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Development of practical postprocessor for 5-axis machine tool with non-orthogonal rotary axes

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Abstract: In order to develop a practical postprocessor for 5-axis machine tool, the general equations of numerically controlled (NC) data for 5-axis configurations with non-orthogonal rotary axes were exactly expressed by the inverse kinematics, and a windows- based postprocessor written with Visual Basic was developed according to the proposed algorithm. The developed postprocessor is a general system suitable for all kinds of 5-axis machines with orthogonal and non-orthogonal rotary axes. Through implementation of the developed postprocessor and verification by a cutting simulation and machining experiment, the effectiveness of the proposed algorithm is confirmed. Compatibility is improved by allowing exchange of data formats such as rotational total center position (RTCP) controlled NC data, vector post NC data, and program object file (POF) cutter location (CL) data, and convenience is increased by adding the function of work-piece origin offset. Consequently, a practical post-processor for 5-axis machining is developed.

Key words: post-processor; 5-axis machining; non-orthogonal rotary axes; numerically controlled (NC) data; CL data

1 Introduction

Since a 5-axis machine tool has two rotary axes, it offers numerous advantages, including expansion of the machining field by rotating the cutter to the suitable position and posture, as well as reducing the cutter length and the set-up process. So, it is widely used in machining of mechanical parts such as turbine blades [1−3], impellers [4], aircraft parts [5], molds and dies [6]. However, there are also some notable problems, including complicated motion in each axis and the introduction of various kinematics models as a result of adding two rotary axes. Moreover, special kinematics models with non-orthogonal rotary axes as well as typical kinematics models with orthogonal rotary axes have recently been introduced. Typical kinematics models have two rotational axes that are orthogonal to the machine coordinate system, while special kinematics models have two rotational axes that are non-orthogonal to the machine coordinate system. Compared with the typical kinematics models, these special kinematics models are very flexible in spite of their compact configuration. The postprocessor is an important interface. Its role is to change the cutter location (CL) data, including the cutter position vector and cutter posture vector, to numerically controlled (NC) data.

LEE and SHE [7], JUNG et al [8], TUTUNEA-FATAN and FENG [9], and TOURNIER et al [10] presented postprocessors for 5-axis machine tools with orthogonal rotary axes. However, few works have focused on obtaining inverse kinematics solutions for 5-axis machine tools with non-orthogonal rotary axes. HAN and ZHAO [11], HAN et al [12], OH et al [13] and KNUT [14] proposed the inverse kinematics of a 5-axis machine tool that has a rotary table with only one non-orthogonal rotary axis. SHE and CHANG [15] proposed the inverse kinematics of a 5-axis machine tool that has a tilting head with only one non-orthogonal rotary axis. However, the general inverse kinematics of a 5-axis machine tool with two non-orthogonal rotary axes including a tilting axis and a rotating axis were not investigated in the aforementioned studies.

The authors in this study extended the work presented by the authors in Refs.[7−10] and developed a general postprocessor system suitable for all kinds of 5-axis machine tools, not only with orthogonal rotary axes but also with non-orthogonal rotary axes. Thereby, the range of application of the developed postprocessor was extended. To verify the precision of the developed postprocessor, a designed test-piece was machined on a 5-axis machine tool and then measured on a coordinate measuring machine (CMM). In addition, compatibility of the postprocessor was improved by allowing the exchange of data formats such as rotational total center position (RTCP) controlled NC data, vector post NC data, and program object file (POF) cutter location (CL) data, and convenience was enhanced by adding the function of work-piece origin offset.

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2 Postprocessor of 5-axis machine with non-orthogonal rotary axes

2.1 Configuration of 5-axis machine with non-orthogonal rotary axes

The configuration of a 5-axis machine with non-orthogonal rotary axes is shown in Fig.1, where θ and ϕ are variables. A special feature of the configuration is that the rotary axes including a rotating axis C and a tilting axis B are non-orthogonal.

