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Design of a generic five-axis postprocessor based on generalized kinematics model of machine tool

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Abstract

This paper presents a generic five-axis postprocessor system for various five-axis machine tools. The generalized kinematics model of common five-axis machines is constructed by combining two rotational degrees of freedom on the fixture table and two rotational degrees of freedom on the spindle. The complete analytical equations for NC data are obtained through homogeneous coordinate transformation matrix and inverse kinematics. The derived five-axis NC code expression is a general form suitable for all kinds of five-axis machine tools with three orthogonal linear axes and two orthogonal rotational axes. A window-based postprocessor software written by Borland C++ Builder and OpenGL has been developed according to the presented algorithm. The wireframe model of the configured five-axis machine tool can be promptly shown and rotated/zoomed dynamically on the screen to assist the user to input relevant parameters correctly and efficiently. Through the implementation of the developed postprocessor and the verification by the solid cutting simulation software as well as the real machining experiment, the effectiveness of the proposed scheme was confirmed.

Keywords: Five-axis; Postprocessor; Kinematics model; Coordinate transformation matrix; NC programming

1. Introduction

Five-axis machining is one of the important processes in precision manufacturing. It has been used in defense, aerospace and even consumer industry. Compared with conventional three-axis machine tools, five-axis machine tools can provide the flexibility of tilting the tool axis to various orientations, increase the cutting efficiency and avoid the tool collision against workpiece. However, it is almost impossible to generate the five-axis numerically controlled (NC) data manually. The data should be transformed by the postprocessor depending on the configuration of the machine tool. Postprocessor is the important interface that coverts the cutter location (CL) data including cutter tip position and the tool orientation, to NC data. Since various combinations may be synthesized to configure the five-axis machine tool, Sakamoto and Inasaki [1] classified the configuration of five-axis machine tool into three typical types. Various studies [2–6] have utilized the coordinate transformation matrix to develop the multi-axis postprocessor for these three typical types. However, the above studies can only be applicable to the specific machine tool configuration.

The kinematics structure of a five-axis machine tool is an important factor for developing the postprocessor. Bohez [7] classified the possible kinematics structure of five-axis machine tools into four main groups and investigated their advantages and disadvantages. She and Lee [8] proposed a postprocessor for general five-axis machine tools using the kinematics model that adds two rotary movements on the workpiece table and two rotary movements on the spindle. Tutunea-Fatan and Feng [9] have recently presented a generic and unified model for all the five-axis machine tools with two rotational axes, and derived a general coordinate transformation matrix for five-axis machine tools. Nevertheless, the complete analytical solutions of NC data dealing with different configurations effectively are not further investigated in the above studies.

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This paper extends the previous researches [5,8] proposed by the authors and develops a generic five-axis postprocessor system from a generalized kinematics model adding four rotational degrees of freedom where two of them are applied to the workpiece table and the other two are applied to the spindle. The analytical equations for NC data are determined by equating the CL data matrix and the form-shaping function matrix. In addition, the original NC data for a specific machine tool can be transformed to the other machine tool configuration using the derived analytical equations so that the portability of the NC data can be greatly promoted. A window-based postprocessor software is developed and implemented with two typical configurations of five-axis machine tool. Verification by the solid cutting simulation software and the real machining experiment confirms the validity of the proposed methodology.

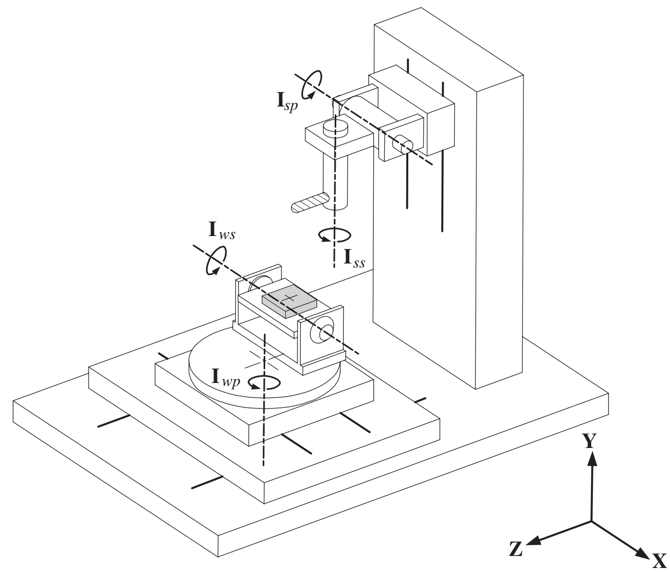

Fig. 1. Generalized five-axis machine tool with four rotational degrees of freedom.

2. Postprocessor of generalized five-axis machine tools

2.1. Link and joint modeling

Any machine tool may be thought of as a set of links connected in a chain by joints. Typical configuration for five-axis machine tools can be divided into three basic types [1]: (1) table-tilting type with two rotations on the table, (2) spindle-tilting type with two rotations on the spindle, and (3) table/spindle-tilting type with one rotation each on the table and spindle. To manipulate the position and orientation of the cutting tool and the machine tool, the relationship of the coordinate system between the adjacent links and joint should be established. Assume that a joint connects two connects two links numbered i and j. Coordinate systems $O_iX_iY_iZ_i$ and $O_jX_jY_jZ_j$ are attached to link i and link j, respectively. The relative position and orientation of jth system with respect to ith system can be mathematically expressed as follows:

$$ {}^{i}\mathbf{A}_j = \mathbf{T}\mathrm{rans}(L_{i,j,x}, L_{i,j,y}, L_{i,j,z})\mathbf{R}\mathrm{ot}(N, \phi_N), \tag{1} $$

where ${}^{i}\mathbf{A}_j$ represents the relative transformation matrix of system $O_jX_jY_jZ_j$ with respect to system $O_iX_iY_iZ_i$. $\mathbf{L}_{i,j} = L_{i,j,x}\mathbf{i} + L_{i,j,y}\mathbf{j} + L_{i,j,z}\mathbf{k}$ is the distance vector from origin O_i to O_j. Symbol $N \equiv x, y, z$, and $\mathbf{T}$rans and $\mathbf{R}$ot are the 4×4 homogeneous translation and rotation matrices adopted by Paul's notation [10].

