# Design And Research on Machining Orientation Control Based on Five Axis CNC Machine Tools

Hualiang Li *

School Of Civil Engineering, Southwest Jiaotong University, Chengdu, China, 611756

* Corresponding Author Email: 17877876495@163.com

**Abstract.** This article establishes a model for machining orientation control of a five axis CNC machine tool based on methods such as constructing translation matrix, rotation matrix, and composite matrix. Using the optimal path and rotation angle search algorithm based on rotation transformation and composite transformation, the displacement of the machining center relative to the initial state, the rotation angle of the rotation axis, and the drilling number under the minimum total displacement and total rotation angle are studied. For the given machining task and initial state, since the required holes (simplified as line segments) are all perpendicular to the X-axis, Bi=0 is obtained. This article first obtains the rotation angle Ai around the A-axis through the given angle conditions, and then establishes a composite transformation equation around the A-axis to solve for the new coordinates of each machining center, hole and plate intersection point after composite transformation. The displacement from the intersection point to the drill bit is the same as the displacement from the machining center to the drill bit, in order to determine the displacement of the machining center relative to the initial state. If the parameters of the first hole processed are (x1, y1, z1), $(0,1)=(25,44,106,24)$, the displacement of the machining center relative to the initial state, and the required rotation angles $(A_1, B_1, X_1, Y_1, Z_1)=(66,0,-15,-159.732,113.082)$. (A1, B1, X1, Y1, Z1)=(66, 0, −15, −159.732, 113.082) 1..

**Keywords:** Rotation Matrix, Composite Transformation Equation, Azimuth Control Optimization Algorithm, Optimal Search Algorithm.

## 1. Introduction

Five axis linkage CNC machine tool is a high-precision high-tech equipment that can process complex spatial surfaces. At present, the five-axis linkage CNC machine tool has become one of the core equipment in the high-end equipment manufacturing industry. Technically, its spindle speed can reach tens of thousands of revolutions per minute, and in terms of machining accuracy, it reaches the micrometer level. Five axis CNC machine tools also have the characteristics of high stiffness, stability, and reliability, which enable them to ensure efficient and stable machining results in practical applications. It is widely used in the manufacturing of precision components, such as impellers, blades, and marine propellers. This machine tool has five active coordinate axes, including three linear moving coordinate axes (X, Y, Z) and two rotating coordinate axes (A, B) [1], and can achieve complex collaborative motion under the control of a computer numerical control system. During the machining process, the drill bit remains vertical and only moves up and down along the Z-axis, while the center of the flat plate is located on the Z-axis. In the initial state, all displacement and rotation angles are zero. The CNC system guides the machining center to reach the predetermined position and direction by precisely controlling three displacements and two rotation angles, achieving the machining of inclined holes in different directions on the flat plate. (Data source: Provided by the Mathematical Modeling Competition of Southwest Jiaotong University)

## 2. Construction of geometric relationship of rotation angle of rotation axis

### 2.1. A-axis rotation angle

For the convenience of constructing the model, this article first moves the hole to be processed to the center position P of the zeroed flat plate, and then projects it onto the Y OZ plane θ I>0 θ the schematic diagram for processing the flat plate in two cases where i<0 is shown in Fig.1:

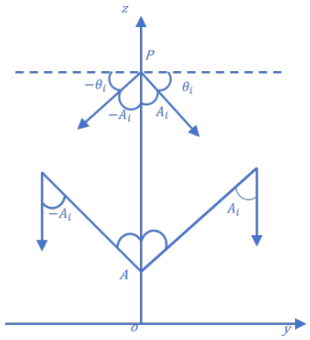


**Figure.1.** A-axis rotation angle Ai and θi Relationship Diagram

After projection, point A represents the projection of the A-axis on the Y OZ plane. After the hole (line segment) rotates around the A-axis by an angle of Ai, its direction is the negative direction of the Z-axis. The arrow represents the drilling direction. When processing the i-th hole, the A-axis rotation angle Ai is the angle between the projection of the hole on the Y OZ plane and the y-axis θ There is a relationship between i as follows:

$$A\begin{cases}\dfrac{\pi}{2}-\theta_i,\theta_i>0\\ -\left(\dfrac{\pi}{2}+\theta_i\right),\theta_i<0\end{cases} \tag{1}$$

Since the required holes (simplified as line segments) are all perpendicular to the X-axis, the rotation angle Bi of the B-axis [2] satisfies:

$$B_i=0 \tag{2}$$

### 2.2. Construction of composite matrices

Translation transformation refers to moving each point on a graph in the same direction and distance, so that the position of the entire graph in space changes, but the shape, size, and direction of the graph remain unchanged. The translation transformation of the coordinate system is shown in Fig.2:

