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Developing a General Postprocessor for Multi-Axis CNC Milling Centers

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ABSTRACT

Most of the current college design and manufacturing curricula are primarily focused on computer aided design (CAD), while less emphasis is given to computer aided manufacturing (CAM). A great opportunity has been missed as the benefits of CAD/CAM cannot then be fully learned. This paper proposes a 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. The strategy comprises a systematic methodology of using CL data information for developing a machine specific code. 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. The developed post processor was validated by manufacturing five axes parts and by using different CAM tool paths. 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.

Keywords: computer aided manufacturing, post-processor, error compensation.
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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 researchers use different methods to investigate on post processor for five- axis machine tools. Lee [4] 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.

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 errors. 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, the following three key elements are essential: 1) Post- processing based on Cutter Location (CL) data; 2) Kinematic model of machining center; and 3) Error compensation. These elements are discussed below.

2.1 Post-processing Based on Cutter Location (CL) data

The model of the 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 center tip and not the cutter contact point. Hence, the CL point is a given point on the cutter [3]. Fig. 1 shows CL and CC (cutter contact) data information.

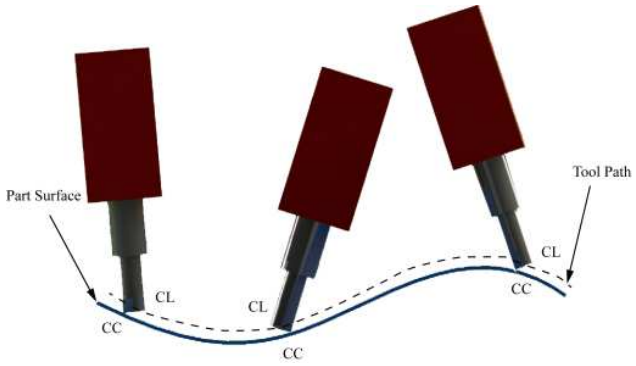


Fig. 1: The representation of Cutter contact (CC) points and cutter location (CL) points on part surface.

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.

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

Tab. 1: Keywords of CL data in NX/UG system.

For illustration purpose, NX is used as an example. After a CAD model is created, and the raw material shape and size have been defined, we are set to model the part in the Manufacturing module by [12]

Select START → MANUFACTURING

The primary use of the *manufacturing* module is to generate tool paths in order to manufacture parts. Within the *manufacturing* module, tools, tool paths, tool parameters (e.g., tool geometry), cutting parameters (e.g., spindle speed, feed rate), need to be defined. One can also validate the defined parameters by simulate the cutter tool path. After validation, it is ready to output the data. Generally, we cannot just send an unmodified tool path file to a machine and start cutting because there are many different types of machines. Each type of machine has unique hardware capabilities, requirements and control systems. There are two steps involved in generating the final post-processed tool path: 1) Create the tool path data file; 2) Post process the CLSF into Machine CNC code (Post processed file). This program reads the tool path data and reformats it for use with a particular machine and its accompanying controller. The CLSF file can be created in NX by:

Click TOOLS → OPERATION NAVIGATOR → OUTPUT → CLSF (XXX.cls)

Postprocessor is a program that reads the tool path data and reformats it for particular machine and its accompanying controller. 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). Hsu and Wang [1] have discussed the post processing method of UG/POST system in detail. One can click on a program in the Operation Navigator in NX to define post processor.

Click TOOLS → OPERATION NAVIGATOR → OUTPUT → NX POSTPROCESSING

Within NX post processor, the machine parameters related to specific machine, such as machine travel limits, rotational axis limits, maximum feed rate, machine configuration, as well as associated controller specifications, such as operation start sequence, definition of G-code and M-code, program end sequence, word sequencing, etc. can be defined. Once a machine specific post processor is defined, it can convert the CLSF file and output the machine codes for the specific machine.

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 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, describing the tool path of CAM system through MOM, and translated the tool pose vector to the position vector, in the machine axes coordinates with the inverse kinematic transformation [1].