2.2. Forward kinematics modeling

Four rotational movements occur on the generalized five-axis machine tool as shown in Fig. 1, where $\mathbf{I}_{\mathrm{wp}}$ and $\mathbf{I}_{\mathrm{ws}}$ are the primary and secondary rotational axes on the workpiece fixture table, while $\mathbf{I}_{\mathrm{sp}}$ and $\mathbf{I}_{\mathrm{ss}}$ denote the primary and secondary rotational axes on the spindle, respectively. Note that the primary rotational axis is defined to be located closer to the machine bed. The other rotational axis is called the secondary rotational axis, which rotates accordingly when the primary axis rotates. This definition agrees with those used by most of the commercial postprocessor systems, e.g. IntelliPost® [11]. To describe the relative position and orientation of the cutting tool with respect to the workpiece, appropriate coordinate systems shown in Fig. 2 should be established. The coordinate system for the workpiece and the cutting tool are $O_{\mathrm{w}}X_{\mathrm{w}}Y_{\mathrm{w}}Z_{\mathrm{w}}$ and $O_{\mathrm{t}}X_{\mathrm{t}}Y_{\mathrm{t}}Z_{\mathrm{t}}$, respectively. Coordinate systems $O_{\mathrm{wp}}X_{\mathrm{wp}}Y_{\mathrm{wp}}Z_{\mathrm{wp}}$ and $O_{\mathrm{ws}}X_{\mathrm{ws}}Y_{\mathrm{ws}}Z_{\mathrm{ws}}$ are attached to the primary and secondary rotations on the workpiece fixture table, respectively. Similarly, coordinate systems $O_{\mathrm{sp}}X_{\mathrm{sp}}Y_{\mathrm{sp}}Z_{\mathrm{sp}}$ and $O_{\mathrm{ss}}X_{\mathrm{ss}}Y_{\mathrm{ss}}Z_{\mathrm{ss}}$ are attached to the primary and secondary rotations, respectively on the spindle. Coordinate systems $O_{\mathrm{b}}X_{\mathrm{b}}Y_{\mathrm{b}}Z_{\mathrm{b}}$, $O_{\mathrm{T}x}X_{\mathrm{T}x}Y_{\mathrm{T}x}Z_{\mathrm{T}x}$, $O_{\mathrm{T}y}X_{\mathrm{T}y}Y_{\mathrm{T}y}Z_{\mathrm{T}y}$ and $O_{\mathrm{T}z}X_{\mathrm{T}z}Y_{\mathrm{T}z}Z_{\mathrm{T}z}$ are attached to the machine bed, X, Y and Z table, respectively.

The relative position and orientation of coordinate system $O_{\mathrm{t}}X_{\mathrm{t}}Y_{\mathrm{t}}Z_{\mathrm{t}}$ with respect to the coordinate system $O_{\mathrm{w}}X_{\mathrm{w}}Y_{\mathrm{w}}Z_{\mathrm{w}}$, ${}^{\mathrm{w}}\mathbf{A}_{\mathrm{t}}$, can be obtained by transforming ${}^{\mathrm{w}}\mathbf{A}_{\mathrm{ws}}$ to ${}^{\mathrm{ss}}\mathbf{A}_{\mathrm{t}}$ in series, and expressed in matrices product as follows:

$$ \begin{aligned} {}^{\mathrm{w}}\mathbf{A}_{\mathrm{t}} &= {}^{\mathrm{w}}\mathbf{A}_{\mathrm{ws}}\,{}^{\mathrm{ws}}\mathbf{A}_{\mathrm{wp}}\,{}^{\mathrm{wp}}\mathbf{A}_{\mathrm{T}x}\,{}^{\mathrm{T}x}\mathbf{A}_{\mathrm{T}z}\,{}^{\mathrm{T}z}\mathbf{A}_{\mathrm{b}}\,{}^{\mathrm{b}}\mathbf{A}_{\mathrm{T}y}\,{}^{\mathrm{T}y}\mathbf{A}_{\mathrm{sp}}\,{}^{\mathrm{sp}}\mathbf{A}_{\mathrm{ss}}\,{}^{\mathrm{ss}}\mathbf{A}_{\mathrm{t}} \\ &= \mathbf{T}\mathrm{rans}(L_{\mathrm{w,ws},x}, L_{\mathrm{w,ws},y}, L_{\mathrm{w,ws},z})\mathbf{R}\mathrm{ot}(\mathrm{nws}, -\phi_{\mathrm{nws}}) \\ &\quad \times \mathbf{T}\mathrm{rans}(L_{\mathrm{ws,wp},x}, L_{\mathrm{ws,wp},y}, L_{\mathrm{ws,wp},z}) \\ &\quad \times \mathbf{R}\mathrm{ot}(\mathrm{nwp}, -\phi_{\mathrm{nwp}})\mathbf{T}\mathrm{rans}(P_x, P_y, P_z)\mathbf{R}\mathrm{ot}(\mathrm{nsp}, \phi_{\mathrm{nsp}}) \\ &\quad \times \mathbf{T}\mathrm{rans}(L_{\mathrm{sp,ss},x}, L_{\mathrm{sp,ss},y}, L_{\mathrm{sp,ss},z})\mathbf{R}\mathrm{ot}(\mathrm{nss}, \phi_{\mathrm{nss}}), \end{aligned} \tag{2} $$

where subscripts nwp, nws, nsp, nss $\equiv x$, y, z. P_x, P_y, P_z denote the relative translation distances of the X, Y, Z tables, respectively. In addition, ϕ_{nwp}, ϕ_{nws}, ϕ_{nsp} and ϕ_{nss} represent the rotation angles for the fixture table and the spindle, respectively.