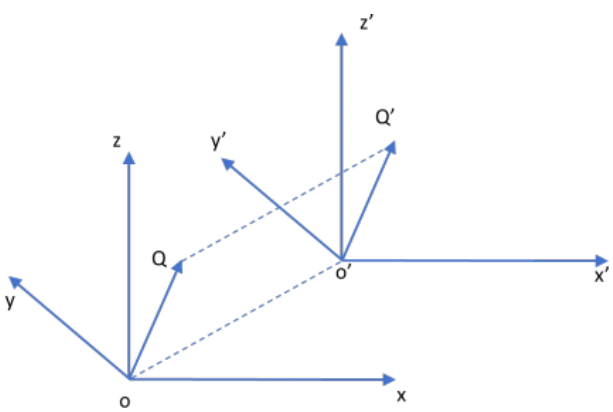



**Figure.2** Translation transformation of coordinate system

The coordinate system O′- x′y′z′ is a new coordinate system that has been transformed by translation from the coordinate system O−xyz, and both have the same attitude. The position of point Q in the coordinate systems O-xyz and O′- x'y'z 'is represented by O-xyzQ and O′- x'y'z'Q, respectively. The origin of the coordinate systems O′- x'y'z' and O-xyz is represented by O′- x'y'z'E and O-xyzEA, respectively. After vector addition, the following relationship can be constructed:

$$^{O'-x'y'z'}Q = ^{O-xyz}Q + ^{O'-x'y'z'}E_A \tag{3}$$

Among them, the translation transformation matrix EA with the A-axis as the rotation axis can be expressed as:

$$E_A = \begin{pmatrix} 0 \\ 0 \\ z_i - h_A \end{pmatrix} \tag{4}$$

### 2.3. Rotational transformation

Rotation transformation refers to rotating a shape around a fixed point (rotation center) at a specific angle, so that each point on the shape changes its position in this way, but the overall shape and size of the shape remain unchanged. The schematic diagram of the rotation of the coordinate system O-xyz around the x-axis is shown in Fig.3:

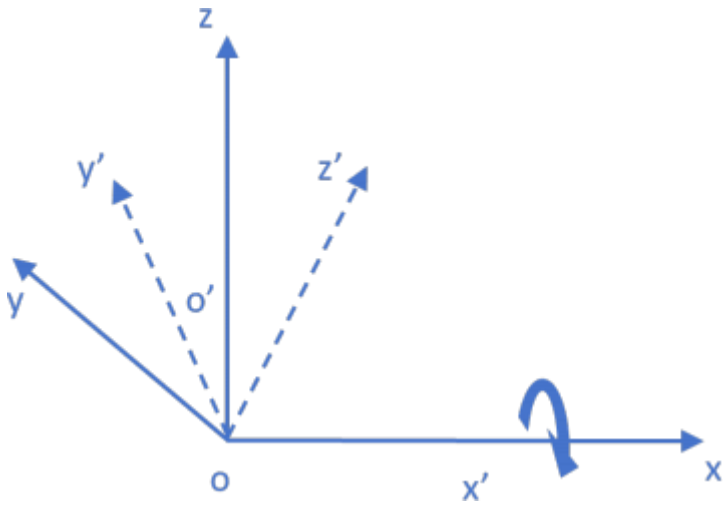



**Figure.3** Rotation transformation of coordinate system

The rotation matrix R (Ai) [3] obtained by rotating the coordinate system O-xyz around the x-axis can be expressed as:

$$R(A_i) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(A_i) & -\sin(A_i) \\ 0 & \sin(A_i) & \cos(A_i) \end{pmatrix} \tag{5}$$

Among them, R (Ai) is a 3x3 rotation matrix used to rotate the coordinate system around the A-axis by an angle of Ai. The Q point in space is represented by position vectors O-xyzQ and O′- x'y'z'Q in the coordinate systems O-xyz and O′- x'y'z'z ', respectively. The two position vectors have the following relationship:

$$^{O'-x'y'z'}Q = R(A_i)^{O-xyz}Q \tag{6}$$

### 2.4. Composite matrix

For any point Q on the coordinate system O′- x′y′z′, if its coordinates are to be represented by the coordinate system O−xyz, a composite transformation is required, which includes translation transformation and rotation transformation. The schematic diagram is shown in Fig.4:

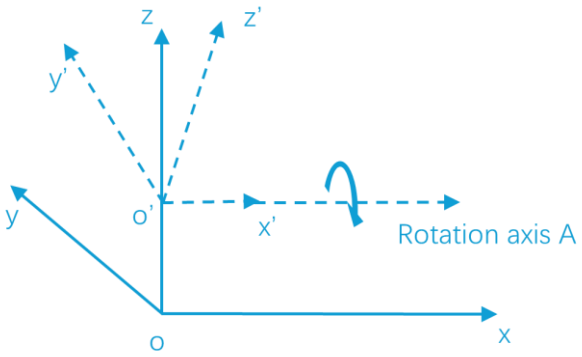



**Figure.4** Composite transformation of coordinate system

The origin and attitude of the coordinate systems O−xyz and O′-x′y′z′are different. For the position vector O′-x′y′z′Q of point Q, it can be obtained through composite transformation in the coordinate system O−xyz. The composite transformation equation [4] is as follows:

$$^{O'-x'y'z'}Q = R(A_i)^{O-xyz}Q \tag{7}$$

### 2.5. New coordinates of the intersection point between the machining center, hole, and plate surface

#### 2.5.1 New coordinates of machining center after composite transformation

The coordinates of the machining center in the coordinate system O-xyz are (0, 0, 0), and after composite transformation, their coordinates are represented as (xci, yci, zci) [5], and the two satisfy the following relationship:

$$^{O-xyz}\begin{bmatrix} x_{ci} \\ y_{ci} \\ z_{ci} \end{bmatrix} = R(A_i)\left( ^{O-xyz}\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} - E_A \right) + E_A \tag{8}$$

#### 2.5.2 The new coordinates of the intersection point between the hole and the board surface after composite transformation

Similarly, let (xi ', yi', zi ') [6]be the new coordinates of the intersection points of each hole and the plate surface after composite transformation, then:

$$^{O-xyz}\begin{bmatrix} x_i' \\ y_i' \\ z_i' \end{bmatrix} = R(A_i)\left( ^{O-xyz}\begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} - E_A \right) + E_A \tag{9}$$

#### 2.5.3 The coordinate increment of the intersection points between the hole and the plate surface translated to the drill bit

The coordinate increment ($x_{iB}$, $y_{iB}$, $z_{iB}$) can be obtained from the drill bit coordinates ($x_0$, $y_0$, $z_0$) in the zeroing state and the new coordinates (xi ', yi', zi ') [7] of the intersection point between the hole and the plate surface after composite transformation:

$$\begin{cases} \Delta x_i = x_0 - x_i' \\ \Delta y_i = y_0 - y_i' \\ \Delta z_i = z_0 - z_i' \end{cases} \tag{10}$$

### 2.5.4 The displacement of the machining center relative to the initial state

According to the coordinate increment of the machining center during translation and the coordinate increment of the intersection point between the hole and the plate surface being the same, the displacement (Xi, Yi, Zi) [8] of the machining center relative to the initial state when machining the i-th hole can be given by the following equation:

$$\begin{cases} X_i = x_{ci} + \Delta x_i \\ Y_i = y_{ci} + \Delta y_i \\ Z_i = z_{ci} + \Delta z_i \end{cases} \tag{11}$$

### 2.6. Model solving results

Under given conditions, based on the above model, the B-axis rotation angle Bi=0 is obtained. This article also provides the displacement of the machining center relative to the initial state (Xi, Yi, Zi), and the required rotation angle Ai for the A-axis. The relevant solution results are shown in Tab.1:

**Table.1:** Model solution results

| Number | Ai | Bi | Xi | Yi | Zi |
|---|---|---|---|---|---|
| 1 | 66 | 0 | -15 | -159.732 | 113.082 |
| 2 | 78 | 0 | -15 | -153.258 | 115.481 |
| 3 | -78 | 0 | -15 | 63.258 | 115.481 |
| 4 | -66 | 0 | -15 | 69.732 | 113.082 |
| 5 | -66 | 0 | -2.5 | 69.732 | 113.082 |
| 6 | -78 | 0 | -2.5 | 63.258 | 115.481 |
| 7 | 78 | 0 | -2.5 | -153.258 | 115.481 |

## 3. Construct a rotation equation for any point around any axis

### 3.1. A. B-axis rotation angle

When both the A and B axes rotate, the rotation of the B axis has no effect on the rotation of the A axis. Therefore, the rotation angle of the A axis is consistent with the rotation angle of the A axis mentioned above, and there is the following relationship:

$$A = \begin{cases} \dfrac{\pi}{2} - \theta_i, \theta_i > 0 \\ -\left(\dfrac{\pi}{2} + \theta_i\right), \theta_i < 0 \end{cases} \tag{12}$$