2.2 Kinematic Model of Machining Center

In order to handle error compensation, kinematic model of machining center is needed. Extensive research has been carried out on developing a kinematic model multi-axis machining center with different approaches. Based on the previous work [4] 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. Fig. 2 shows the geometric definition of CL data.

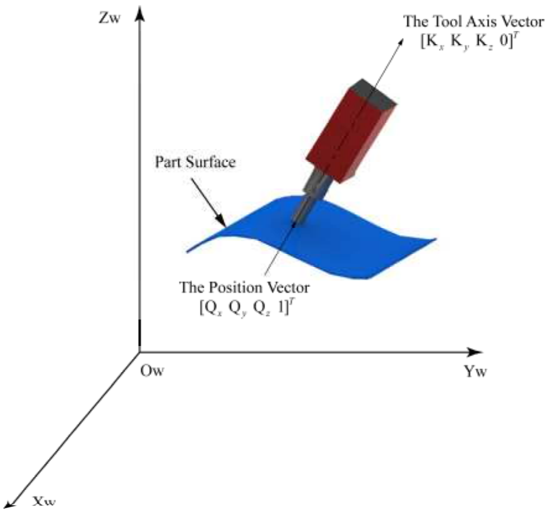


Fig. 2: Geometric definition of Cutter Location (CL) data in workpiece coordinate system, the position vector is $[Q_x\ Q_y\ Q_z\ 1]^T$ and the tool axis vector is $[K_x\ K_y\ K_z\ 0]^T$

For the spindle tilting type configuration with rotational axes A and C, the pivot point is selected to be the intersection of these two axes as shown in Fig 3. 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_t. It can be calculated by,

$$L_t = L_{HO} + L_{LO} \tag{1}$$

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. Fig. 3 shows coordinate system of spindle- tilting AC type configuration.

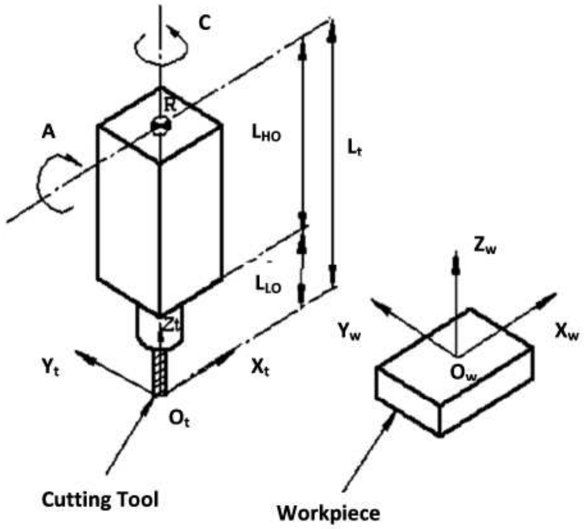


Fig. 3: Coordinate system of spindle- tilting AC type configuration.

The inverse kinematics transformations are given by,

$$[K_x K_y K_z 0]^T = T(P)R_z(\theta_C)R_x(\theta_A)[0 0 1 0]^T \quad (2)$$

$$[Q_x Q_y Q_z 1]^T = T(P)R_z(\theta_C)R_x(\theta_A)[0 0 -L_t 0]^T \quad (3)$$

$$[X\ Y\ Z\ 1]^T = [P_x\ P_y\ P_z - L_t\ 1] \quad (4)$$

Where,

$$T(P) = \begin{bmatrix} 1 & 0 & 0 & Px \\ 0 & 1 & 0 & Py \\ 0 & 0 & 1 & Pz \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R_z(\theta_C) = \begin{bmatrix} cos\theta_C & -sin\theta_C & 0 & 0 \\ sin\theta_C & cos\theta_C & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R_x(\theta_A) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & cos\theta_A & -sin\theta_A & 0 \\ 0 & sin\theta_A & cos\theta_A & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Solving Equations (2) - (4) gives,

$$A = \theta_A = \cos^{-1}(K_z) \quad (5)$$

$$C = \theta_C = -\tan^{-1}(K_x/K_y) \quad (6)$$

$$X = P_x = Q_x + L_t \sin\theta_A \sin\theta_C \quad (7)$$

$$Y = P_y = Q_x - L_t \sin\theta_A \cos\theta_C \quad (8)$$

$$Z = P_z - L_t = Q_z + L_t \cos\theta_A - L_t \quad (9)$$

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.

