Post-processing optimization algorithm for blade six-axis NC machining

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Abstract. In order to solve the problem of fluctuation in the six-axis NC polishing machining, in this paper, a post-processing optimization algorithm for six-axis NC polishing machining is proposed, which can solve the problem of fluctuation in the machining process of six-axis NC machining. First, the initial A-axis angle value corresponding to the tool position is solved according to the tool position information contained in the toolpath file; Second, use B-spline to smooth the data of A-axis, and solve the corresponding B-axis and C-axis angle value according to the angle value of A-axis; Third, calculate the moving value of X-axis Y-axis and Z-axis to realize the post-processing of the toolpath file; Finally, the algorithm is verified that it can solve the machine trajectory fluctuation in the current six-axis post-processing using VERICUT and the machining experiments, and realize the high quality six-axis NC polishing machining.

1. Introduction

At present blade profile polishing process methods have manual polishing, industrial robot polishing and NC machine tool polishing[1]. The manual polishing is being phased out due to the lack of guarantee of contour and surface consistency[2]. In recent years, industrial robot polishing has made important progress in such techniques as precise calibration of system, efficient matching of measuring point cloud, adaptive planning of machining trajectory, and precise control of flexibility force. However, the research is still in the exploratory stage[3]. NC machine polishing has been widely used in China because of its good rigidity and high machining accuracy. In order to realize the polishing task of various complex blades, 6-axis NC machine tools are usually used for polishing[4]. However, the six-axis NC machine has movement redundancy, and different motion planning will affect the final machining quality and machining efficiency.

In the post algorithm for motion solution of six-axis NC machine, Guangling Wu[5] got the initial c-axis according to the direction of the minimum principal curvature of the surface. After smoothing the initial C-axis solve the A-axis and B-axis angle, however, the current general CAM system cannot directly output the minimum principal curvature and other information of the surface, also in the processing process, such as when the direction of the minimum principal curvature is approximately parallel to the a-axis, the phenomenon of tool path singular region is very easy to occur in the post-processing process, affecting the processing quality [6]. Jingwei Li [7] Yue Zhang[8] and Pengxiang Zhang[9] made the normal vector of the tool contact in the YZ plane by rotating the a-axis, and then solved the swing angle of B-axis and C-axis. however, due to tool contact fluctuates greatly, the
calculated angle of A-axis fluctuates greatly, resulting in the fluctuation of other five axes, which makes the running speed of the machine change sharply, the processing quality decline, even causes machining scrap.

To solve the above problems, in this paper, a post-processing optimization algorithm for six-axis NC polishing machining is proposed, which can solve the problem of fluctuation in the machining process of six-axis NC machining. First, the initial A-axis angle value corresponding to the tool position is solved according to the tool position information contained in the toolpath file; Second, uses B-spline to smooth the data of A-axis, and solves the corresponding B-axis and C-axis angle value according to the angle value of A-axis; Third, calculate the moving value of X-axis Y-axis and Z-axis to realize the post-processing of the toolpath file; Finally, the algorithm was verified using VERICUT software; furthermore, in machining experiments, the rotation amplitudes of the rotary axis, non-linear errors during the processing were all effectively reduced, and the smoothness of the tool path was effectively improved, this ensures the polishing quality of blades.

2. Structure of six-axis polishing machine and tools for polishing

In order to achieve the full profile polishing of the blade conveniently and quickly, this paper adopts the method of adding C-axis to the traditional vertical A turntable B swing head machine tool to cooperate with the angle head to realize the six degrees of freedom in the polishing process. The specific structure of the machine tool is shown in Fig. 1 a). The c-axis is located in the outer ring of the end face of the machine tool spindle, the C-axis drives the angle head to rotate along the spindle axis to change the normal vector of the polishing tool, so as to realize the high degree of freedom of the machine tool. At the same time, the standard tool magazine of the machine tool can realize automatic tool change and meet the needs of automatic production.

The angle-head and polishing wheel used in this paper are shown in Fig.1b). By selecting different angle-heads and polishing wheel of different specifications, greater degrees of freedom in the machining process can be realized, so as to realize the full profile polishing of the blade. In addition, the polishing tool selected in this paper is the super hard abrasive elastic polishing wheel, as shown in Fig. 1c). This polishing wheel is different from the abrasive belt used for abrasive belt grinding. The super hard abrasive is fixed on the elastic body made of rubber through a special process. Its high elasticity can adopt the fixed trajectory polishing technology, so as to avoid the complex force control device and simplify the structure of the machine tool, And the polishing quality can be improved [10].
3. Initial angle calculation of A-axis

