\delta_z(C)$ : Rotational deviation around Y-axis

$\theta_z$ : Rotational angle of spindle

$$\delta_{c_{21}} = \sin \varepsilon_x \sin \varepsilon_z \cos \theta_z + \cos \varepsilon_x \sin \theta_z$$

$$\delta_{c_{22}} = \cos \varepsilon_x \cos \theta_z - \sin \varepsilon_x \sin \varepsilon_z \sin \theta_z$$

$$\delta_{c_{31}} = -\cos \varepsilon_y \sin \varepsilon_x \sin \theta_z + \sin \varepsilon_y \sin \theta_z$$

$$\delta_{c_{32}} = \sin \varepsilon_y \sin \varepsilon_z \cos \theta_z + \cos \varepsilon_y \sin \theta_z$$

In many cases, the second-order of the deviations can be neglected, and Eq. (3) can be transformed into following formula [11].

$$\mathbf{A}_{RS\_actual} = \begin{bmatrix}
\cos \theta_z & -\sin \theta_z & \varepsilon_y & \delta_z(C)
\end{bmatrix}
\begin{bmatrix}
\sin \theta_z & \cos \theta_z & \varepsilon_x & \delta_x(C)
\end{bmatrix}
\begin{bmatrix}
\varepsilon_y \sin \theta_z - \varepsilon_x \cos \theta_z & \varepsilon_x \sin \theta_z + \varepsilon_y \sin \theta_z & 1 & 0
\end{bmatrix}
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
$$

(4)

(2) Boring bar motion

The motion of boring bar is represented by the following equation.

$$A_{BT\_actual} = \begin{bmatrix}
\cos \theta_z & -\sin \theta_z & \varepsilon_y & \delta_z(C)
\end{bmatrix}
\begin{bmatrix}
\sin \theta_z & \cos \theta_z & \varepsilon_x & \delta_x(C)
\end{bmatrix}
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
$$

(5)

where, $z_B$ is the length along the Z-axis

(3) Tool tip motion

The motion of the tool tips are represented by the following equation based on Eq. (5).

$$A_{BT\_actual} = \begin{bmatrix}
\cos \theta_z & -\sin \theta_z & \varepsilon_y & \delta_{a44}
\end{bmatrix}
\begin{bmatrix}
\sin \theta_z & \cos \theta_z & \varepsilon_x & \delta_{a43}
\end{bmatrix}
\begin{bmatrix}
\delta_{a31} & \delta_{a32} & \delta_{a33} & \delta_{a34}
\end{bmatrix}
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
$$

(6)

where,

$R_T$ : Radial position of tool tip

$$\delta_{a44} = \delta_{a44}(C) - R_T \sin \theta_z - \varepsilon_y, z_B$$

$$\delta_{a43} = \delta_{a43}(C) + R_T \cos \theta_z + \varepsilon_x, z_B$$

$$\delta_{a31} = \varepsilon_y \sin \theta_z - \varepsilon_x \sin \theta_z$$

$$\delta_{a32} = \varepsilon_x \sin \theta_z + \varepsilon_y \sin \theta_z$$

$$\delta_{a34} = -z_B + R_T ( \varepsilon_x \cos \theta_z + \varepsilon_y \sin \theta_z )$$

(4) Cutting edge in tool tips

There are various inserted tool tip geometries are used in the cutting tools and seventeen inserted tool tip shapes are defined in ISO 13399 standards [7]. The generalized geometric model of the inserted tools is shown in Fig. 3, which are presented starting with the placement of the tool tips on the cutter bodies, the identification of oblique tool angles needed in the cutting mechanics model and the kinematics of cutting operations. The geometry of the tool tips are defined in their local coordinate system $O_T$ analytically.

