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Constant Stability Control Method for Three-axis Machining Swing Based on Surface Decomposition

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Abstract: In the three-axis machining process, it is easy to be affected by the tool disturbance factors on the whole processed surface, which leads to the tool swing and the machining error. In order to reduce the swing and reduce the machining error, a three-axis machining swing constant stability control method is proposed based on surface decomposition. The geometric constraint model of tool movement in triaxial machining is established. According to the geometric constraint of tool motion described, the critical cutter axis vector at a single tangent contact is solved, and the constraint parameter model of tool axis swing control in triaxial machining is analyzed. According to the relation between the radius change of the three-axis machining ball head cutter and the feasible pendulum cutter field, the surface decomposition is carried out, all the cutter axis vectors are obtained, and the tool length corresponding to each tool axis vector in the feasible pendulum cutter field is calculated. According to the parameter correlation analysis of the curved surface formed by the number curve, the steady stability control of the three-axis machining swing is realized. The simulation results show that the stability of the tool can be improved by using this method to control the oscillating stability of the tool. The optimization of tool size parameters is helpful to improve the process stability.

1. Introductions

With the continuous improvement of the performance requirements of modern aeronautical and spaceflight vehicles, more stringent requirements have been put forward for the high precision manufacture of aeronautical integral structural parts. Complex curved surface channel parts, such as integral impellers and impellers, are widely used in aerospace. The structure of the complex curved channel parts is complex, the channel is long and narrow, the blade is ultra-thin and the bending and torsion is serious, so the triaxial machining method is often used in the machining and manufacturing[1]. The machining efficiency and process stability of triaxial machining are the key factors that restrict the machining accuracy of complex curved surface parts. How to select the tool reasonably according to the geometric characteristics of the parts is the key problem to improve the machining efficiency and the stability of the machining process. Large tool diameters help to improve machining efficiency and machining stability, and at the same time increase the possibility of interference, while small tool diameters are helpful to avoid interference, but cutting tool breakage and other risks are easy to occur in the process of machining, and the machining efficiency is low[2]. It is easy to appear tool swing, which leads to poor machining accuracy. It has great significance to study the control method of constant stability of three-axis machining swing for improving the machining...
efficiency and accuracy of parts\cite{3}.

The triaxial machining needs to consider the position and direction of the cutting tool with respect to the workpiece synchronously, so the path fairing and interpolation calculation are more complicated than the traditional 2-axis or single-axis machining. The main problems are expressed as follows: synchronous parameterization and error control of tool tip locus and cutter axis direction, nonlinear mapping from workpiece coordinate system to machine tool coordinate system, the motion of each servo shaft is not only related to the movement of the cutter, but also influenced by the nonlinear mapping. In addition, considering the practical application, it is also necessary to be real-time. These problems have not been solved effectively\cite{4}. Aiming at the problem of tool swing in triaxial machining, a tool selection method based on minimum tool length constraint is proposed in reference \cite{5} to avoid local interference by comparing the differential geometric characteristics between the surfaces to be processed and the cutting tools. The wobble error is reduced, and the method has high calculation efficiency, but it is easy to be affected by the small disturbance of the tool. The constant stability control performance is not good. In reference \cite{6}, a method for judging whether a given annular cutter can finish finishing the whole surface is proposed. Firstly, the machining surface is discretized as a feature point set, considering the limit of the machine tool axis and the curvature interference. In this paper, a curvature matching tool diameter optimization method is used to control the swing of triaxial machining, which does not take into account the impact of collision interference on tool size.

In order to solve the above problems, a three-axis machining swing constant stability control method is proposed based on surface decomposition. The geometric constraint model of tool movement in triaxial machining is established. According to the relation between the radius change of the three-axis machining ball head cutter and the feasible pendulum cutter field, the surface decomposition is carried out, all the cutter axis vectors are obtained, and the tool length corresponding to each tool axis vector in the feasible pendulum cutter field is calculated. The parameter correlation analysis is carried out according to the surface formed by the number curve to realize the constant stability control of the three-axis machining swing. Finally, the simulation experiment is carried out and the superiority of this method is demonstrated.