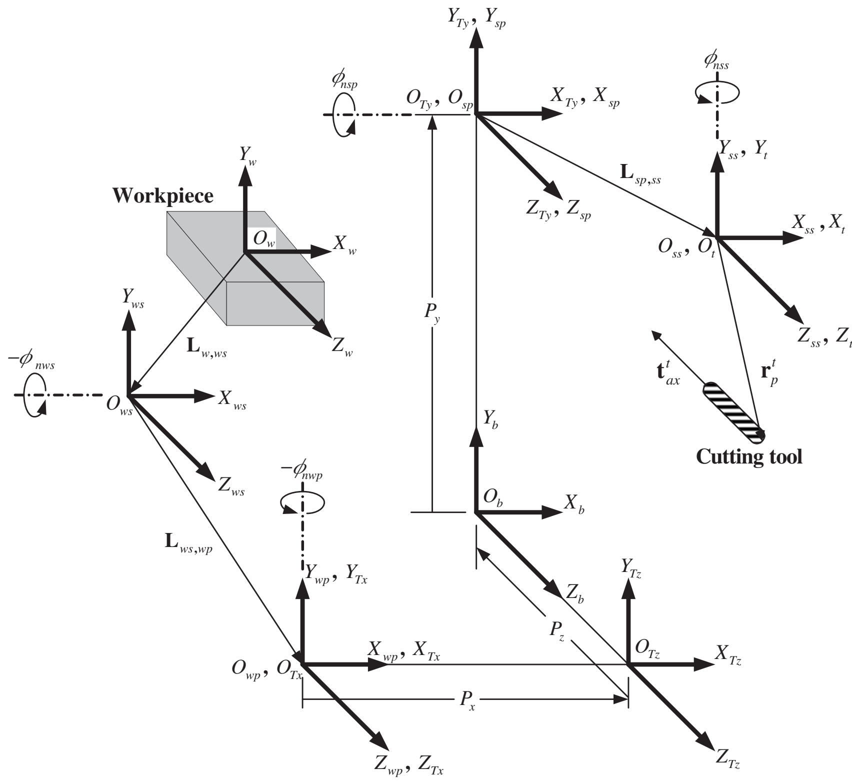

Fig. 2. Coordinate systems for generalized five-axis machine tool.

The tool axis vector $\mathbf{t}_{ax}^{t}$ and the position vector of the cutter tip center $\mathbf{r}_{p}^{t}$ with respect to system $O_tX_tY_tZ_t$ can be transformed to system $O_wX_wY_wZ_w$, and obtain $\mathbf{t}_{ax}^{t}$,$\mathbf{r}_{p}^{t}$ using Eq. (2). The transformation is as follows:

$$\begin{aligned}\begin{bmatrix}\mathbf{t}_{ax}^{w} & \mathbf{r}_{p}^{w}\\ 0 & 1\end{bmatrix} &= {}^{w}\mathbf{A}_{t}\begin{bmatrix}\mathbf{t}_{ax}^{t} & \mathbf{r}_{p}^{t}\\ 0 & 1\end{bmatrix}\\ &= \mathbf{T}\mathrm{rans}(L_{w,ws,x}, L_{w,ws,y}, L_{w,ws,z})\mathbf{R}\mathrm{ot}(\mathrm{nws}, -\phi_{\mathrm{nws}})\\ &\quad\times\mathbf{T}\mathrm{rans}(L_{ws,wp,x}, L_{ws,wp,y}, L_{ws,wp,z})\\ &\quad\times\mathbf{R}\mathrm{ot}(\mathrm{nwp}, -\phi_{\mathrm{nwp}})\mathbf{T}\mathrm{rans}(P_x, P_y, P_z)\\ &\quad\times\mathbf{R}\mathrm{ot}(\mathrm{nsp}, \phi_{\mathrm{nsp}})\mathbf{T}\mathrm{rans}(L_{sp,ss,x}, L_{sp,ss,y}, L_{sp,ss,z})\\ &\quad\times\mathbf{R}\mathrm{ot}(\mathrm{nss}, \phi_{\mathrm{nss}})\begin{bmatrix}\mathbf{t}_{ax}^{t} & \mathbf{r}_{p}^{t}\\ 0 & 1\end{bmatrix}.\end{aligned} \tag{3}$$

Eq. (3) describes the form-shaping function matrix [12] of generalized five-axis machine tool consisting of three linear axis motions and four rotational axis motions of which only two of them are active; and this matrix will be employed to determine the desired joint parameters, i.e. ϕ_{nwp}, ϕ_{nws}, ϕ_{nsp}, ϕ_{nss}, P_x, P_y and P_z.

2.3. Inverse kinematics for determining rotary motions

Most current CAD/CAM systems can produce the CL data for five-axis machining of free-form surfaces. The CL data can be expressed in the matrix form as follows:

$$\begin{bmatrix}\mathbf{K} & \mathbf{Q}\\ 0 & 1\end{bmatrix} = \begin{bmatrix}K_x & Q_x\\ K_y & Q_y\\ K_z & Q_z\\ 0 & 1\end{bmatrix}, \tag{4}$$

where K_x, K_y and K_z are direction cosines of the vector of tool orientation $\mathbf{K}$; Q_x, Q_y and Q_z are the components of the tool tip centre's position vector $\mathbf{Q}$. The two vectors are relative to the workpiece coordinate system. Once the CL data matrix is obtained, determining five reference inputs (three linear motions plus two rotary motions) for the five-axis machine used is referred to as inverse kinematics transformation.

Equating CL data matrix and form-shaping function matrix, and taking the corresponding elements of the first column of two matrices lead to the following equation:

$$\begin{aligned}\begin{bmatrix}\mathbf{K}\\ 0\end{bmatrix} &= \mathbf{T}\mathrm{rans}(L_{w,ws,x}, L_{w,ws,y}, L_{w,ws,z})\mathbf{R}\mathrm{ot}(\mathrm{nws}, -\phi_{\mathrm{nws}})\\ &\quad\times\mathbf{T}\mathrm{rans}(L_{ws,wp,x}, L_{ws,wp,y}, L_{ws,wp,z})\\ &\quad\times\mathbf{R}\mathrm{ot}(\mathrm{nwp}, -\phi_{\mathrm{nwp}})\mathbf{T}\mathrm{rans}(P_x, P_y, P_z)\mathbf{R}\mathrm{ot}(\mathrm{nsp}, \phi_{\mathrm{nsp}})\\ &\quad\times\mathbf{T}\mathrm{rans}(L_{sp,ss,x}, L_{sp,ss,y}, L_{sp,ss,z})\mathbf{R}\mathrm{ot}(\mathrm{nss}, \phi_{\mathrm{nss}})\begin{bmatrix}\mathbf{t}_{ax}^{t}\\ 0\end{bmatrix}.\end{aligned} \tag{5}$$