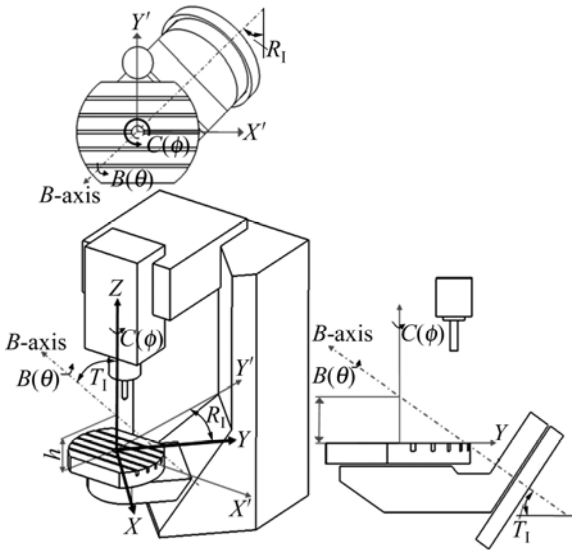

Fig.1 Configuration of 5-axis machine with non-orthogonal rotary axes

The rotating axis C is obtained by rotating the Y-axis at an angle $R_{\rm I}$ around the Z-axis, and the tilting axis B is obtained by rotating the Z-axis at an angle $T_{\rm I}$ around the X'-axis. The center axis of the two rotary axes crosses in a point at a vertical distance, h, from the coordinate frame $X'Y'Z$.

2.2 Inverse kinematics for determining rotary motions

The schematic diagram in Fig.2 illustrates the process matching the cutter posture vector $\boldsymbol{V}$ and the spindle axis vector $\boldsymbol{Z}$. In order to achieve every cutter orientation perpendicular to the surface of the half of a sphere by using the B and C axes, the cutter posture vector $\boldsymbol{V}$ has to coincide with the spindle axis vector $\boldsymbol{Z}$. First, $\boldsymbol{V}'$ is obtained by rotating the cutter posture vector $\boldsymbol{V}$ at an angle θ around the B-axis and $\boldsymbol{Z}'$ is also obtained by the same method. Second, $\boldsymbol{V}''$ is obtained by rotating the transformed cutter posture vector $\boldsymbol{V}'$ at an angle ϕ around the Z'-axis. Finally, the cutter posture vector $\boldsymbol{V}$ coincides with the spindle axis vector $\boldsymbol{Z}$. For the calculation of this process, a set of equations are derived as follows.

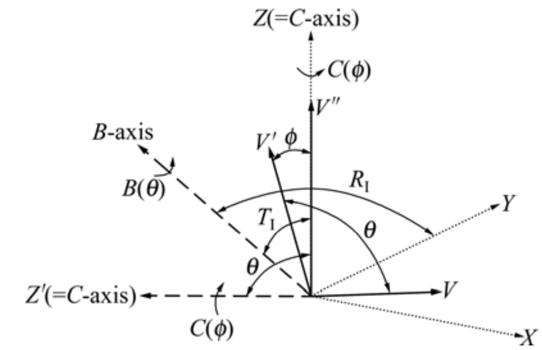

Fig.2 Schematic diagram of process matching cutter posture vector $\boldsymbol{V}$ and spindle axis vector $\boldsymbol{Z}$

$$\boldsymbol{Z}=\boldsymbol{VT},\ \boldsymbol{T}=\prod_{k=1}^{6}\boldsymbol{T}_k \tag{1}$$

$$\boldsymbol{VT}_1=\boldsymbol{ZT}',\ \boldsymbol{T}'=\prod_{k=6}^{2}(\boldsymbol{T}_{\rm k})^{-1}$$

where

$$\boldsymbol{T}_1=\boldsymbol{R}_z(-\phi)=\begin{bmatrix}\cos\phi & -\sin\phi & 0 & 0\\ \sin\phi & \cos\phi & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

$$\boldsymbol{T}_2=\boldsymbol{R}_z(R_{\rm I})=\begin{bmatrix}\cos R_{\rm I} & \sin R_{\rm I} & 0 & 0\\ -\sin R_{\rm I} & \cos R_{\rm I} & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

$$\boldsymbol{T}_3=\boldsymbol{R}_x(T_{\rm I})=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & \cos T_{\rm I} & \sin T_{\rm I} & 0\\ 0 & -\sin T_{\rm I} & \cos T_{\rm I} & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

$$\boldsymbol{T}_4=\boldsymbol{R}_y(-\theta)=\begin{bmatrix}\cos\theta & 0 & \sin\theta & 0\\ 0 & 1 & 0 & 0\\ -\sin\theta & 0 & \cos\theta & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

$$\boldsymbol{T}_5=\boldsymbol{R}_x(-T_{\rm I})=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & \cos T_{\rm I} & -\sin T_{\rm I} & 0\\ 0 & \sin T_{\rm I} & \cos T_{\rm I} & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

$$\boldsymbol{T}_6=\boldsymbol{R}_z(-R_{\rm I})=\begin{bmatrix}\cos R_{\rm I} & -\sin R_{\rm I} & 0 & 0\\ \sin R_{\rm I} & \cos R_{\rm I} & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