2.3 Error Compensation

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 of by the 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]. $\hat{a} \cdot \hat{c} = 0$ 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,

$$[K_x K_y K_z 0]^T = T(P)R_z(\theta_C)\,T(J)R_x(\theta_A)T(T)[0\ 0\ 1\ 0]^T \quad (10)$$

$$[Q_x Q_y Q_z 1]^T = T(P)R_z(\theta_C)\,T(J)R_x(\theta_A)T(T)[0\ 0\ \text{-}L_t 0]^T \quad (11)$$

$$[X\ Y\ Z\ 1]^T = [P_x\ P_y\ P_z\text{-}L_t\ 1] \quad (12)$$

where:
Tool axis compensation vector is $[t]^T = [t_x\ t_y\ t_z\ 1]^T$
Rotation center compensation vector is $[J]^T = [J_x\ J_y\ J_z\ 1]^T$
Equations (10)-(12) gives,

$$A = \theta_A = \cos^{-1}(K_z) \quad (13)$$

$$C = \theta_C = -\tan^{-1}(K_x/K_y) \quad (14)$$

$$X = P_x = Q_x - \cos\theta_C(t_x + J_x) + \sin\theta_C\left[J_y + t_y\cos\theta_A - \sin\theta_A(t_z - L_t)\right] \quad (15)$$

$$Y = P_y = Q_x - \sin\theta_C(t_x + J_x) - \cos\theta_C\left[J_y + t_y\cos\theta_A - \sin\theta_A(t_z - L_t)\right] \quad (16)$$

$$Z = P_z - L_t = Q_z + J_z - t_y\sin\theta_A - \cos\theta_A(t_z - L_t) - L_t \quad (17)$$

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

$$X_{offset} = -\cos\theta_C(t_x + J_x) + \sin\theta_C[J_y + t_y\cos\theta_A - t_z\sin\theta_A] \quad (18)$$

$$Y_{offset} = -\sin\theta_C(t_x + J_x) - \cos\theta_C[J_y + t_y\cos\theta_A - t_z\sin\theta_A] \quad (19)$$

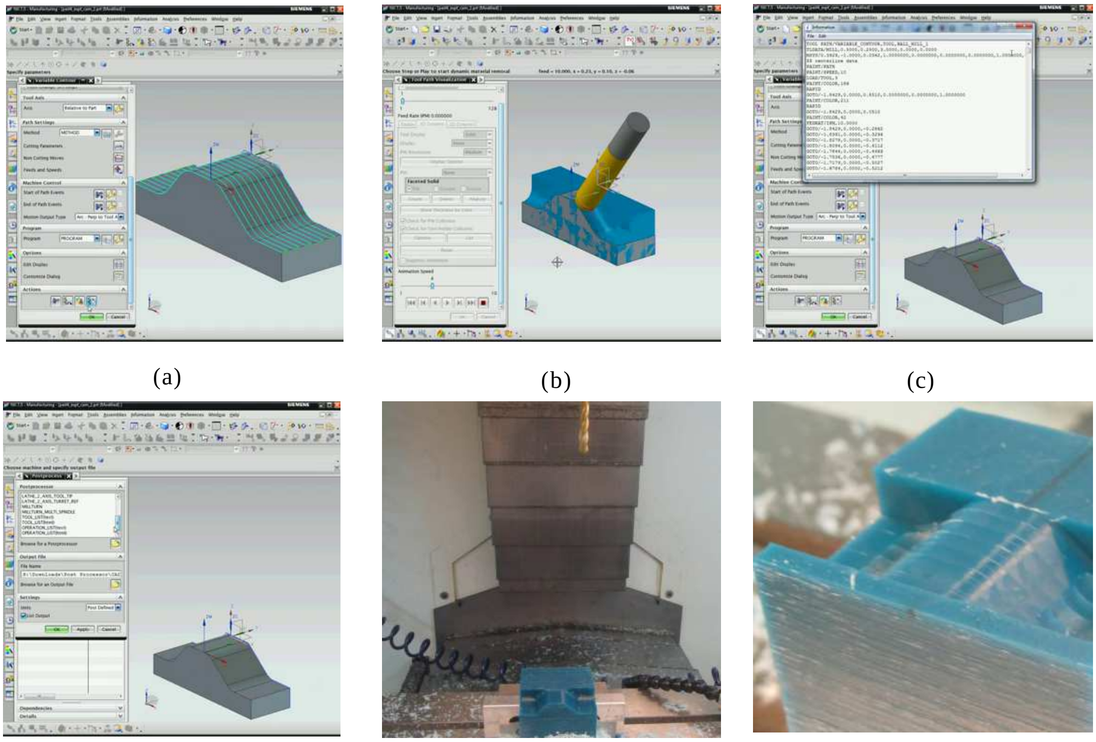
$$Z_{offset} = J_z - t_y\sin\theta_A - t_z\cos\theta_A \quad (20)$$

