METHODOLOGY TO DETERMINE KINEMATIC PARAMETERS FOR THE POSTPROCESSOR OF MULTI-AXIS CNC MILLING CENTER

ABSTRACT
Kinematic models for post processors have been developed for different multi-axis machining centers, but the actual values which define the kinematic model can be obtained by using expensive measurement equipment. A simple procedure can be developed to acquire these values. This paper proposes a methodology to determine tool compensation vector and rotational compensation vector for the post processor of multi-axis milling center. Paper propounds general procedure for developing a post processor, the interface between CAD/CAM systems and NC (Numerically Controlled) machines, for multi-axis CNC (Computer Numerical Control) milling centers. As an example, a post processor was developed using Siemens® NX- Post Builder commercial software for the five-axis CNC milling center- Fryer 5X with a FANUC series 18i-MB5 controller. Identified error sources could be corrected by modifying the kinematic model of the post processor.

Hence, implementation of this procedure for the development of a post processor would streamline the process of integrating CAM systems for multi-axis CNC milling centers. The integrated system is being used to support research and education projects to accurately and quickly produce parts.

1. INTRODUCTION
Multi-axis machining constitutes three translational axes and some rotation axes. Enhancing machine accuracy has been one of the main focuses of research on five-axis machine tools recently, but the simultaneous presence of linear axes and rotation axes in five-axis machine tools, and complex mathematical models resulting from the kinematic interactions, have made the application of related techniques difficult.[1,2]

The number of the axis of a CNC machine implies the number of degrees of freedom that the controller of the machine can be simultaneously interpolated. If the axis number increases, the machining efficiency, effectiveness and accuracy will increase; however, it requires more complex techniques in control programming process. [3].

Many people use different methods to research on post processor for five-axis machine tools. R.-S. Lee and C.-H. Lee presented analytical methodology to develop a post processor for three typical five-axis machine tools. According to the distribution of the rotational movement units, the five-axis machine tool can be classified into three basic types [4].

To measure error of machining center Double Ball Bar (DBB) and laser scanners are widely used in the industries. DBB is a quick measuring system to find out the accuracy of machine tools. The DBB measuring is good for single error origin or error origins having high amplitude. By the DBB method it was very difficult to separate angular error. Hence, offset error in rotation axes error and misalignment in the spindle is very difficult to measure by DBB method [5]. The error modeling technique is very useful in predicting the volumetric errors of CNC machine tools. Although the majority of motional errors in the error model are measurable with modern measurement devices, there are still some link errors that are non-measurable. These not measurable errors include constant link errors of rotary axes block, main spindle block, and tool holder [6]. Even though these methods provide highly accurate and precise data, investment and operational cost associated with these methods is high.

The paper aims to derive the analytical equations of NC code with compensation vectors for five-axis spindle-tilting type CNC milling machine. The methodology discussed in this paper would enable to determine kinematic parameters for the post-processor of multi-axis CNC milling center. Logical, simple and low cost approach of the method would be helpful post processor developers and machine operators.

2. DEVELOPMENT OF POST PROCESSOR
Post processor is an interface that links the CAM system and NC machines and it converts CL data to machine code [4]. It’s a translator that reads, interprets the manufacturing instructions given by CAM system and converts them into appropriate NC
code depending on the combination of machine and controller configuration. For the development of post processor, following three key elements are essential:

1. Kinematic Model of Machining center
2. Format of Cutter Location (CL) data
3. Post processing strategy

2.1 Kinematics Model
Extensive research has been carried out on developing a kinematic model multi-axis machining center with different approaches. R.-S. Lee and C.-H. She has developed the analytical equations for NC data for three typical five-axis machine tool configurations [4]. Based on their work for spindle-tilting/universal rotary head type configuration, the inverse kinematic transformation equations have been developed. The position vector is written as \([Q_x, Q_y, Q_z, 1]^T\) and the tool axis vector is of form \([K_x, K_y, K_z, 0]^T\). The superscript “T” denotes the transposed matrix. Figure (1) shows the geometric definition of CL data.