Figure 3: Tool tips and cutting edges
The control points are derived as functions of insert parameters that have been adapted from M. Kaymakci et al. [7]. The coordinates of the control points are given as follows based on the standardized tool tip geometries.

\[
\begin{align*}
\text{CRP}(x,y,z) &= (0,0,0) \\
\text{A}(x,y,z) &= (b_r + r_c(\cos\kappa_r - \csc\kappa_r), 0, 0) \\
\text{B}(x,y,z) &= (0, r_c(\cos\kappa_r - \csc\kappa_r), 0) \\
\text{O}_z(x,y,z) &= (0, r_c(\cos\kappa_r - \csc\kappa_r), r_c) \\
\text{D}(x,y,z) &= (0, r_c \cos\kappa_r \tan\kappa_r, 0, r_c(1 - \csc\kappa_r)) \\
\text{E}(x,y,z) &= (0, A_x + \frac{1}{2} (L \cos\kappa_r + iW \cos\epsilon_r + \kappa_r), \frac{1}{2} (L \sin\kappa_r + iW \sin\epsilon_r + \kappa_r) - 2 \csc\epsilon_r \sin(\epsilon_r - \kappa_r), \frac{1}{2} (L \sin\kappa_r + iW \sin\epsilon_r + \kappa_r) - 2 \csc\epsilon_r \sin(\epsilon_r - \kappa_r)) \\
\text{O}_y(x,y,z) &= ((0, A_y + \frac{1}{2} (L \cos\kappa_r + iW \cos\epsilon_r + \kappa_r), \frac{1}{2} (L \sin\kappa_r + iW \sin\epsilon_r + \kappa_r) - 2 \csc\epsilon_r \sin(\epsilon_r - \kappa_r)) \\
\times(b_r \sin\kappa_r - r_c(\cos\kappa_r - 1))) \\
\end{align*}
\]

where,

\begin{align*}
\text{CRP} & \quad : \text{Cutting reference point} \\
\text{A, B, D, E} & \quad : \text{Control points of cutting edge} \\
\epsilon_r & \quad : \text{Tool included (nose) angle} \\
iW & \quad : \text{Insert width} \\
L & \quad : \text{Insert length} \\
kappa_r & \quad : \text{Cutting edge angle of the insert} \\
b_r & \quad : \text{Wiper edge length} \\
r_c & \quad : \text{Corner radius}
\end{align*}

Therefore, the motions of the cutting edge in tool tips are represented by the following equation based on Eq. (7) and multiply with Eq. (6).

\[
\begin{align*}
\text{R}_z &= A_z + \frac{1}{2} (L \cos\kappa_r + iW \cos\epsilon_r + \kappa_r) - 2 \cos\epsilon_r + \frac{1}{2} (L \sin\kappa_r + iW \sin\epsilon_r + \kappa_r) - 2 \csc\epsilon_r \sin(\epsilon_r - \kappa_r)) \\
\times(b_r \sin\kappa_r - r_c(\cos\kappa_r - 1))) \\
\text{z}_E &= \frac{1}{2} (L \sin\kappa_r + iW \sin(\epsilon_r + \kappa_r) - 2 \csc\epsilon_r \sin(\epsilon_r - \kappa_r) \\
\times(b_r \sin\kappa_r - r_c(\cos\kappa_r - 1))) \\
\end{align*}
\]

\[
\begin{align*}
\text{A}_{TE, actual} &= \begin{bmatrix}
\cos\theta_r - \sin\theta_r & \epsilon_x & \delta_{314} & 1 & 0 & 0 & 0 \\
\sin\theta_r & \cos\theta_r & -\epsilon_x & \delta_{324} & 0 & 1 & 0 \\
\delta_{313} & \delta_{323} & 1 & \delta_{334} & 0 & 0 & 1 \\
0 & 0 & 0 & 1 & 0 & 0 & 1 
\end{bmatrix} \\
\end{align*}
\]

4.3 Kinematic Motion of Cutting Edge

The kinematic motions of the cutting edge against the reference coordinate system \(O_E\) are obtained by combining Eq. (2) to (8) and represented in the following equations including the kinematic deviations.
Figure 4: Flow chart for boring process simulation