In the polishing process, when the tool is in contact with the workpiece surface, the tool surface and the workpiece surface share the normal vector at the tool contact. Therefore, the normal vector of the workpiece surface at the contact can be obtained by calculating the normal vector of the tool surface contact. The common tool for polishing is drum polishing wheel, as shown in Figure 2, \( D \) is the diameter of polishing wheel, \( R_1 \) is the fillet radius of polishing wheel, \( P_0 \) is the current tool position, \( v_0 \) is the unit normal vector of the current tool axis, \( P_1 \) is the current cutter contact, \( P_2 \) is \( P_1 \) the projection point on the tool axis, \( h \) is distance between \( P_2 \) to \( P_0 \), \( v_1 \) is the unit normal vector at the tool surface corresponding to the current cutter contact, \( v_2 \) is unit vector from \( P_2 \) point to the tool axis, \( v_3 \) is projection vector of \( v_1 \) in \( v_2 \) direction, \( v_4 \) is projection vector of \( v_1 \) in \( v_0 \) direction, among them \( P_0, P_1, v_0 \) can be obtained from tool path files, \( h, P_2, v_2 \) can be calculation from Eq.(1). \( \tau \) is the length of \( v_4 \), also the length \( v_1 \) projection on \( v_0 \). Then \( v_1 \) can be calculation by Eq.(2).

\[
\begin{align*}
    h &= (P_1 - P_0) \cdot v_0 \\
    P_2 &= P_0 + h \cdot v_0 \\
    v_2 &= \frac{P_2 - P_1}{|P_2 - P_1|} \\
    \tau &= (R_1 - h)/R_1 \\
    v_1 &= \tau \cdot v_0 + \sqrt{1 - \tau^2} \cdot v_2
\end{align*}
\]

After calculate the cutter vector \( v_1 \), the initial angle of A-axis can be obtained by calculating the angle between \( v_1 \) and axis Z in YZ plane [7].

4. Smoothing of A-axis angle

In the polishing process, the unidirectional cutting tool path is generally used. According to the characteristic that there is no corresponding tool contact at the tool location in the cross tool process, the single tool path is extracted. There are \( P_i (i = 0, 1, \ldots, n) \) tool positions in a row of tool path, starting from \( P_0 \), calculate the \( A_i (i = 0,1,2 \ldots n) \) angle corresponding to the normal vector of each cutter contact, and take \( P_0 \) as the starting point to successively calculate the tool path length \( l_i (i = 0, 1, \ldots, n) \) corresponding to each tool position \( P_i (i = 0, 1, \ldots, n) \) through Eq.(3).

\[
l_i = \begin{cases}
    0 & i = 0 \\
    l_{i-1} + \text{dis}(P_i - P_{i-1}) & i = 1, 2, \ldots, n
\end{cases}
\]

Taking \( t_i = l_i/l_n \) (\( i = 0, 1, \ldots, n \)) as the corresponding parameters of \( A_i \), then \( A_i \) is fitted into p-order k-segment B-spline by least square algorithm according to the formulated parameters. The specific fitting methods are as follows:

Step1: planning knot vector \( U(u_0, u_1, \ldots, u_{m-1}, u_m) \), where \( m = 2 \times P + K - 1 \), the value of each sub item is obtained by Eq.(3).
\[
u_j = \begin{cases} 0 & j \leq P \\ \frac{j - P}{K} & P < j < m - P \\ 1 & m - P \leq j \leq m \end{cases} \quad (4)
\]

Step2: calculate the basis function corresponding to \(A_i(i = 0, \cdots, n)\) in combination with node vectors \(U\) and \(t_i(i = 0, \cdots, n)\), and write the basis function corresponding to each \(A_i\) into the matrix form of Eq.(5).

\[
N_{j,0} = \begin{cases} 1 & u_j \leq t_i \leq u_{j+1} \ (j = 0, \cdots, m - 1) \\ 0 & \text{otherwise} \end{cases}
\]

\[
N_{j,p}(t_i) = \frac{t_i - u_j}{u_{j+p} - u_j} N_{j,p-1}(t_i) + \frac{u_{j+p+1} - t_i}{u_{j+p} - u_{j+p+1}} N_{j+1,p-1}(t_i)
\]

\[
B = \begin{bmatrix} N_{0,0}(t_0) & \cdots & N_{0,p}(t_0) \\ \vdots & \ddots & \vdots \\ N_{n,0}(t_n) & \cdots & N_{n,p}(t_n) \end{bmatrix}
\]

Step3: write \(A_i(i = 0, \cdots, n)\) in the form of column vector, \(A = (A_0, \cdots, A_n)^T\), and solve the inverse matrix of matrix \(B\). each control point \(X\) of fitted B-spline can be solved through Eq.(6).

\[
X = B^{-1} \cdot A \quad (6)
\]

After fitting \(A_i(i = 0, \cdots, n)\) into B-spline curve, the value of \(A_i(i = 0, \cdots, n)\) can be inversely calculated through the fitted spline curve to obtain the smooth A-axis angle.

5. Solution of BC angle and XYZ value

After calculating the A-axis angle, rotate the normal vector \(v(v_x, v_y, v_z)\) of the tool position around the A-axis according to the A-axis angle corresponding to each tool position, obtain the rotated \(v(v_x, v_y, v_z)\), prepare for the calculation of B-axis angle and C-axis angle.