For the spindle tilting type configuration with rotational axes A & C, the pivot point is selected to be the intersection of these two axes. In case of this type of machines, pivot point is point where rotary head tilts. \(P_x, P_y, P_z\) are the relative translation distances in X, Y and Z respectively. The effective tool length, \(L_t\), is distance between pivot point R to cutter tip center \(O_c\). It can be calculated by,

\[L_t = L_{Ho} + L_{Lo}\]  

Where \(L_{Ho}\) and \(L_{Lo}\) are tool holder offset and tool length offset respectively. In more general terms, tool holder offset is pivot distance and tool length offset is gage length. Figure (2) shows coordinate system of spindle-tilting AC type configuration.

\[\begin{bmatrix} K_x, K_y, K_z, 0 \end{bmatrix}^T = T(P)R_z(\theta_z)R_y(\theta_y)\left[ \begin{array}{ccc} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{array} \right]^T \]  

\[\begin{bmatrix} Q_x, Q_y, Q_z, 1 \end{bmatrix}^T = T(P)R_z(\theta_z)R_y(\theta_y)\left[ \begin{array}{ccc} 0 & 0 & -1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{array} \right]^T \]  

\[\begin{bmatrix} X, Y, Z \end{bmatrix}^T = \left[ \begin{array}{ccc} P_x, P_y, P_z, -L_t, 1 \end{array} \right] \]  

Where,

\[T(P) = \begin{bmatrix} 1 & 0 & 0 & P_x \\ 0 & 1 & 0 & P_y \\ 0 & 0 & 1 & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \]

\[R_z(\theta_z) = \begin{bmatrix} \cos \theta_z & -\sin \theta_z & 0 & 0 \\ \sin \theta_z & \cos \theta_z & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \]

\[R_y(\theta_y) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \theta_y & -\sin \theta_y & 0 \\ 0 & \sin \theta_y & \cos \theta_y & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \]

Solving equations (2) – (4) gives,

\[A = \theta_z = \cos^{-1}(K_x)\]  
\[C = \theta_y = -\tan^{-1}(K_y/K_x)\]

\[X = P_x - L_t \sin \theta_z \sin \theta_c\]  
\[Y = P_y - L_t \sin \theta_z \cos \theta_c\]  
\[Z = P_z - L_t = Q_z + L_t \cos \theta_z - L_t\]
The key point for developing a post processor is the configuration of machine tools. Therefore, it is critical to set up standard machine tools configuration file. All parameters that needed in building kinematic model are defined in the configuration file [2]. The validity and effectiveness of the post processor depends on these parameters of kinematic model. Hence, exact information of these parameters and their accurate values are crucial.

2.2 Cutter Location (CL) Data
The model of part to be machined is designed in CAD/CAM software as surfaces. To increase the generality of part model, CL data are generated without considering the structure of multi-axis machine tools. The part is assumed to be fixed, and all motions are completed by the cutters. Different structures of multi-axis machines have the same CL data [6].

The cutter location data consists of the cutter position and orientation of the cutter with respect to the part coordinate system. In ISO format, the CL data is represented by (X, Y, Z, I, J, K) where (X, Y, Z) is coordinates of cutter location and (I, J, K) is direction cosines of the tool axis orientation correspondingly. Cutter position is defined as the cutter centre tip and not the cutter contact point. Hence, the CL point is a given point on the cutter [3]. Figure (3) shows CL data information.

![Figure 3: CL data information](image)

The CLSF (Cutter Location Source File) file is converted from the operations of CAM in UG software, which belongs to a ASCII file contained mainly coordinates of geometry and other auxiliary codes to operate machine tool, to explain the operation information [7]. The keywords of CL data are shown in Table 1.

