Study on the Safety for Five-axis CNC Machine with A―C Dual Rotary Tables

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Abstract. In order to solve the problem of interfering and processing blinds in the machining of five-axis machine tools with A-C dual rotary tables, the actual situation of NC machining was analyzed. Starting from the cause of problem, two aspects were selected to avoid the interference of the tool, handle or spindle parts with non-processing parts. One is to set the CAM software to control the tool spindle. Another method is to calculate the safe height of the fixture to lift the workpiece. Then the problem of processing blind spots was solved through optimization of the A, C rotation angle to rule A angle value was zero or negative. Finally, the VERICUT software simulation and example machining were used to verify great practical value that these three methods promotes the safety of five-axis machine tools with A―C dual rotary table.

1. Introduction

The five-axis CNC machine tool adds two to the traditional three-axis machine tool. Each rotation axis can make the tool reach any spatial position and direction, but it also makes the tool movement more complicated, which greatly increases the possibility of collision and interference between the tool or the spindle and other components[1]. This article mainly discusses the safety of CNC machining of A-C double-turn table five-axis machining center. (As shown in the figure 1)

![Coordinate system relation of five-axis machining center of A-C double rotary table](image_url)

Figure 1. Coordinate system relation of five-axis machining center of A-C double rotary table

In the actual processing process, five-axis machining of A-C double turntable Interferences and collisions in the center CNC machining include: interference between the tool and the workpiece or fixture; interference between the tool holder and the workpiece or fixture; interference between the
machine tool spindle and the table[2]. Through the analysis of these three cases, it is found that the first two cases are mainly due to the poor control of the tool axis during the programming process, while the third case is because the A-turn angle is too large and the height between the workpiece and the table is not sufficient, resulting in the spindle interfere with the table during the machining process. At the same time, it has been found in production practice that when the A angle of the A-C double-turn table five-axis machine tool is positive, the operator's line of sight is blocked, the machining process is not easy to observe, it is difficult to ensure the safety of the machining process, and it is particularly not suitable for the first test Cutting or machining of important parts. Finally, due to the high cost of five-axis CNC machine tools and the complex tool movements, there are high requirements for the safety of their machining programs. Generally, in some factories, in order to verify the safety of the program, the program is run on the machine tool or the feed speed is reduced for trial cutting[3]. Not only is this inefficient and time-consuming, but some accident may also occur.

This paper mainly from the four aspects of CAM software programming, A-C rotation Angle optimization, fixture safety height calculation and the use of numerical control simulation software Vericut verification NC program, to improve the safety of A-C double turntable five-axis machining center NC machining.

2. CAM Software programming
When using CAM software to program, the five axis tool path, because of the large free space of the tool axis, it is easy for the tool to interfere with the non-machining parts. In order to avoid the interference between the tool and other parts, learn to control the movement space of the tool axis:

- when calculating the tool path, add the tool handle model consistent with the actual size of the tool path. In this way, the interference between the tool, the handle and the non-machining part of the workpiece can be avoided.
- Add the fixture model to the tool path, and set it as the colliding body, which means to add some constraints to the tool axis, limit its movement space, and avoid interference with the fixture in the process of machining.

At present, the mainstream CAM software with five axis function includes hyper MILL, Power MILL, UG Master cam, etc. These software generally has the function of tool path checking and anti-collision. When using Power MILL software to program, the five axis impeller model, add the tool handle and fixture model to the program (as shown in Figure 2), and set the collision in the "part allowance" tab The model of the fixture is set as the collision body to directly participate in the calculation of five axis tool path, which avoids the risk of interference and collision between the tool, tool handle and other parts, and improves the safety of five axis machining.

Figure 2. Add tool holder and tool
3. Optimization of rotation angles A and C

Generally, for A-C double-turn table five-axis machine tools, when the A-axis rotates to a positive angle, the line of sight of the machine operator is blocked by the rotating table (as shown in Figure 3), which is not convenient to observe the processing process and is not conducive to ensuring the processing Safety.

![Figure 3. The machining blind zone when axis A Angle is positive](image)

In order to solve the problem of the blind zone of the machine tool, the angle A can be specified to be zero or negative during the post-processing process. In this way, the process of processing the parts is facing the machine operator, and its line of sight is not obstructed.