From the sequential operation delineated by Eq.(1), the angles of tilting and rotating are derived as

$$\cos\phi u_i + \sin\phi\, u_j = (-\cos R_\mathrm{I}\sin\theta - \sin T_\mathrm{I}\sin R_\mathrm{I} + \sin T_\mathrm{I}\sin R_\mathrm{I}\cos\theta)\cos T_\mathrm{I} \quad (2)$$

$$-\sin\phi u_i + \cos\phi u_j = (\cos R_\mathrm{I}\sin\theta - \sin T_\mathrm{I}\sin R_\mathrm{I} + \sin T_\mathrm{I}\sin R_\mathrm{I}\cos\theta)\cos T_\mathrm{I} \quad (3)$$

$$u_k = \sin^2 T_\mathrm{I} + \cos^2 T_\mathrm{I}\cos\theta \quad (4)$$

The inverse solution for the angle of the rotating axis *C* can be derived from Eqs.(2)−(3) as

$$\phi = \cos^{-1}\left(\frac{Q_1 u_i + Q_2 u_j}{u_i^2 + u_j^2}\right) \quad (5)$$

where

$$Q_1 = (-\cos R_\mathrm{I}\sin\theta - \sin T_\mathrm{I}\sin R_\mathrm{I} + \sin T_\mathrm{I}\sin R_\mathrm{I}\cos\theta)\cos T_\mathrm{I}$$

$$Q_2 = (\cos R_\mathrm{I}\sin\theta - \sin T_\mathrm{I}\sin R_\mathrm{I} + \sin T_\mathrm{I}\sin R_\mathrm{I}\cos\theta)\cos T_\mathrm{I}$$

The inverse solution for the angle of the tilting axis *B* can be derived directly from Eq.(4) as

$$\theta = \cos^{-1}\left(\frac{u_k - \sin^2 T_\mathrm{I}}{\cos^2 T_\mathrm{I}}\right) \quad (6)$$

The inverse solutions for the rotary motions of the DMU 70-eVolution 5-axis machine, which has only one non-orthogonal rotary axis, can be obtained from Eqs.(5)−(6) as

$$\begin{cases} \theta = \cos^{-1}(2u_k - 1) \\ \phi = \cos^{-1}\left(\dfrac{-\cos 45°\sin\theta u_i + \sin 45° u_j + \sin 45°\cos\theta u_j}{u_i^2 + u_j^2}\right) \end{cases} \quad (7)$$

And the inverse solutions for the rotary motions of the DMU 50-Linear 5-axis machine, which has two non-orthogonal rotary axes, can be expressed from Eqs.(5)−(6) as

$$\begin{cases} \theta = \cos^{-1}\left(\dfrac{u_k - \sin^2 35°}{\cos^2 35°}\right) \\ \phi = \cos^{-1}\left(\dfrac{Q_1 u_i + Q_2 u_j}{u_i^2 + u_j^2}\right) \end{cases} \quad (8)$$

where

$$Q_1 = (-\sin\theta - \sin 35° + \sin 35°\cos\theta)\cos 35°\cos 45°$$

$$Q_2 = (\sin\theta - \sin 35° + \sin 35°\cos\theta)\cos 35°\cos 45°$$

2.3 Inverse kinematics for determining linear motions

After defining the inverse solutions for rotary motions, the inverse solutions for linear motions can be obtained from the equation below:

$$\boldsymbol{P}_\mathrm{NC} = \boldsymbol{P}_\mathrm{CL}\boldsymbol{T},\ \boldsymbol{T} = \boldsymbol{T}_1\boldsymbol{T}_2\boldsymbol{T}_{-h}\boldsymbol{T}_3\boldsymbol{T}_4\boldsymbol{T}_5\boldsymbol{T}_h\boldsymbol{T}_6 \quad (9)$$

where

$$\boldsymbol{T}_{-h} = \boldsymbol{T}_z(-h) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -h & 1 \end{bmatrix}$$

$$\boldsymbol{T}_h = \boldsymbol{T}_z(h) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & h & 1 \end{bmatrix}$$

Consequently, N_C=P_NC, θ, ϕ, representing the NC data of the five-axis machine tool with non-orthogonal rotary axes, are obtained.