<table>
<thead>
<tr>
<th>Keywords in CLSF</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOOL PATH</td>
<td>Tool path operation in CAM</td>
</tr>
<tr>
<td>TLDATA</td>
<td>Tool cutter information</td>
</tr>
<tr>
<td>MSYS</td>
<td>Machining coordinate system in CAM</td>
</tr>
<tr>
<td>PAINT</td>
<td>Color in verification in CAM</td>
</tr>
<tr>
<td>GOTO/X,Y,Z,I,J,K</td>
<td>Linear interpolation, X, Y, Z is the reference point of cutting tool, I, J, K is the spindle vector of the cutting tool</td>
</tr>
<tr>
<td>SPINDL</td>
<td>Spindle revolution</td>
</tr>
<tr>
<td>FEDRAT</td>
<td>Feed rate</td>
</tr>
<tr>
<td>RAPID</td>
<td>Move with the max. speed</td>
</tr>
<tr>
<td>$$</td>
<td>Comment statement</td>
</tr>
<tr>
<td>CIRCLE</td>
<td>Circle interpolation</td>
</tr>
</tbody>
</table>

Table 1: Keywords of CL data in UG system

2.3 Post Processing
The main functions of a post processor are (i) Understanding and interpreting the CL data generated by CAM software, (ii) Transformation of machine independent CL data (x, y, z, i, j, k) into machine dependent NC commands such as (X,Y,Z,A,B),(X,Y,Z,A,C) or (X,Y,Z,B,C) [4]. Most of the commercial CAM software provides CL data file in ISO format. This CL data file is saved as Cutter Location Source File (CLSF). Y.Y. Hsu and S.S. Wang have discussed the post processing method of UG/POST system in detail in [1].

In UG/POST system, CAM tool path data including tool tip position and tool axial direction are used to produce the CLSF. This is followed by applying a specific machine post processor to produce NC code corresponding to the positions of machine axes according to different machine structure and controller. This study adopted to develop a postprocessor with the function of error compensation. The flowchart for establishing the compensation mechanism is shown in Fig. (4). The postprocessor employed in UG/POST is semi-open structure and the development program language is Tool Command Language (TCL). The core technology of UG/POST is the use of manufacturing output manager (MOM) as a driving tool for events, whose functions include reading tool path data, conducting kinematics transformation, and loading event handler and definition file. Therefore, the present study installed the compensation model in the event handler obtained the tool compensation and rotational compensation vector Vs, describing the tool path of CAM system through MOM, and translated the tool pose vector to the position vector, Us, in the machine axes coordinates with the inverse kinematic transformation [1].

3. ERROR COMPENSATION MODEL
Equations (5)-(9) give the theoretical machine dependent coordinates. The actual coordinates vary because of the tool length compensation vector for each axis. Tool length compensation for Z axis has been already taken care by controller.

Tool length compensation for X and Y axis must be calculated for accurate NC program. If the rotational axes are not perpendicular to each other, then there exists rotation around an arbitrary axis in the space; the dot product of orthogonal axis is not zero [5]. $\vec{a} \cdot \vec{c} = 0$ is assumed. Hence,
angular compensation of rotary axis is negligible. The following derivations give the actual machine dependent coordinates. Equations (2)-(4) can be written as,

\[
\begin{align*}
X &= P_x = Q_x + \cos \theta_c(t_x + J_x) + \sin \theta_c[t_x + t, \cos \theta_t \sin \theta_t(t_z - L_z)] \\
Y &= P_y = Q_y \sin \theta_c(t_y + J_y) - \cos \theta_c[t_y + t, \cos \theta_t \sin \theta_t(t_z - L_z)] \\
Z &= P_z \cdot L_z = Q_z + J_z \cdot t \sin \theta_a - \cos \theta_a(t_z - L_z) - L_z
\end{align*}
\]

Comparing Equations (15)-(17) with (7)-(9), offsets in X, Y and Z will be,

\[
\begin{align*}
X_{\text{offset}} &= -\cos \theta_c(t_x + J_x) + \sin \theta_c[t_x + t, \cos \theta_t \sin \theta_t] \\
Y_{\text{offset}} &= -\sin \theta_c(t_y + J_y) - \cos \theta_c[t_y + t, \cos \theta_t \sin \theta_t] \\
Z_{\text{offset}} &= J_z \cdot t \sin \theta_a - \cos \theta_a
\end{align*}
\]

Now for a machine under consideration, as \( \hat{a} \) and \( \hat{c} \) are assumed it to be orthogonal, \( \hat{a} \times \hat{c} \) will have component in Y axis. Hence, rotational compensation will have only \( J_y \). Also, machine controller itself calculates tool compensation in Z direction. Hence \( t_z \) will be zero.