Two of the joint angles (ϕ_{nwp}, ϕ_{nws}, ϕ_{nsp} and ϕ_{nss}) on the right-hand side of Eq. (5) are unknown and should be solved. According to the rotational movement characteristics, the five-axis machine tool can be designated as six types, i.e. AB, AC, BA, BC, CA and CB types. There are two feasible tool orientations for each type, which meet the five-axis machining requirement. The spindle-tilting AB type is chosen as an example. In this case, $\phi_{\text{nws}} = \phi_{\text{nwp}} = 0$, $\text{nsp} \equiv x$ and $\text{nss} \equiv y$, the right-hand side of Eq. (5) for tool orientation along the X, Y and Z axis can be obtained as follows:

$$\mathbf{R}\text{ot}(x,\phi_x)\mathbf{R}\text{ot}(y,\phi_y)\begin{bmatrix}1 & 0 & 0 & 0\end{bmatrix}^{\mathrm{T}} = \begin{bmatrix}\mathrm{C}\phi_y & \mathrm{S}\phi_x\mathrm{S}\phi_y & -\mathrm{C}\phi_x\mathrm{S}\phi_y & 0\end{bmatrix}^{\mathrm{T}}, \tag{6}$$

$$\mathbf{R}\text{ot}(x,\phi_x)\mathbf{R}\text{ot}(y,\phi_y)\begin{bmatrix}0 & 1 & 0 & 0\end{bmatrix}^{\mathrm{T}} = \begin{bmatrix}0 & \mathrm{C}\phi_x & \mathrm{S}\phi_x & 0\end{bmatrix}^{\mathrm{T}}, \tag{7}$$

$$\mathbf{R}\text{ot}(x,\phi_x)\mathbf{R}\text{ot}(y,\phi_y)\begin{bmatrix}0 & 0 & 1 & 0\end{bmatrix}^{\mathrm{T}} = \begin{bmatrix}\mathrm{S}\phi_y & -\mathrm{S}\phi_x\mathrm{C}\phi_y & \mathrm{C}\phi_x\mathrm{C}\phi_y & 0\end{bmatrix}^{\mathrm{T}}, \tag{8}$$

where "C" and "S" refer to cosine and sine functions, respectively. Eq. (7) indicates that the tool orientation along the Y-axis is infeasible for the AB type machine tool since the rotational effect of the B axis (ϕ_y) cannot be exhibited and does not appear in the right-hand side of Eq. (7). Consequently, the AB type machine tool should have the tool orientation along the X or Z-axis only. The joint angle solutions for the spindle-tilting type are summarized in Table 1, where $\arctan 2(y,x)$ is the function that returns angles in the range of $-\pi \leqq \theta \leqq \pi$ by examining the sign of both y and x [10]. Similarly, the joint angle solutions of the other types (table-tilting and table/spindle-tilting type) can also be obtained by the same procedure.

2.4. Inverse kinematics for determining linear motions

As before, equating CL data matrix and form-shaping function matrix, and taking the corresponding elements of the second column of two matrices yield

$$\begin{bmatrix}\mathbf{Q}\\1\end{bmatrix} = \mathbf{T}\text{rans}(L_{\text{w,ws,}x}, L_{\text{w,ws,}y}, L_{\text{w,ws,}z})\mathbf{R}\text{ot}(\text{nws}, -\phi_{\text{nws}}) \times \mathbf{T}\text{rans}(L_{\text{ws,wp,}x}, L_{\text{ws,wp,}y}, L_{\text{ws,wp,}z}) \times \mathbf{R}\text{ot}(\text{nwp}, -\phi_{\text{nwp}})\mathbf{T}\text{rans}(P_x, P_y, P_z) \times \mathbf{R}\text{ot}(\text{nsp}, \phi_{\text{nsp}})\mathbf{T}\text{rans}(L_{\text{sp,ss,}x}, L_{\text{sp,ss,}y}, L_{\text{sp,ss,}z}) \times \mathbf{R}\text{ot}(\text{nss}, \phi_{\text{nss}})\begin{bmatrix}\mathbf{r}_{\text{p}}^{\text{t}}\\1\end{bmatrix}. \tag{9}$$

Three unknowns (P_x, P_y and P_z) in Eq. (9) should be solved. Let $\begin{bmatrix}\mathbf{P} & 1\end{bmatrix}^{\mathrm{T}} = \begin{bmatrix}P_x & P_y & P_z & 1\end{bmatrix}^{\mathrm{T}}$, then Eq. (9) reduces to

$$\begin{bmatrix}\mathbf{Q}\\1\end{bmatrix} = \mathbf{T}\text{rans}(L_{\text{w,ws,}x}, L_{\text{w,ws,}y}, L_{\text{w,ws,}z})\mathbf{R}\text{ot}(\text{nws}, -\phi_{\text{nws}}) \times \mathbf{T}\text{rans}(L_{\text{ws,wp,}x}, L_{\text{ws,wp,}y}, L_{\text{ws,wp,}z})\mathbf{R}\text{ot}(\text{nwp}, -\phi_{\text{nwp}}) \times \left\{\begin{bmatrix}\mathbf{P}\\1\end{bmatrix} + \mathbf{R}\text{ot}(\text{nsp}, \phi_{\text{nsp}}) \times \mathbf{T}\text{rans}(L_{\text{sp,ss,}x}, L_{\text{sp,ss,}y}, L_{\text{sp,ss,}z})\mathbf{R}\text{ot}(\text{nss}, \phi_{\text{nss}})\begin{bmatrix}\mathbf{r}_{\text{p}}^{\text{t}}\\1\end{bmatrix}\right\}. \tag{10}$$

Therefore, the linear joint parameters (P_x,P_y and P_z) can be obtained as follows:

$$\begin{bmatrix}\mathbf{P}\\1\end{bmatrix} = \{\mathbf{T}\text{rans}(L_{\text{w,ws,}x}, L_{\text{w,ws,}y}, L_{\text{w,ws,}z})\mathbf{R}\text{ot}(\text{nws}, -\phi_{\text{nws}}) \times \mathbf{T}\text{rans}(L_{\text{ws,wp,}x}, L_{\text{ws,wp,}y}, L_{\text{ws,wp,}z}) \times \mathbf{R}\text{ot}(\text{nwp}, -\phi_{\text{nwp}})\}^{-1}\begin{bmatrix}\mathbf{Q}\\1\end{bmatrix} - \mathbf{R}\text{ot}(\text{nsp}, \phi_{\text{nsp}}) \times \mathbf{T}\text{rans}(L_{\text{sp,ss,}x}, L_{\text{sp,ss,}y}, L_{\text{sp,ss,}z}) \times \mathbf{R}\text{ot}(\text{nss}, \phi_{\text{nss}})\begin{bmatrix}\mathbf{r}_{\text{p}}^{\text{t}}\\1\end{bmatrix}. \tag{11}$$