For the convenience of constructing the model, this article first moves the hole to be machined to the center position P of the zeroed flat plate. For solving the rotation angle of the B-axis, it is projected onto the XOZ plane $\varphi_i > 0$ 、 $\varphi_i < 0$, The schematic diagram for processing the flat plate in two cases where i<0 is shown in Fig.5:

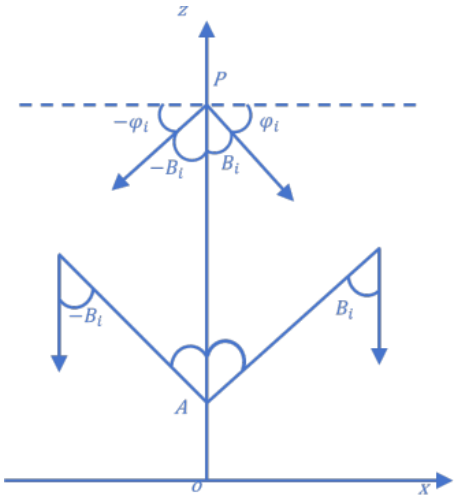



**Figure.5** B-axis rotation angle Bi and φi Relationship Diagram

After projection, point B represents the projection of the B-axis on the XOZ plane. After the hole (line segment) is rotated by an angle of Bi around the B-axis, its direction is the negative direction of the Z-axis. The arrow represents the drilling direction. When processing the i-th hole, the rotation angle of the B-axis, $B_i$, is the angle between the projection of the hole on the XOZ plane and the x-axis $\varphi_i$ There is a relationship between i as follows:

$$A=\begin{cases}\dfrac{\pi}{2}-\theta_i, \theta_i>0\\ -\left(\dfrac{\pi}{2}+\theta_i\right), \theta_i<0\end{cases} \tag{13}$$

### 3.2. Proof of the relationship between rotation of A-axis and no effect on Bi

If there is a vector o'a on the coordinate system o-xyz, and the projection vectors of this vector on yoz and xoz are a-yoz and a-xoz, respectively, then translate the coordinate system o-xyz to the x-axis and coincide with the A-axis. The coordinate system o-xyz and vector o'a rotate around the A-axis to obtain the coordinate system o-xy'z 'and vector o'a', respectively. The projection vectors of vector o'a 'on y'oz' and xoz 'are a-y'oz' and a-xoz ', respectively. According to the projection related properties, it can be inferred that the vectors o'a and z' The angle between the positive half axis of the axis and the angle between the vector o'a 'and the positive half axis of the z-axis are both Bi, indicating that rotating the A-axis has no effect on $B_i$ [9], as shown in Fig 6

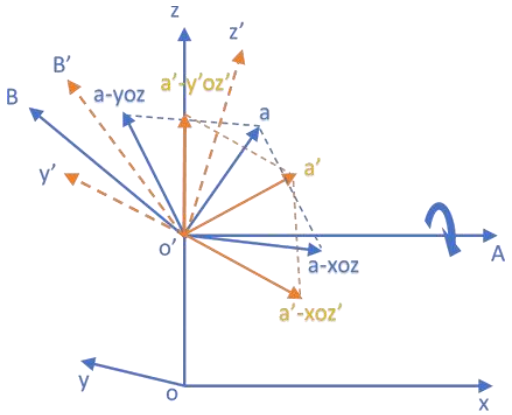



**Figure.6** Schematic diagram of proving the relationship between rotating the A-axis and having no effect on Bi

### 3.3. Establishment of the Equation for Rotation Around Any Axis at Any Point in Three-Dimensional Space

For any point P (Px, Pg, Pz) in three-dimensional space, assume its rotation angle around any axis α Obtain new points P′ (P′x, P′g, P′z) [10], The unit direction vector of the axis is NNN, and the schematic diagram of passing through point QQ is shown in Fig.7.