2.4 Implementation of postprocessor

To develop a practical postprocessor including a 5-axis machine tool with non-orthogonal rotary axes, windows based software has been implemented under a Windows-XP environment with Visual Basic programming language. Fig.3 shows a snapshot of the developed 5-axis postprocessor.

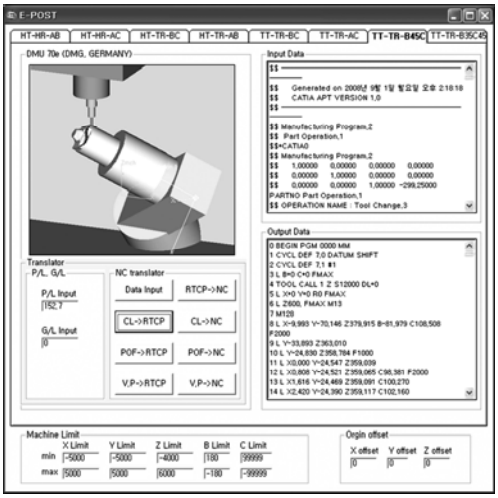

Fig.3 Snapshot of developed 5-axis post-processor

The user should click the tab button in the main menu to select the target kinematics model among the various kinematics models, which consist of not only typical kinematics models but also special kinematics models. After inserting the pivot length, gage length, machine limit values, and origin offset values, the target CL data can be opened by clicking the data input button. Finally, by clicking the desired button to select post-processing types, which consist of seven commands, e.g. RTCP→NC, CL→NC, POF→NC, vector poster (V.P)→NC, CL→RTCP, POF→RTCP and V.P→RTCP in the NC translator frame, NC data will be generated accordingly.

3 Verification of developed postprocessor

3.1 Design of test-piece for verification of postprocessor

To verify the precision of the developed postprocessor, a test-piece was designed, as shown in Fig.4. In Fig.4, element (1) depicts an inclined plane to inspect the angle by plane end-milling; element (2) depicts a cylinder to inspect the diameter by circular end-milling; element (3) depicts a rectangle to inspect the squareness by linear end-milling. These elements are devised to verify the precision of the postprocessor for 5-axis machining with fixed controlled rotary axes. Element (4) depicts a helix shape devised to verify the precision of the postprocessor for 5-axis machining with a fixed controlled tilting axis and a simultaneously controlled rotating axis; finally, element (5) depicts a free-formed surface devised to verify the precision of the postprocessor for 5-axis machining with simultaneously controlled rotary axes. 5-1, 5-2, 5-3 and 5-4 are local sections devised to use the mean error on the free-formed surface.

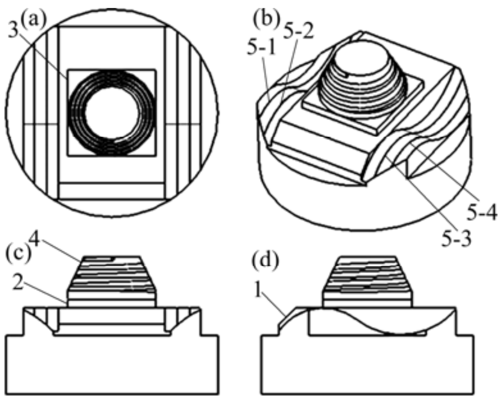

Fig.4 Sketch of test-piece to verify precision of developed postprocessor: 1—Angle; 2—Diameter; 3—Squreness; 4—Helix; 5—Surface

3.2 Cutting simulation of test-piece

The produced NC data were verified by a cutting simulation on VERICUT software (S/W), which can build a kinematics model of a 5-axis machine tool and simulate NC data. Fig.5 shows that two kinematics models of 5-axis machine tools are constructed in the S/W and the cutting shapes of the test-pieces were simulated while reading the produced NC data. Fig.5(a) shows the kinematics model of the DMU 70-eVolution 5-axis machine, which has one non-orthogonal rotary motion, and Fig.5(b) shows the kinematics model of the DMU 50-Linear 5-axis machine, which has two non-orthogonal rotary axes. Through the verification by VERICUT S/W, the feasibility of the developed postprocessor is successfully demonstrated.