Table 1
General joint angle solutions for spindle-tilting type machine tool

Configuration type	Tool orientation	Joint angle solutions
AB	X-axis	$\phi_y = \arccos(K_x)$, $\phi_x = \arctan 2(K_y,-K_z)$
AB	Z-axis	$\phi_y = \arcsin(K_x)$, $\phi_x = \arctan 2(-K_y,K_z)$
AC	X-axis	$\phi_z = \arccos(K_x)$, $\phi_x = \arctan 2(K_z,K_y)$
AC	Y-axis	$\phi_z = \arccos(-K_x)$, $\phi_x = \arctan 2(K_z,K_y)$
BA	Y-axis	$\phi_x = \arccos(K_y)$, $\phi_y = \arctan 2(K_x,-K_z)$
BA	Z-axis	$\phi_x = \arccos(-K_y)$, $\phi_y = \arctan 2(K_x,K_z)$
BC	X-axis	$\phi_z = \arccos(K_y)$, $\phi_y = \arctan 2(-K_z,K_x)$
BC	Y-axis	$\phi_z = \arccos(K_y)$, $\phi_y = \arctan 2(K_z,-K_x)$
CA	Y-axis	$\phi_x = \arccos(K_z)$, $\phi_z = \arctan 2(-K_x,K_y)$
CA	Z-axis	$\phi_x = \arccos(K_z)$, $\phi_z = \arctan 2(K_x,K_y)$
CB	X-axis	$\phi_y = \arccos(-K_z)$, $\phi_z = \arctan 2(K_y,K_x)$
CB	Z-axis	$\phi_y = \arccos(K_z)$, $\phi_z = \arctan 2(K_y, K_x)$

Note that P_x, P_y and P_z are not the actual NC code expressions (denoted as X, Y and Z). The axis command of linear movements of the machine tool should be referred to the program coordinate system. The program coordinate system is assumed here to coincide with the workpiece coordinate system. Consequently, the desired X, Y and Z values of NC data in programming can then be determined using Eq. (10) under the condition $\phi_{\mathrm{nwp}} = \phi_{\mathrm{nws}} = \phi_{\mathrm{nsp}} = \phi_{\mathrm{nss}} = 0$, and $\begin{bmatrix} Q_x & Q_y & Q_z & 1 \end{bmatrix}^{\mathrm{T}} = \begin{bmatrix} X & Y & Z & 1 \end{bmatrix}^{\mathrm{T}}$. This leads to

$$\begin{aligned}
\begin{bmatrix} X & Y & Z & 1 \end{bmatrix}^{\mathrm{T}} &= \mathbf{T}\mathrm{rans}(L_{\mathrm{w,ws},x}, L_{\mathrm{w,ws},y}, L_{\mathrm{w,ws},z}) \\
&\quad \times \mathbf{T}\mathrm{rans}(L_{\mathrm{ws,wp},x}, L_{\mathrm{ws,wp},y}, L_{\mathrm{ws,wp},z}) \\
&\quad \times \left\{ \begin{bmatrix} \mathbf{P} \\ 1 \end{bmatrix} + \mathbf{T}\mathrm{rans}(L_{\mathrm{sp,ss},x}, L_{\mathrm{sp,ss},y}, L_{\mathrm{sp,ss},z}) \begin{bmatrix} \mathbf{r}_{\mathrm{p}}^{\mathrm{t}} \\ 1 \end{bmatrix} \right\} \\
&= \mathbf{T}\mathrm{rans}(L_{\mathrm{w,ws},x}, L_{\mathrm{w,ws},y}, L_{\mathrm{w,ws},z}) \\
&\quad \times \mathbf{T}\mathrm{rans}(L_{\mathrm{ws,wp},x}, L_{\mathrm{ws,wp},y}, L_{\mathrm{ws,wp},z}) \\
&\quad \times \{ (\mathbf{T}\mathrm{rans}(L_{\mathrm{w,ws},x}, L_{\mathrm{w,ws},y}, L_{\mathrm{w,ws},z}) \mathbf{R}\mathrm{ot}(\mathrm{nws}, -\phi_{\mathrm{nws}}) \\
&\quad \times \mathbf{T}\mathrm{rans}(L_{\mathrm{ws,wp},x}, L_{\mathrm{ws,wp},y}, L_{\mathrm{ws,wp},z}) \\
&\quad \times \mathbf{R}\mathrm{ot}(\mathrm{nwp}, -\phi_{\mathrm{nwp}}))^{-1} \begin{bmatrix} \mathbf{Q} \\ 1 \end{bmatrix} - \mathbf{R}\mathrm{ot}(\mathrm{nsp}, \phi_{\mathrm{nsp}}) \\
&\quad \times \mathbf{T}\mathrm{rans}(L_{\mathrm{sp,ss},x}, L_{\mathrm{sp,ss},y}, L_{\mathrm{sp,ss},z}) \mathbf{R}\mathrm{ot}(\mathrm{nss}, \phi_{nss}) \begin{bmatrix} \mathbf{r}_{\mathrm{p}}^{\mathrm{t}} \\ 1 \end{bmatrix} \\
&\quad + \mathbf{T}\mathrm{rans}(L_{\mathrm{sp,ss},x}, L_{\mathrm{sp,ss},y}, L_{\mathrm{sp,ss},z}) \begin{bmatrix} \mathbf{r}_{\mathrm{p}}^{\mathrm{t}} \\ 1 \end{bmatrix} \Bigg\}.
\end{aligned} \tag{12}$$

Eq. (12) represents the complete desired analytical solutions for NC data of the generalized five-axis machine tool. Once the appropriate joint angle values shown in Table 1 are specified, the NC data of the specific five-axis machine tool's configuration can be readily obtained.

3. Discussion

1. The joint angle solutions shown in Table 1 for each type of configuration are typical solutions. For the same CL data, there is another possible solution. The AB configuration type with the X axis tool orientation is chosen as an example. The joint angle solution of the B axis is $\phi_y = \arccos(K_x)$, whose value is in the range of $0 \leqslant \phi_y \leqslant \pi$. However, if the operating range of the tilting head is in the range between $-\pi$ and 0, the solution should be modified as $\phi_y = -\arccos(K_x)$. On the other hand, if the operating range of the tilting head meets the two possible solutions, the shortest rotational angle movement of the tilting head is usually to be chosen.
2. The advantage of the proposed algorithm is that the linear joint parameters (P_x, P_y and P_z) are explicitly determined in the matrix form. On the contrary, the conventional approach, which solves three simultaneous equations to derive the parameters, is tedious and time-consuming for various kinds of configurations. Moreover, because of the simplicity of derivation, the two rotary axes for table-tilting and spindle-tilting type configuration are usually assumed to intersect for each other for most of the previous researches. In this paper, there is an offset vector between the two rotary axes. Consequently, the presented NC data equation is a general form for the generalized five-axis machine tool.
3. Because many combinations can be synthesized to generate various multi-axis machine tool configurations and the multi-axis NC data can only be applied to the specific configuration, the portability of the NC data is inevitably reduced. In this paper, the NC data are explicitly expressed in terms of the CL data. The CL data can also be obtained by using Eqs. (5), (9) and (12) if the original NC code is known, and can then be transformed to the dedicated NC data for different configurations. Therefore, the presented methodology can enhance the facility and flexibility of machine tools.
4. The developed multi-axis postprocessor method deals with the machine tool configuration whose linear and rotational movements are orthogonal. In case of the five-axis machine tool with a nutating head/table whose rotational axis is in an inclined plane, the general rotation transformation matrix [10] should be used. However, the analytical equations of NC data can be derived by the same procedure as described in the orthogonal configuration.
5. Since the analytical equations of the output NC data are explicitly expressed in terms of CL data, the computational error can be assured during the transformation. However, considering the practical viewpoint where the rotary and linear motion takes place simultaneously for multi-axis machine tool, the actual tool motion trajectory with respect to the workpiece will be not linear and become a curved path. The non-linear curved path will deviate from the linearly interpolated straight line path between successive path points, and this is known as the linearization problem [2]. To deal with this situation, most postprocessors use the post command LINTOL to specify the deviation tolerance and additional intermediate control points should be added to ensure that the deviation is less than the tolerance [14,15].