Now for a machine under consideration, if â and ĉ are assumed it to be orthogonal, â x ĉ will have component in Y axis. Hence, rotational compensation will have only J_y i.e. J_x and J_z will be zero. Also, machine controller itself calculates tool compensation in Z direction. Hence t_z will be zero. It is also possible to compensate the situation when â and ĉ are not orthogonal, but it will involve more experiments to obtain all 6 compensation variables (t_x, t_y, t_z, J_x, J_y, J_z).

3 EXPERIMENTAL IMPLEMENTATION

3.1 Machining Using 5-axis Machining Center

The first step in the experiment is to actually cut the part by following the post-processing procedure discussed in Section 2.1. Fig. 4 shows some screen shots of the procedure. Figure 5 shows the machining of a semi-sphere. The parts are pretty accurate, but this paper would explore more accurate procedure as discussed in the following section.



(a) (b) (c)

(d) (e) (f)

Fig. 4: Using NX Post processor to output CNC code to drive Fryer 5X machining center: (a) Tool path planned on the CAD model; (b) Validation by simulation of tool path; (c) CLSF file generated; (d) Post-processing for Fryer 5X; (e) Machining using Fryer 5X; (f) Close-up of the Wax part.

Fig. 5: Using NX Post processor to drive Fryer 5X machining center to make a wax part.

3.2 Experimental Plan for Error Compensation

Based on the analysis in Section 2.2 and 2.3, experiments for error compensation were designed and 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. The objective is to use simple cutting operations to decouple and find the variables in the compensation vectors. For illustration purpose, $\hat{a}$ and $\hat{c}$ are assumed it to be orthogonal and machine controller itself calculates tool compensation in Z direction, thus t_z, J_x and J_z will be zero. This assumption is that the mounting of two rotational axes is according to the specifications. The experiment designs consist of simple machining of wax block with different combinations of A and C axis along both X and Y axis. Wax was chosen so that we can assume that there is no tool wear during experiment to concentrate on the machine axis errors. The sequence of the cutting operation is shown in Tables 2 and 3 along with corresponding expressions for X_{offset} and Y_{offset} derived in the above section.

θ_C	0°	90°	180°	-90°	-180°
X_{offset}	$-t_x$	(J_y+t_y)	t_x	$-(J_y+t_y)$	t_x
Y_{offset}	$-(J_y+t_y)$	$-t_x$	(J_y+t_y)	t_x	(J_y+t_y)

Tab. 2: Expressions for X_{offset} and Y_{offset} when $\theta_A = 0$.