### 4. EXPERIMENTAL IMPLEMENTATION

#### 4.1 Experimental Plan

Based on the analysis done in previous section, experiments were carried out. The objective of experiments is to determine the numerical value of rotational compensation vector and tool axis compensation vector for spindle-tilting five-axis CNC milling machine Fryer-5X 45. Experiments consist of simple machining of wax block with different combinations of \( A \) and \( C \) axis along both X and Y axis. The sequence of the cutting operation is shown in table (2) and (3) along with corresponding expressions for \( X_{\text{offset}} \) and \( Y_{\text{offset}} \) derived in above section.

<table>
<thead>
<tr>
<th>( \theta_C )</th>
<th>0°</th>
<th>90°</th>
<th>180°</th>
<th>-90°</th>
<th>-180°</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \hat{X}_{\text{offset}} )</td>
<td>( -t_x )</td>
<td>( (J_y + t_y) )</td>
<td>( t_x )</td>
<td>( -(J_y + t_y) )</td>
<td>( t_x )</td>
</tr>
<tr>
<td>( \hat{Y}_{\text{offset}} )</td>
<td>( -(J_y + t_y) )</td>
<td>( -t_x )</td>
<td>( (J_y + t_y) )</td>
<td>( t_x )</td>
<td>( (J_y + t_y) )</td>
</tr>
</tbody>
</table>

Table 2: Expressions for \( X_{\text{offset}} \) and \( Y_{\text{offset}} \) when \( \theta_A = 0 \)

<table>
<thead>
<tr>
<th>( \theta_A )</th>
<th>0°</th>
<th>90°</th>
<th>-90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \hat{X}_{\text{offset}} )</td>
<td>( -t_x )</td>
<td>( -t_x )</td>
<td>( -t_x )</td>
</tr>
<tr>
<td>( \hat{Y}_{\text{offset}} )</td>
<td>( (J_y + t_y) )</td>
<td>( -J_y )</td>
<td>( -J_y )</td>
</tr>
</tbody>
</table>

Table 3: Expressions for \( X_{\text{offset}} \) and \( Y_{\text{offset}} \) when \( \theta_C = 0 \)

Figure (5) shows the deviation associated with the reference cut \( \theta_C = 0^\circ \) \( \theta_A = 0^\circ \) and measured cut. Hence from figure,

\[
L = D = 2r + \delta_2 - \delta_1.
\]
Figure (5): Deviation associated with the reference cut $\theta_c=0^\circ$ $\theta_A=0^\circ$ and measured cut

Where,

- $L =$ Thickness of uncut portion;
- $R =$ Radius of tool

$\delta_1 =$ deviation with reference cut $\theta_c=0^\circ$ $\theta_A=0^\circ$

$\delta_2 =$ deviation with following cut

During the experiment $D$ is kept constant. $D=0.5"$. Radius of tool is 0.125" and $(\delta_2 - \delta_1)$ gives total deviation from original value of $L$ along the measured direction. With different combinations of $\theta_c$ and $\theta_A$, the table (4) gives the deviation in $X$ and $Y$ axis.

<table>
<thead>
<tr>
<th>Combination of $\theta_A$ &amp; $\theta_c$</th>
<th>Deviation along $X$ axis</th>
<th>Deviation along $Y$ axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_c=0^\circ$ $\theta_A=0^\circ$</td>
<td>$\delta_x$</td>
<td>$\delta_y$</td>
</tr>
<tr>
<td>$\theta_c=90^\circ$ $\theta_A=0^\circ$</td>
<td>$(-)\delta_y$</td>
<td>$\delta_x$</td>
</tr>
<tr>
<td>$\theta_c=180^\circ$ $\theta_A=0^\circ$</td>
<td>$(-)\delta_x$</td>
<td>$(-)\delta_y$</td>
</tr>
<tr>
<td>$\theta_c=-(90^\circ)$ $\theta_A=0^\circ$</td>
<td>$\delta_y$</td>
<td>$(-)\delta_x$</td>
</tr>
<tr>
<td>$\theta_c=-(180^\circ)$ $\theta_A=0^\circ$</td>
<td>$(-)\delta_x$</td>
<td>$(-)\delta_y$</td>
</tr>
</tbody>
</table>