4. Implementation and verification

4.1. Software implementation

To verify the effectiveness of the proposed methodology, a window-based postprocessor software has been developed under the Windows-XP environment with the Borland C++ Builder programming language and the OpenGL graphics library. Fig. 3 shows the snapshot of the system initiation dialogue, indicating the generalized kinematics model including the primary and secondary rotary axes on the workpiece table and the spindle for the

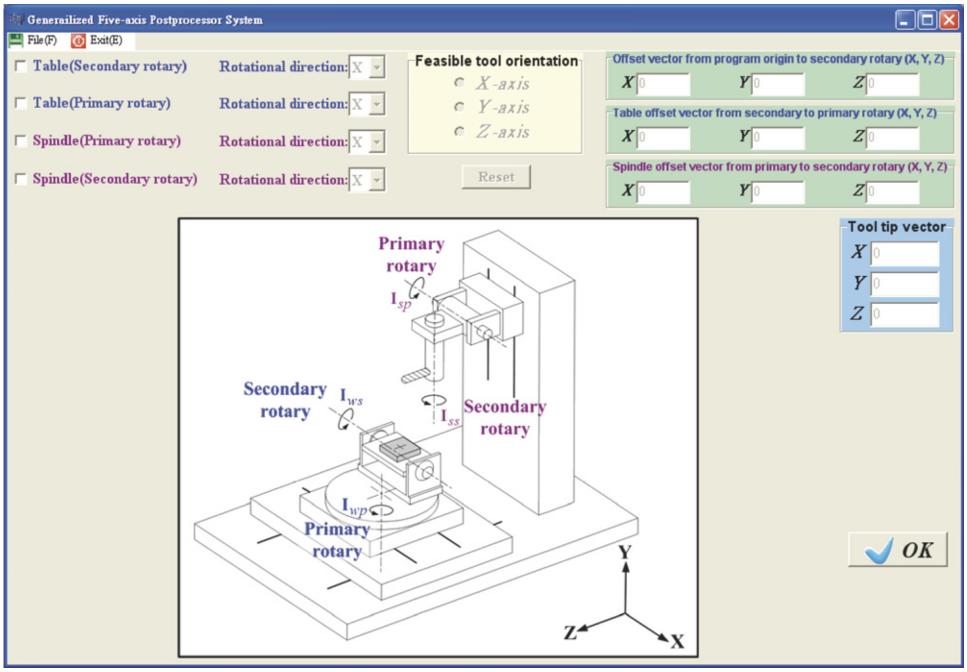

Fig. 3. Initiation dialog of the developed general five-axis postprocessor.

five-axis machine tool. The user first selects two rotary axes and the corresponding rotational directions. The system will automatically display the wireframe model of the configured machine tool and two feasible tool orientations. The user can use the mouse to rotate/zoom the model to assure whether the kinematics model is correct or not, or pick the "Reset" button to restart the configuration procedure.

Once the kinematics model has been configured correctly, the user should enter the relevant parameters for NC machining, e.g. the offset vector from the program origin to the centre of the secondary rotary table, the offset vector from the centre of the secondary rotary table to the centre of the primary rotary table, the offset vector from the centre of the primary rotary spindle to the centre of the secondary rotary spindle and the tool tip vector. Finally, the target CL data are opened by clicking the "File" button and the NC data will be generated accordingly. Moreover, since the presented system is a generalized postprocessor, the corresponding CL data can also be transformed if the user opens the NC data for the configured machine tool. In addition, to confirm the feasibility of the proposed algorithm, two typical machine tool's configurations, namely the table-tilting type and the spindle-tilting type, are tested respectively. Figs. 4 and 5 show the screenshots of the system execution dialogue for the table-tilting type and the spindle-tilting type with Z-axis tool orientation.

4.2. VERICUT® verification

The generated five-axis NC data are further verified on the solid cutting simulation software VERICUT® [13], which can build the kinematics model of an NC machine tool and simulate the NC data as well as CL data. Fig. 6 shows that a table-tilting type machine tool is constructed in the software environment and the final shape of the workpiece is simulated. Note that the two rotary axes are assumed not to intersect each other, and the offset vector from the centre of the secondary rotary table to the centre of the primary rotary table, as shown in Fig. 4, is $\mathbf{L}_{ws,wp} = -10\mathbf{i} - 20\mathbf{j} - 30\mathbf{k}$. This phenomenon should be reflected in the VERICUT®component tree as shown in Fig. 6. Moreover, the stock should be placed in the appropriate position so that the offset vector from the program origin to the center of the secondary rotary table is $\mathbf{L}_{w,ws} = -25\mathbf{i} - 25\mathbf{j} - 15\mathbf{k}$, as indicated in Fig. 4. Once the configuration process has been completed, the software system reads the NC data to perform the cutting action. In addition, the system can output the transformed CL data that can be double-checked with the original CL data.