3.3 Machining experiment

The produced NC data were also verified by a machining experiment on the DMU 70-eVolution 5-axis machine. The CL data for machining the test-piece was generated by the CATIA S/W CAM module and then converted to NC data by the developed postprocessor. Fig.6 shows the machining experiment and the final shape of the machined test-piece.

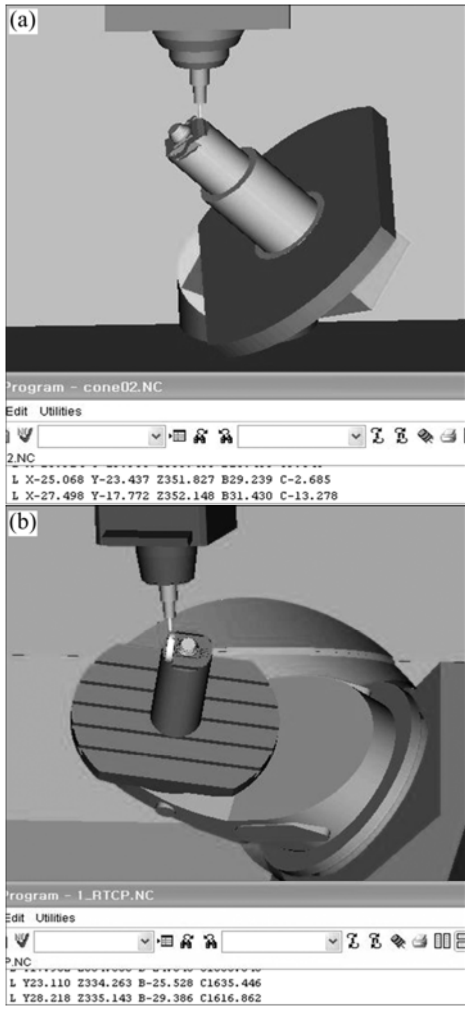

Fig.5 Cutting simulation using test-piece on VERICUT S/W: (a) DMU 70-eVolution; (b) DMU 50-Linear

3.4 Inspection of machined test-piece

The precision of the proposed postprocessor was verified in an inspection of the machined test-piece on a Brown & Sharp CMM. Table 1 shows that the inspection data of the machined test-piece satisfy the allowable tolerance, thus demonstrating that the developed postprocessor is very accurate.

Elements (1), (2) and (3) show the precision of the postprocessor for 5-axis machining with fixed controlled rotary axes. Element (4) shows that it has a fixed controlled tilting axis and a simultaneously controlled rotating axis. Finally, element (5) shows that it has simultaneously controlled rotary axes.

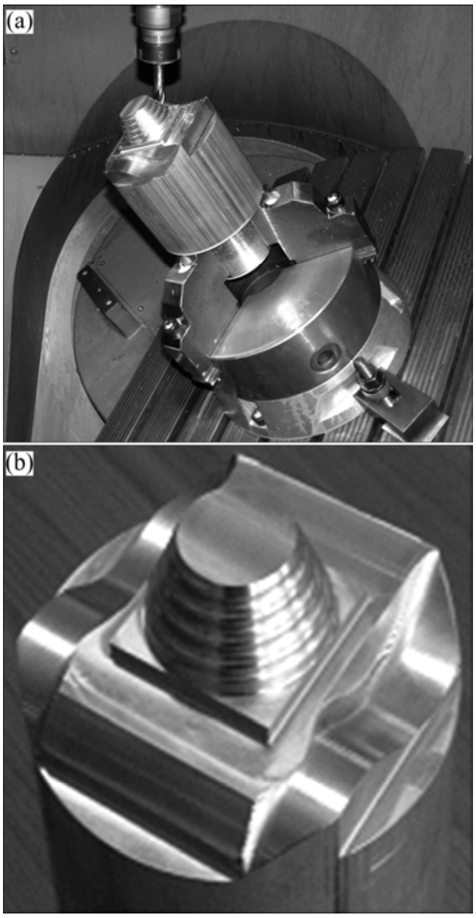

Fig.6 Machining experiment on DMU-70eV 5-axis machine: (a) 5-axis machining; (b) Machined test-piece

Table 1 Inspection results of machined test-piece

Measuring element	Description	Nominal data	Measured data	Deviation
1	Angle/(°)	45± 0.1	45.060	0.060
2	Diameter/mm	50.0 ± 0.1	50.009	0.009
3	Squareness/(°)	90± 0.1	89.930	−0.070
4	Helix	Modeling	Satisfied	—
5-1	Surface shape accuracy/mm	0 ± 0.1	Average of 8 points	0.027
5-2				0.029
5-3				0.031
5-4				0.030
5 (Average)			Average of 32 points	0.029

4 Additional functions

4.1 RTCP control

Rotational tool center position (RTCP) control is a method of controlling 5-axis machining by synchronizing linear motion and rotary motion such that the axes move on the tool center position, not on the pivot center position.