θ_A	0°	90°	-90°
X_{offset}	$-t_x$	$-t_x$	$-t_x$
Y_{offset}	(J_y+t_y)	$-J_y$	$-J_y$

Tab. 3: Expressions for X_{offset} and Y_{offset} when $\theta_C = 0$.

Fig. 6 shows the deviation associated with the reference cut $\theta_C = 0^\circ$ $\theta_A = 0^\circ$ and measured machining of wax block. It is designed so that we can use two simple cuts to find the errors and necessarily compensation factors of the CNC machine. The errors (or deviations) can be easily measured through the dimension of L as shown in Fig. 6:

$$L = D - 2r + \delta_2 - \delta_1. \tag{21}$$

where:

L= Thickness of uncut portion;

r= Radius of tool

δ_1= deviation with reference cut $\theta_C = 0^\circ$ $\theta_A = 0^\circ$

δ_2= deviation with following cut $\theta_C = 0^\circ$ $\theta_A = 0^\circ$

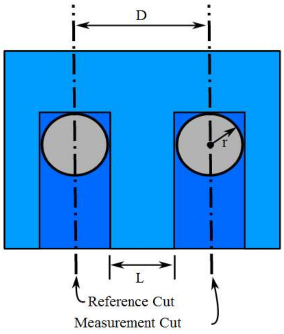


Fig. 6: Deviation associated with the reference cut $\theta_C = 0^\circ$ $\theta_A = 0^\circ$ and measured cut.

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. In other words, by measuring L at various points, the deviations in x and y directions, δ_x and δ_y, can be obtained. Similarly, with different combinations of θ_C and θ_A, the Table 4 gives the deviations in X and Y axis.

Combination of θ_A & θ_C	***Deviation along X axis***	***Deviation along Y axis***
$\theta_C=0^o$ $\theta_A=0^o$	δ_x	δ_y
$\theta_C=90^o$ $\theta_A=0^o$	$(-)\delta_y$	δ_x
$\theta_C=180^o$ $\theta_A=0^o$	$(-)\delta_x$	$(-)\delta_y$
$\theta_C=(-)90^o$ $\theta_A=0^o$	δ_y	$(-)\delta_x$
$\theta_C=(-)180^o$ $\theta_A=0^o$	$(-)\delta_x$	$(-)\delta_y$

Tab. 4: Deviation in X and Y axis for different θ_C and θ_A

Later, different parts were machined to check the validity and effectiveness of post processor developed in UG system- Post Builder. Fig. 7 shows actual machining on 5- axis CNC milling center

3.3 Experimental Setup

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

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

The part was machined along both X and Y directions as shown in Fig. 7. Experiments were conducted with the following machining parameters:

Workpiece Material: Wax;
Tool: 0.25” Flat end mill
Spindle speed: 1000 rpm
Feed rate: 60 ipm

Fig. 7: Actual machining on 5- axis CNC milling center.

The dimension of L of the machined part in Figure 6 was measured using high-speed, high-accuracy Keyence LK G-5000 Series laser displacement sensor. The sensor has repeatability of 0.005μm, accuracy of 0.02%. Fig. 8 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. Using the compensation algorithm, the improvement is about 10% better than the original capability.

Fig. 8: Measurements taken by laser displacement sensor.

4 CONCLUSIONS

Post processor for 5-axis CNC milling machine - Fryer 5X-45 with FANUC Series18i-MB5 controller has been demonstrated in NX/UG system – Post Builder. Postprocessor reads the tool path data and reformats it for Fryer 5X-45 with FANUC Series18i-MB5 controller. The post processor interpreted the CL data generated by NX CAM software, and then transformed the machine independent CL data into machine dependent NC commands. Actual parts were fabricated using the multi-axis capability of Fryer 5X-45. The paper also 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 obtain these vectors. In addition, the post processor for 5-axis CNC milling machine - Fryer 5X-45 with FANUC Series18i-MB5 controller have been developed in NX/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.

5 ACKNOWLEDGEMENTS

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