The calculation of A and C rotation angles is generally determined by the tool axis vector \((i, j, k)\). \((i, j, k)\) is the unit vector of the tool axis of the tool in the workpiece coordinate system. The tool axis vector is first rotated by the C angle around the Z axis to the YOZ plane, and then rotated by the A angle around the X axis, which can be consistent with the Z axis direction. In order to ensure that the rotation angle A of the A turntable is always negative, all the tool axis vectors must be converted to the (+ Y) OZ plane, that is, the tool axis vector \((i, j, k)\) is first rotated along the Z axis Rotate C \((0 \leq C \leq 360^\circ)\) in the clockwise direction to (+ Y) OZ plane, and then rotate A in the clockwise direction around the X axis \((-120^\circ \leq A \leq 0)\). The angle is consistent with the Z-axis direction. Since the rotation of the turntable and the swing of the tool are a relative process, this process can be seen as the turntable first rotates A around the X axis and then rotates C around the Z axis. The five-axis tool axis vector conversion diagram is shown in Figure 4. The calculation results of angles A and C are as follows:

![Figure 4. The five-axis tool axis vector conversion diagram](image)

The calculation results of angles A and C are as follows:
4. Calculation of fixture safety height

When using A-C double-turn 5-axis machining center for 5-axis simultaneous machining, the A-axis rotates a certain angle, and the machine tool spindle and the table plane have a certain angle. If the height of the blank and the table is very low, the spindle is very easy to interfere with the workbench. Especially when the A-axis rotates 90° or more than 90°, the distance between the machine tool’s spindle and the table decreases, and interference is extremely likely to occur at this time. Therefore, in order to improve the safety of five-axis machining, it is necessary to design a special fixture to lift the workpiece to a safe height to avoid the danger of collision.

When using A-C dual-turn 5-axis machining center for 5-axis simultaneous machining, the A-axis rotation angle is less than 90° and more than 90°, the positional relationship between the workpiece and the tool is different, so when calculating the safe height of the fixture, with the A-axis rotated 90° as the limit, it is discussed in two cases.

4.1. \( A_{\text{MAX}} \leq 90° \)

Generally, when determining the safe height of the jig or checking whether the height of the jig is safe, it is necessary to know the maximum angle of rotation of the A axis in the machining program for processing the part. For the calculation of the A angle, the tool axis vector in the tool position file can be substituted into equation (1) to calculate and find the maximum value of A. For easy calculation, the fixture is usually installed in the middle of the workbench. Figure 5 (a) is a schematic diagram of the critical collision between the spindle and the table when the A-axis rotation angle is less than 90°. The O coordinate system is fixedly connected to the middle of the table, and its initial state is consistent with the direction of the machine coordinate system. Since the fixture cannot be installed exactly in the middle of the workbench during the actual processing, the dotted line in the figure indicates that the fixture is offset from the middle of the workbench. If biased to the negative direction of Y, it means that assuming that the distance of the collision point is longer, the offset length should be added to the corresponding length in Figure 5 (b); if it is offset to the positive direction of Y, the offset should be

\[
A = \begin{cases} \arctan \frac{i}{j} & (k > 0) \\ -90° & (k = 0) \\ -90° + \arctan \frac{k}{\sqrt{i^2 + j^2}} & (k < 0) \end{cases}
\]

\[
(120° \leq A \leq 0, i^2 + j^2 + k^2 = 1)
\]

\[
C = \begin{cases} 270° + \arctan \frac{j}{i} & (i > 0, j \geq 0) \\ 90° - \arctan \frac{j}{i} & (i < 0, j \geq 0) \\ 90° + \arctan \frac{j}{i} & (i < 0, j < 0) \\ 270° - \arctan \frac{j}{i} & (i > 0, j < 0) \end{cases}
\]

\[
C = 180° (i = 0, j < 0) \\
C = 0° (i = 0, j > 0)
\]
subtracted from the corresponding length in Figure 5 (b) Figure 5 (b) is a simplified geometric diagram, and the dashed lines in the figure are auxiliary lines.

![Diagram of critical collision and geometric diagram](image)

**Figure 5.** the rotation Angle of axis A is less than 90°

Precondition for collision between spindle and worktable: the distance between installation position of fixture and theoretical critical collision point in Y direction shall be less than or equal to the actual distance between them, that is:

\[ k - b \pm g \leq r_1 - b \pm g \]  \hspace{1cm} (1)

Where, + indicates that the installation position of the fixture is offset in the negative direction of Y; - indicates that the installation position of the fixture is offset in the positive direction of Y. Safety height of tooling H:

\[ H = (d + a + r_2) \sin A - e \cos A \]  \hspace{1cm} (2)

Here \( r_1 \) is half of the length of turntable A in Y direction; \( a \) is half of the width of spindle in Y direction; \( b \) is half of the length of blank in Y direction; \( d \) is the safety clearance between spindle and worktable; \( e \) is the vertical height from tool tip to collision risk point; \( k \) is the distance from the middle of turntable to collision risk point in Y direction; \( g \) is the distance of fixture from the middle of worktable in Y direction; \( H \) is the safe height of tooling; \( A \) is the maximum swing angle of turntable A.