After the angle-head is installed, the normal vector \(n\) of the initial tool axis can be obtained from Eq.(7).

\[
n(n_x, n_y, n_z) = (\sin B \times \cos C, \ sin B \times \sin C, -\cos B) \quad (7)
\]

The maximum value of Z-direction component \(n_z\) of tool axis vector \(n\) is limited to \(l = \sqrt{n_x^2 + n_z^2}\). After the b-axis swings, \(n_z\) shall be equal to the z-direction component \(v_z\) of the tool axis \(v\). The initial angle of B-axis is calculated according to Eq.(8).

\[
\hat{b} = \cos^{-1}(n_z/l) \quad b_0 = \begin{cases} b & n_x \geq 0 \\ -b & n_x < 0 \end{cases} \quad (8)
\]

Due to the rotation of C-axis, there are two possibilities for the included angle B between the tool axis \(v'(v'_x, v'_y, v'_z)\) and Z-axis, \(b_{10} = \cos^{-1}(v'_x/l)\) or \(b_{11} = -\cos^{-1}(v'_x/l)\). After Eq.(8) obtains the swing angle \(b\), the choice of \(b_{10}\) and \(b_{11}\) is determined according to the principle of minimum swing amount of angle B.

\[
\left\{ \begin{array}{ll} b_1 = \pm \cos^{-1}(v'_x/l) & -l \leq v'_x \leq l \\ b = b_1 - b_0 & b < -pi \\ b = 2 \pi - b & b > pi \end{array} \right. \quad (9)
\]

Rotate the initial tool axis vector B along the \(b\) axis to obtain the rotated tool axis normal vector \(\hat{n}\), and solve the included angle \(c\) between \(\hat{n}\) and tool axis \(v'\) in the xoy plane. The included angle \(c\) is the swing angle of the C-axis.

When the initial cutter axis is parallel to the Z axis and the tool axis over quadrant in the XOZ plane, the C-axis will swing greatly. Therefore, take \(\hat{b} = -b\) for the angle of B-axis and Calculation \(\hat{b}\)
Corresponding C-axis angle \( \tilde{c} \), compare \( |b| + |c| \) with \( |\tilde{b}| + |\tilde{c}| \), and take the smaller sum as the swing angle of BC axis to optimize BC swing angle.

The tool setting point is at the center of A-axis, and the intersection point of A-axis and B-axis is the zero point of coordinate workpiece, and the distance from the rotation center of B-axis to the end face of the spindle is \( L_0, n, L_1, L_2, L_3 \), E is the initial parameter of the angle head, the value of XYZ corresponding to the tool position \( P_1(P_x, P_y, P_z) \) can be calculated by Eq.(10).

\[
(x, y, z) = (P_x, P_y, P_z) \times \text{rot}(a, X) + \left( (0, 0, L_0 + L_1) + \left( (n \times (L_2 + L_3)) + (0, 0, E) \right) \times \text{rot}(c, Z) \right) \times \text{rot}(b, Y)
\]  

(10)

6. Experiments

The local polishing path of the tool generated during the polishing of a fan blade is shown in Fig 3. Post-process the generated path and select one line of tool path. As can be seen from Figure 4 a), the machine motion track not generated by the a-axis Fairing Algorithm, the cutter contact vector fluctuation caused by the complex blade characteristics will lead to the A-axis fluctuation, and then cause the operation fluctuation of other motion axes. A section of third-order B-spline is used to smooth the rotation angle of the original a-axis. The motion trajectory of each axis of the machine after processing is shown in Fig. 4b). It can be seen from Fig. 4b) that the smoothness of the motion of each axis of the machine has been significantly improved after smoothing.
VERICUT cutting simulation is used to simulate the before and after optimization trajectory. The simulation results are shown in Fig. 5. From the simulation results in Fig. 5a), it is obvious that the tool path has serious overcutting problems due to the fluctuation of the moving axis of the tool path without optimization, resulting in the scrapping of the machined workpiece, after optimization, it can be seen from the simulation results Fig. 5b) that there is no obvious overcut phenomenon.

The optimized tool path is used for the actual processing of the blade, and the processing results are shown in Fig. 6. It can be seen from Fig. 6a) that there is no overcut on the blade surface after processing. The accuracy of five sections of the blade is tested by three coordinates, and the test results are shown in Fig. 6b). From the test data, it can be seen that the optimization method proposed in this paper can meet the actual processing needs.
This method has been applied in the polishing of a fan blade with damping table as shown in Figure 7a). Figure 7b) shows the processing site, figure 7c) shows the actual effect after processing, figure 7d) shows the three coordinate measurement error of the section line, and the surface roughness is Ra0.4μm.

### Conclusion

Based on the results and discussions presented above, the conclusions are obtained as below:

1. In order to solve the problem of fluctuation in the six-axis NC polishing machining, an optimization algorithm for six-axis post-processing of blade polishing is proposed in this paper, which effectively solves the problem of trajectory fluctuation in the polishing process of six-axis NC machine tool;

2. The algorithm is verified that it can solve the machine trajectory fluctuation in the current six-axis post-processing using VERICUT and the machining experiments, and realize the high quality six-axis NC polishing machining.

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