Fig. 7 shows the result for simulating the NC data in a spindle-tilting type machine tool. As before, the two rotary axes are assumed not to intersect each other and the offset vector from the centre of the primary rotary spindle to the centre of the secondary rotary spindle is $\mathbf{L}_{sp,ss} = 120\mathbf{i} + 20\mathbf{j} + 10\mathbf{k}$ as shown in Fig. 5. Since the spindle will rotate during machining, the tool tip vector determined from the centre of the secondary rotary spindle to the tool tip centre is required for NC data generation. As shown in Fig. 7, the signed distance from the centre of the secondary rotary spindle to the gauge plane is $0\mathbf{i} + 0\mathbf{j} - 440\mathbf{k}$ and the gauge length for the tool is 150 mm. Therefore, the tool tip vector shown in Fig. 5 should be entered as $0\mathbf{i} + 0\mathbf{j} - 590\mathbf{k}$. The results shown in Figs. 6 and 7 demonstrate that the developed postprocessor method is highly effective and reliable.

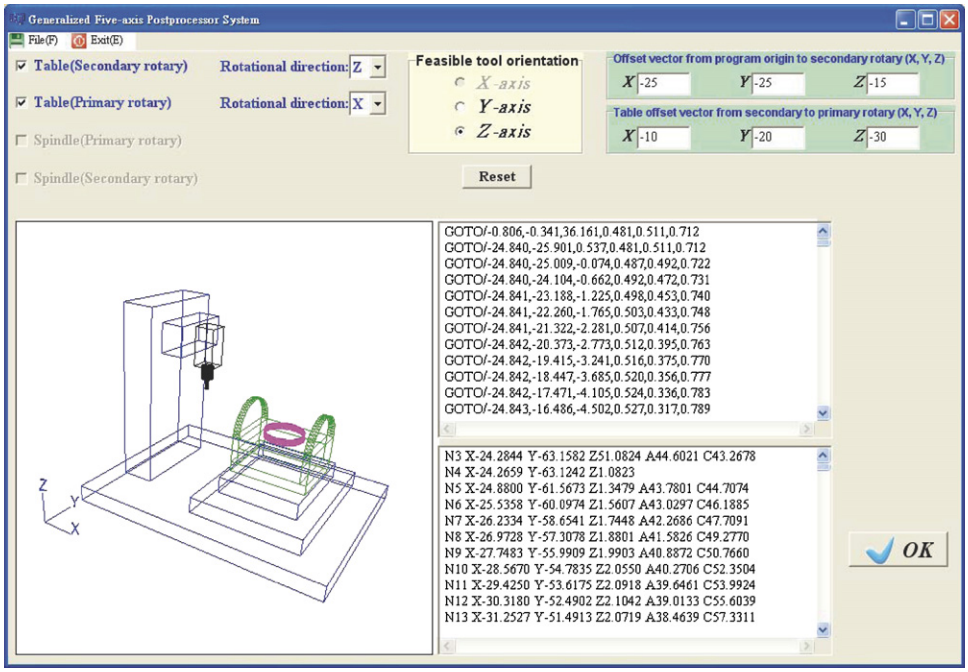

Fig. 4. Execution dialog for generating the table-tilting type machine tool's NC data.

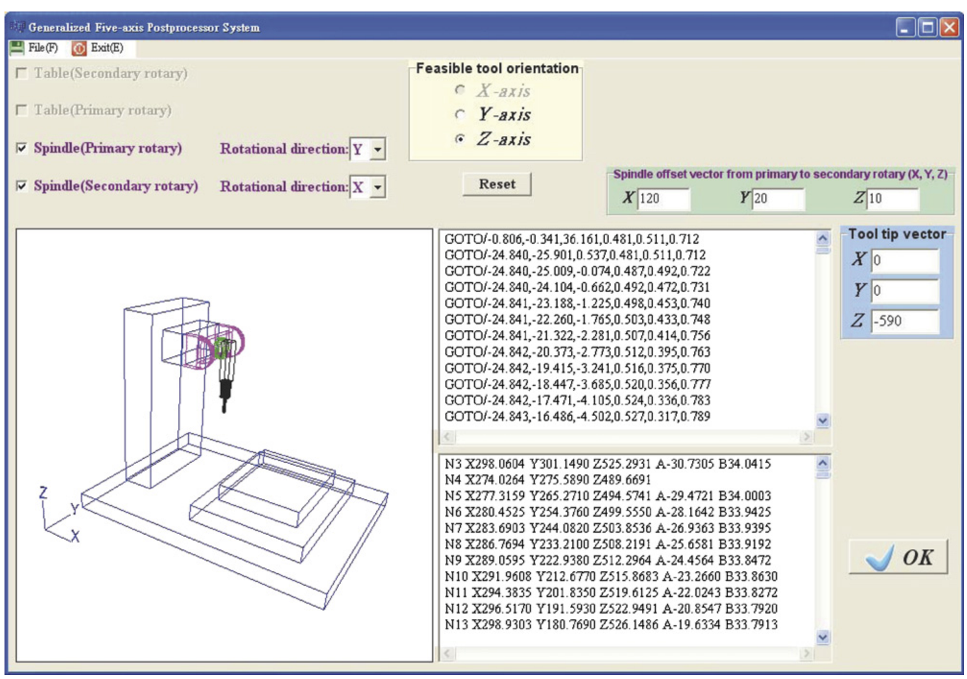

Fig. 5. Execution dialog for generating the spindle-tilting type machine tool's NC data.

4.3. Machining experiment

The effectiveness of the presented postprocessor was conducted in an experiment to machine a turbine blade on a table/spindle-tilting type machining centre. The CL data for machining the turbine blade is generated by the Unigraphics® CAM module and then converted to the NC code by the developed postprocessor software. The aluminium alloy workpiece was cut by a CNC lathe machine and then clamped on the rotary table of a five-axis machine tool. Figs. 8 and 9 show the actual machining and the machined turbine blade, demonstrating that the proposed methodology can be successfully applied to the practical five-axis machining.