4.2. \( |A_{max}| \geq 90° \)

Fig. 6 (a) is a schematic diagram of the hypothetical collision between the main shaft and the workbench when the rotation angle of the axis A is greater than 90°. Fig. max6 (b) is a simplified geometric schematic diagram, in which the meaning of each letter is the same as that of Fig. 5, which will not be repeated here.
When the rotation angle of the axis A is more than 90°, the case of collision is that the edge of the worktable interferes with the main axis, so the vertical distance from the tool tip of the collision risk point is always less than or equal to the movement distance of the main axis in the Z direction.

Safety height of tooling:

\[
H = \frac{d+a-r_2}{\sin A} - \frac{r_1-b \pm g}{\tan A}
\]  

5. Simulation and verification of five-axis NC machining based on VERICUT

The five axis machining program is a space coordinate point. The simulation provided by CAM software only simulates the movement path of the tool, and cannot verify the machining program of the final control machine tool, which brings great risk to the machining. A little omission will cause great loss to the machine tool and users[6].

By using VERICUT, we can simulate the machining process of the machine tool in the virtual environment of the computer, find and correct the errors in the program in time, avoid the collision and interference of the machine tool, protect the machine tool effectively, improve the efficiency and machining quality[7]. Figure 7 shows the process of machining simulation with VERICUT.

In order to get closer to the actual machining environment, when Vericut is used for simulation, all settings should be consistent with the actual situation[8]: (1) firstly, according to the actual machine tool, the main motion modules are decomposed and simplified to draw the 3D model of each component; Secondly, according to the dependency relationship between the parts of the machine tool, the whole digital model of the machine tool is built in VERICUT software. It should be noted that there is a certain distance between the axis of the rotary axis of the a-c double turntable, five-axis machine tool and the end face of the spindle. This distance must be fully considered consistent with the actual machine size after assembly when establishing the machine model; otherwise, the direct connection will lead to the failure of simulation processing. (2) Next, according to the blank and fixture used in practice, build the relevant digital model, add it under the “stock” and “fixture” nodes of the machine structure tree, and set its placement position and direction. When establishing a tool, it must be consistent with the setting in the cam software, including the tool diameter, tool extension length, tool handles size, etc. The setting of the machining coordinate system is the same as the actual tool setting principle, mainly to determine the distance from the spindle end face to the programmed zero point. (3) Finally, the MDI can be used to check whether the zero point of machining and the zero point of machine tool coincide, to check whether the tool setting is correct. After all the settings are completed, the simulation can be performed.
Figure 7. Vericut Process of machining simulation

Figure 8 shows the simulation of machining impeller with VERICUT on A-C double turntable five axis machine tool. The collision and interference are found in time by simulation, and the tool path and cutting parameters are optimized. Finally, the actual machining of impeller is carried out by DMU 65 mono block five axis machining centre. There is no collision or interference in the whole machining process. The actual machining effect is completely consistent with the simulation result, and the satisfactory machining effect is finally achieved. Figure 9 is an example of impeller machining.

Figure 8. Vericut Impeller machining simulation

Figure 9. DMU 65 Mono BLOCK impeller machining example
6. Conclusion
The CNC machining of five-axis machine tool includes the kinematics of machine tool, CAD / CAM technology, post-processing, machining tool and machining technology. From the point of view of geometric simulation, aiming at the problem of interference and machining blind area of A-C double turntable, five axis machine tool, the author discusses the machining safety from four aspects: CAM software programming, optimization of A and C rotation angles, fixture safety height and VERICUT simulation. In this way, the accidents in processing are avoided to the greatest extent, the safety of CNC processing is greatly improved, the cost is saved, and the production efficiency is improved. However, this kind of geometric simulation cannot avoid the danger of tool fracture, tool wear and the vibration of the whole process system of the tool work piece in the process of quitting due to excessive cutting force. With the continuous development of simulation technology and finite element technology, the combination of geometric simulation and physical simulation may have more scientific guidance and practical significance for CNC machining.

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