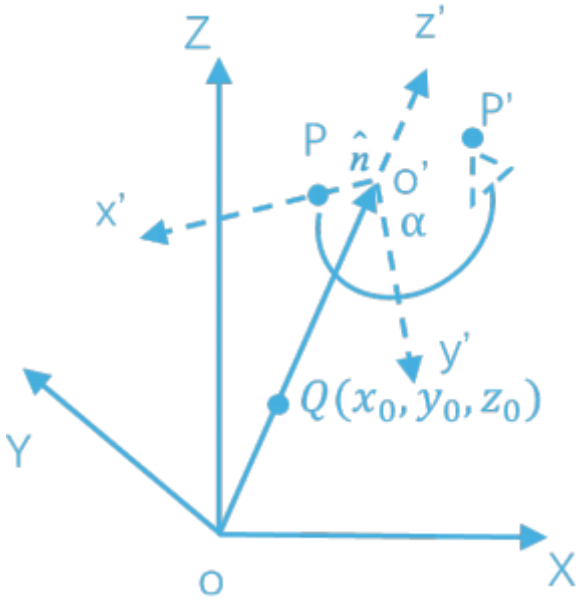



**Figure.7** Rotation relationship of any point in three-dimensional space around any axis

### 3.4. Calculation results

Under the given conditions, the algorithm is solved based on the model. This article provides the required rotation angle Ai for the A-axis, the required rotation angle Bi for the B-axis, and the displacement of the machining center relative to the initial state (Xi, Yi, Zi). The relevant solution results are shown in Tab.2:

**Table.2** Model Solution Results

| Number | Ai | Bi | Xi | Yi | Zi |
|---|---|---|---|---|---|
| 1 | 70 | 60 | -99.171 | -36.996 | 38.107 |
| 2 | 78 | 60 | -97.864 | -23.210 | 57.829 |
| 3 | 86 | 60 | -95.704 | -15.303 | 79.640 |
| 4 | -86 | 60 | -95.704 | -74.697 | 79.640 |

## 4. Conclusions

This article establishes a model for machining orientation control of a five axis CNC machine tool based on methods such as constructing translation matrix, rotation matrix, and composite matrix. Using the optimal path and rotation angle search algorithm based on rotation transformation and composite transformation, the displacement of the machining center relative to the initial state, the rotation angle of the rotation axis, and the drilling number under the minimum total displacement and total rotation angle are studied. At the same time, the orientation control of CNC machining parts has been well achieved, which can better describe the motion of the machining parts in the spatial Cartesian coordinate system, calculate and analyze the coordinates of the motion process. The model has good scalability and can add a degree of freedom or a fixed axis according to the actual situation, making it easy to transfer the model to other practical problems.

## References

[1] Wang Leiyuan, Qin Cuilan, Zhao Qunxi, et al. Development Status and Trends of Five Axis Linkage CNC Machine Tools [J]. Southern Agricultural Machinery, 2024,55 (03): 30-33

[2] Rao Yongjian, Fu Guoqiang, Tao Chun, et al. Universal Post Processing for Five Axis 3D Printing [J]. China Mechanical Engineering, 2021,32 (1): 74-81

[3] Wang Min, Hu Jianzhong, Zan Tao, et al. Modeling and testing techniques for motion errors in five axis CNC machine tools [J]. Journal of Beijing Institute of Technology, 2010,36 (4): 433-439

[4] Cai Anjiang, Liu Chenyang, Wang Peipeng. Post processing algorithm for five axis CNC machine tools under rotation angle optimization [J]. Journal of Jilin University (Engineering Edition), 2023,53 (9): 2493-2498

[5] Zhang Wenbin, Liu Huanlao, Wang Yulin, et al. Identification of geometric errors independent of position for the rotation axis of a dual turntab.five axis machine tool [J/OL]. China Mechanical Engineering,1-12 [2024-04-28]

[6] Wang Shida, Pan Guorong. Research on Closed Solution Models for Spatial Similarity Transformation of Large Rotation Angle [J]. Surveying and Mapping Geographic Information, 2021,46 (S1): 282-287.

[7] Jiang Lei, Zhang Yue Xinkai, Liang Bin, et al. Research on Machine Tool Motion Pose Algorithm for Five Axis CNC Machining Simulation [J]. Aviation Manufacturing Technology, 2023,66 (05): 47-55.

[8] Meng Tianfang. Geometric error identification and compensation of five axis CNC machine tools based on conformal geometry algebra [D]. Tianjin University of Technology, 2022.

[9] Chen Xiaohua, Liu Zhibing, Wang Xibin, et al. Kinematic Characteristics Analysis of Typical Parts in Turning and Milling Composite Processing [J]. Computer Integrated Manufacturing System, 2013,19 (07): 1569-1576.

[10] Li Zimao, Tang Xianyi, Yin Fan, et al. Adaptive knowledge representation method based on three-dimensional space rotation and translation [J]. Computer Application Research, 2024,41 (01): 59-64.