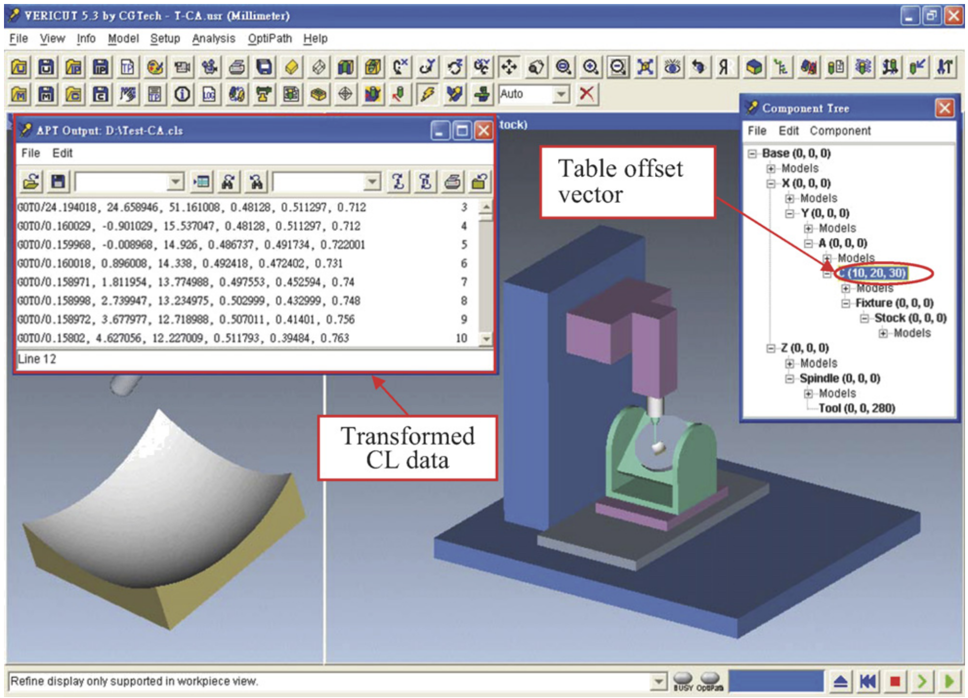

Fig. 6. Screenshot of the VERICUT® simulation and verification for the table-tilting type machine tool.

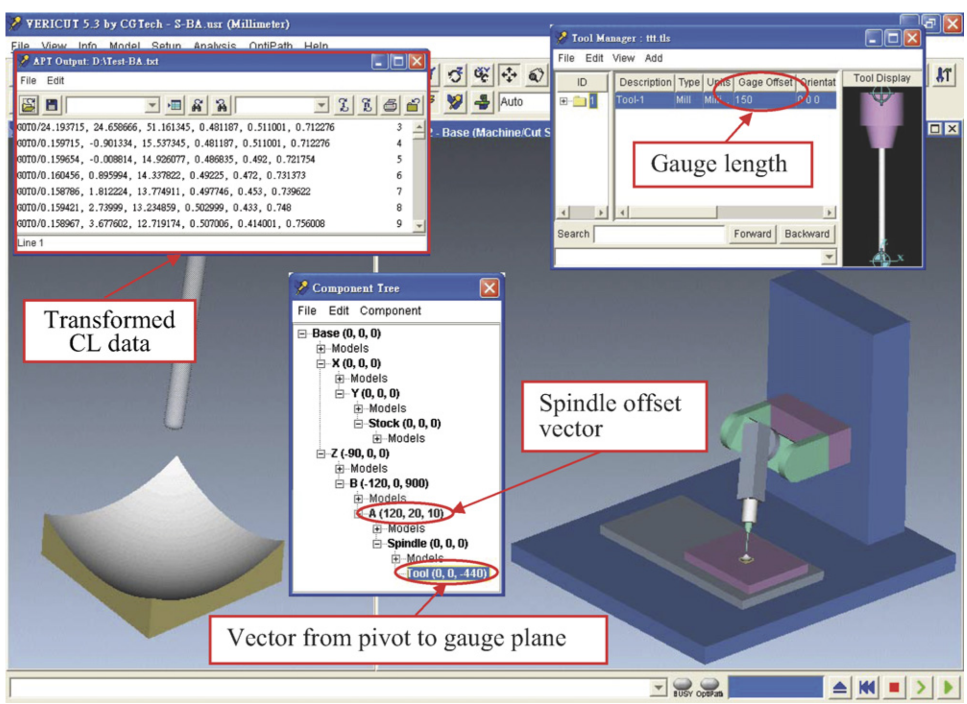

Fig. 7. Screenshot of the VERICUT® simulation and verification for the spindle-tilting type machine tool.

5. Conclusion

This paper has proposed a generic five-axis postprocessor methodology based on the generalized kinematics model. The analytical equations of NC data for various five-axis machine tools with three orthogonal linear axes and two orthogonal rotational axes can be explicitly expressed in terms of CL data. Moreover, the NC data for a specific machine tool can be transformed to the other machine tool configuration using the derived analytical

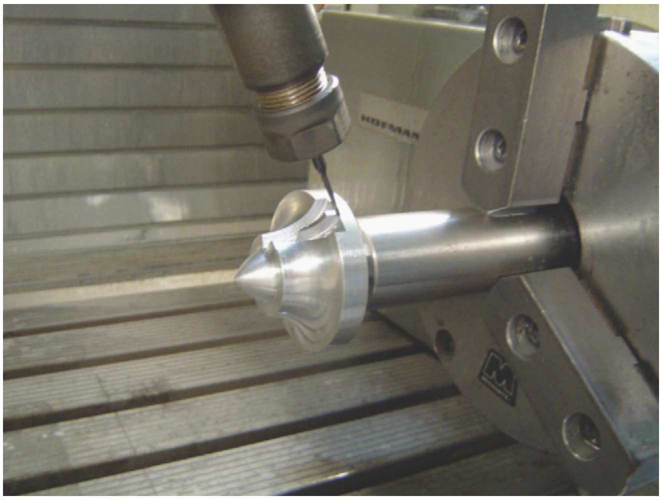

Fig. 8. Machining experiment on a table/spindle-tilting type machine tool.

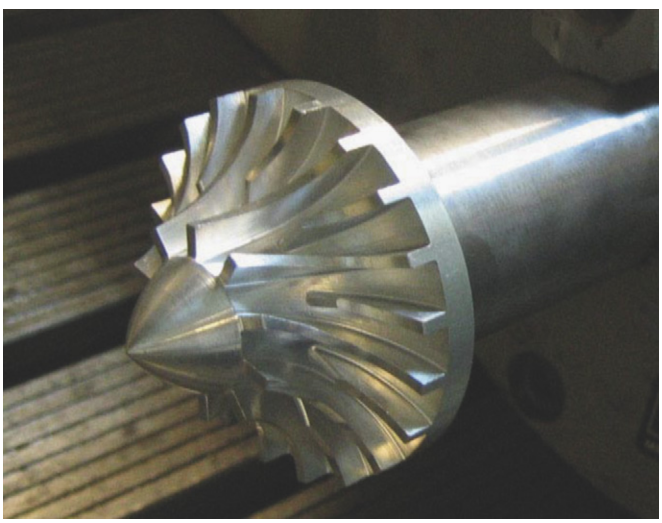

Fig. 9. Snapshot of the machined turbine blade.

equations so that the portability of the NC data can be greatly promoted. The presented methodology is a general form that can make the design of five-axis postprocessors more efficiently and systematically.

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