Fig.7(a) shows that collision is detected between linear motions and rotary motions without RTCP control, while Fig.7(b) shows that the same motions can be performed collision-freely with RTCP control.

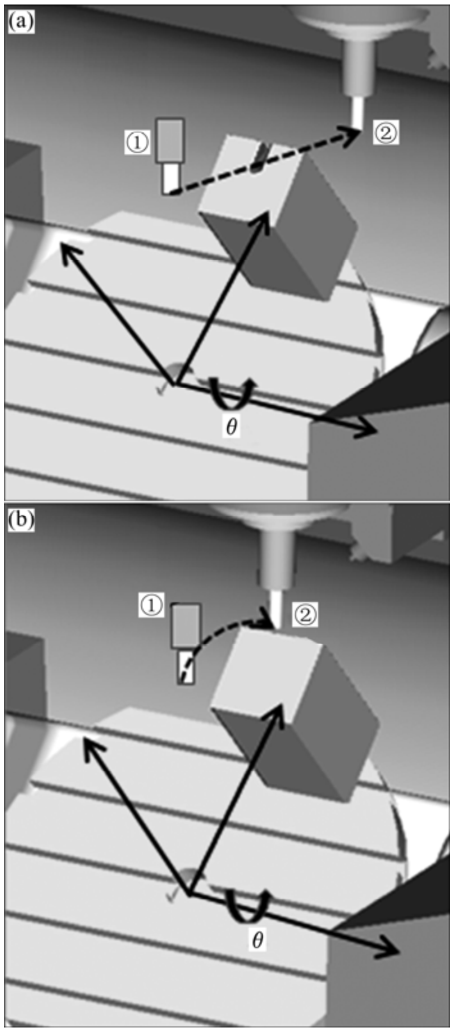

Fig.7 Schematic diagrams of RTCP control: (a) Without RTCP; (b) With RTCP

Because a controller with RTCP function can internally control the position given by NC data, it is not necessary to obtain the inverse kinematics solution of linear motion. Therefore, only the inverse kinematics solution of rotary motion is obtained as

$$NC = P_{\mathrm{CL}}, \theta, \phi \tag{11}$$

RTCP controlled NC data can be obtained by clicking the CL → RTCP button in the developed postprocessor, whereas NC data can be obtained by clicking the RTCP → NC button. Compatibility is improved through this process.

4.2 Vector post NC data

It is not necessary to obtain inverse kinematics solutions of linear motion and rotary motion in the controller, e.g. in the case of SIEMENS, which can use vector post NC data. Therefore, it can use NC data with CL data as

$$NC = P_{CL}, V \tag{12}$$

Vector post NC data can be obtained by clicking the V.P → NC or V.P → RTCP button in the developed postprocessor.

4.3 POF CL data

NC data can also be obtained as POF CL data, which has a different format from ISO CL data used in the HYPER MILL CAM module. POF NC data can be obtained by clicking the POF → NC or POF → RTCP button in the developed postprocessor.

4.4 Function of work-piece origin offset

When the initial work-piece origin is shifted by adding a process and changing the fixture, the CAM programmer will reset the shifted origin in the CAM S/W in order to obtain the new CL data. Post-processing must then be performed again. In order to overcome this problem and provide greater convenience to the user, the function of work-piece origin offset, which can be used by inserting the offset value in the origin offset text box in the developed postprocessor, is added.

5 Conclusions

1) A practical postprocessor for a 5-axis machine tool is presented. The general equation of NC data for a 5-axis configuration with non-orthogonal rotary axes can be precisely expressed by the inverse kinematics. The NC data can be obtained easily by applying the proposed general equation even if any 5-axis machine tool will be adopted, thus, the applicable range of the developed postprocessor is expanded. And through machining experiment of designed test-piece, the accurate of the proposed algorithm is confirmed.

2) Compatibility is improved by allowing exchange of data formats such as RTCP controlled NC data, vector post NC data, and POF CL data, and convenience is enhanced by adding the function of work-piece origin offset.

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