Table 4: Deviation in $X$ and $Y$ axis for different $\theta_c$ and $\theta_A$

Later, different parts were machined to check the validity and effectiveness of post processor developed in UG system-Post Builder. Figure (6) shows actual machining on 5-axis CNC milling center.

4.2 Experimental Setup

Experiments were carried out on spindle-tilting 5-axis CNC milling center -Fryer 5X-45 with A and C as rotational axis. Following are the specifications of machine:

- X Travel = 45"
- Y Travel = 25"
- Z Travel = 25"
- Rotational axis limits: A = +/- 150°; C = +/- 213°
- Positioning accuracy: +/- 0.0002"

The part was machined along both X and Y directions as shown in Fig.(6) Experiments were conducted with following machining parameters:

- Workpiece Material: Wax
- Tool: 0.25" Flat end mill
- Spindle speed: 1000 RPM and Feed rate: 60 IPM

5. RESULT AND DISCUSSIONS

High speed, High accuracy Keyence LK G-5000 Series laser displacement sensor was used for the measurement of the machined part. It has repeatability of 0.005µm, accuracy of 0.02%. Figure (7) shows measurements taken by laser displacement sensor. Using the expressions discussed in the previous section and measurements taken, values of $t_x$, $t_y$ and $J_y$ were found out.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_x$</td>
<td>0.02469&quot;</td>
<td>0.00890</td>
</tr>
<tr>
<td>$t_y$</td>
<td>-0.09364&quot;</td>
<td>0.00083</td>
</tr>
<tr>
<td>$J_y$</td>
<td>-0.00405&quot;</td>
<td>0.00346</td>
</tr>
</tbody>
</table>

Table 5: Values of $t_x$, $t_y$ and $J_y$
For the Fryer 5X-45, the tool axis compensation vector and rotation center compensation vector are:

\[[t]^T = [0.02469 -0.09364 0]\] and \[[J]^T = [0. -0.00405 0]\]

Hence, this proves that there exists error that kinematic model of FANUC controller does not take into account. Error of 0.0008” was found with the measured cut of \(\theta_c=0^\circ\ \theta_A=0^\circ\). Ideally this should be zero.

**6. CONCLUSIONS**

The paper presents an alternative method to double ball test, R-Tests and laser scanner for obtaining kinematics parameters of CNC multi-axis machining center. The methodology for determining kinematics parameters of tool compensation vector for post processor has been developed successfully. First of all, the analytical equations of NC code were presented for spindle tilting type of five-axis machining center. Secondly, analytical equations with compensation vectors were obtained and the experiments were carried out to obtain these vectors. In addition, post processor for 5-axis CNC milling machine -Fryer 5X-45 with FANUC Series18i-MB5 controller has been developed in UG system –Post Builder. The same procedure can be used for other CNC machining systems of which the structure, kinematics parameters of machine and controller configuration is the same with Fryer 5X-45.

**7. FUTURE WORK**

A further extension of the research work includes the application of same methodology to other types of five-axis CNC milling centers – table tilting with two rotations on the table type and table/ spindle tilting with one rotation each on the table and spindle type. Based on the further analysis of kinematic parameters, generalized kinematics model (with compensation vectors) of multi-axis machining centers can be developed. Future work also includes use of higher fidelity measurement system for experimental data measurement and use of other test material such as aluminum. This will enable to obtain accurate and precise compensation vectors. Moreover, authors have planned to use the same technique to determine kinematics parameters for industrial robot IRB-6000. The error compensation can also be developed for same robot using same principle.

**8. ACKNOWLEDGEMENTS**

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**9. REFERENCES**