Once the position of the cutting edge is obtained, the next step is to generate all points on the generated face of the workpiece. The cutting edge of a single point cutting tool has a nose radius, therefore, the contact points of the cutting edge and the workpiece can be described in the cross sectional plane represented by YZ-plane shown in Fig. 5. The critical tool angles are estimated for representing the extent of the tool nose, which generate the machined face. When the kinematic deviations are considered, the tool nose centers are no longer on a straight line, and the extents of the tool nose also changes continuously. Under these conditions, the discretized tool nose radius can then be represented and evaluated as shown in Fig. 6 [12].

\[
\begin{align*}
\phi_{ij} &= \cos^{-1}\left(\frac{P_{int-i} C_{i-1} \cdot C_{i-1} C_i}{P_{int-i} C_{i-1} C_{i-1}}\right) \\
\phi_{ij+1} &= \cos^{-1}\left(\frac{P_{int-i+1} C_{i+1} \cdot C_{i+1} C_i}{P_{int-i+1} C_{i+1} C_{i+1}}\right)
\end{align*}
\]

In triangle \(P_{int-i}, C_{i-1}, \) and \(C_i\), Eq. (10) is obtained.

At any given tool nose locations related to the angular orientation \(\theta\) of the spindle with respect to the reference orientation, the span of the tool contact angle between the start and end angle can be divided into as many divisions as required. The profile of the machined face can then be generated as a function of the final position of the tools considering all kinematic deviations, by applying the following equation.

\[
x = E_x \\
y = R_y + P_{int+i} (\cos \phi_j) \\
z = P_{int+i} (\sin \phi_j)
\]

where: \(x, y, z\) is the position of a point of the tool nose, \(R_y\) is the position of tool tip, and \(E_x\) is the geometric deviations of position in the X-axis.

The transformation from the YZ-plane to the appropriate orientation depending on the spindle angular orientation can be performed using the following transformation matrix.

\[
T = \begin{bmatrix}
\cos \theta_z & -\sin \theta_z & 0 & 0 \\
\sin \theta_z & \cos \theta_z & 0 & 0 \\
0 & 0 & 1 & F_i \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
\begin{bmatrix}
X_{surface} \\
Y_{surface} \\
Z_{surface}
\end{bmatrix} = \begin{bmatrix}
x \\
y \\
z
\end{bmatrix}
\]

\[
F_i = (f) \cdot \left(\frac{\theta}{2\pi}\right)
\]

where: \(X_{surface}, Y_{surface}, Z_{surface}\) represent the positions of a point on the machined face given by the point with \(x, y,\) and \(z\) and \(F_i\) is the feed rate per revolution

Figure 6 shows examples of the generated face. As shown in the figure, a set of the points on the machined face are generated and interpolated. The geometric deviations of any points on the machined face can be evaluated by comparing the generated face with the kinematic deviations and one without any deviations.

6. Conclusions

A simulation model for the boring processes is proposed to evaluate the geometric deviations of the generated faces. The followings are concluded.

(1) A model is proposed to represent the kinematic motions of the cutting edges against the reference coordinate systems of the spindle heads, taking into consideration of the kinematic deviations of the boring tool systems.

(2) A systematic method is proposed to estimate the geometric deviations of the machined face based on the kinematic motions of the cutting edges.
A proposed model and method are applied to the simulation of the simple boring process and the geometries of the machined face is estimated, based on the cutting conditions, the tool geometries and the kinematic deviations of the boring processes.

References


(a) Feed rate: 1 mm/rev; Tool nose radius: 1 mm; The position deviations are given randomly, normal distribution N(0, 10 µm); The orientation deviations are given randomly, normal distribution N(0, 1 µrad.)

(b) Feed rate: 1 mm/rev; Tool nose radius: 1 mm; The position deviations are given randomly, normal distribution N(0, 10 µm); The orientation deviations are given randomly, normal distribution N(0, 0.1 µrad.)

Figure 6: Estimated geometries of machined face including kinematic deviations of boring processes on CNC machining centers