2. Analysis of geometric constraint model and control constraint parameters of 3-axis machining tool

2.1 Geometric constraint model for cutting tool motion in three-axis machining

In order to control the oscillating constant stability of triaxial machining, a geometric constraint model of triaxial machining tool motion is established\cite{7}. The critical cutter axis vector at a single tangent contact is solved according to the geometric constraint of tool motion described, and the local interference is avoided. The range of tool shaft swing should be limited to the tangent plane $PC$ of point $C$, and the range of tool shaft swing should be further limited between the critical plane $P0$ and the tangent plane $Pc$, which is perpendicular to the direction of the cutter. The geometric constraint model of triaxial machining tool motion is shown in Fig. 1. In figure 1, $S0$ is the surface to be machined, $nc$ is the normal vector direction of the curved surface at the tangent contact $C$, $fe$ is the cutter direction of $C$ point, $fe \perp fn c$.

![Fig. 1 Geometric constraints on the movement of triaxial cutting tools](image)
2.2 Analysis of constraint parameters of three-axis machining swing Control

Considering the geometric shape of the tool, it is abstracted into a ray and the geometric constraint term of the tool motion is obtained as follows:

\[ K = \begin{bmatrix} K_1^T & K_2^T & K_3^T & K_4^T & K_5^T \end{bmatrix}^T \]  \hspace{1cm} (1)

\[ L = \begin{bmatrix} L_1^T & L_2^T & L_3^T & L_4^T & L_5^T \end{bmatrix}^T \]  \hspace{1cm} (2)

\[ M = \begin{bmatrix} M_1^T & M_2^T & M_3^T & M_4^T & M_5^T \end{bmatrix}^T \]  \hspace{1cm} (3)

The global finite time convergence equation is established within the range of allowable oscillations of the tool, and the constraint conditions of the critical cutter axis for triaxial machining are obtained as:

\[
\begin{bmatrix}
\Psi & h_K & h_M \\
-h_i (Z_i + Z_j + Z_k) & 0 & -h_i (Z_i + Z_j)
\end{bmatrix} < 0 
\]  \hspace{1cm} (4)

\[
\begin{bmatrix}
\Psi & h_K & h_L \\
-h_i (Z_i + Z_j + Z_k) & 0 & -h_i (Z_i + Z_j)
\end{bmatrix} < 0 
\]  \hspace{1cm} (5)

\[
\begin{bmatrix}
\Psi & h_W & h_L & h_M \\
-h_i Z_1 & 0 & 0 & -h_i (Z_i + Z_j)
\end{bmatrix} < 0 
\]  \hspace{1cm} (6)

\[
\begin{bmatrix}
\Psi & h_W & h_L & h_M \\
-h_i Z_1 & 0 & 0 & -h_i (Z_i + Z_j)
\end{bmatrix} < 0 
\]  \hspace{1cm} (7)

\[
\Psi = \begin{bmatrix}
\Psi_{11} & \Psi_{12} & \Psi_{13} & \Psi_{14} & \Psi_{15} & A^T U \\
\Psi_{22} & \Psi_{23} & \Psi_{24} & \Psi_{25} & 0 \\
\Psi_{33} & \Psi_{34} & \Psi_{35} & 0 \\
\Psi_{44} & \Psi_{45} & 0 \\
\Psi_{55} & 0 \\
0 & -U
\end{bmatrix} < 0 
\]  \hspace{1cm} (8)

In the critical knife plane \( P_i \), it satisfies:

\[ \Psi_{11} = PA + A^T P + Q_i + R_i + R_j + K_i^T \]

\[ \Psi_{12} = W_i - K_i + M_i + K_j^T \]

\[ \Psi_{13} = P + L_i + M_i + K_k^T \]

\[ \Psi_{14} = -L_i + K_j^T , \hspace{0.5cm} \Psi_{15} = -W_i + K_j^T \]  \hspace{1cm} (9)

The critical cutter axis vector is the unit vector from the tangent contact to the critical point. If the characteristic of the error covariance is directed to the satisfied quantity \( \Psi(d_i(t), d_j(t)) < 0 \), there are:

\[ V(t) \leq \zeta^T(t) \Psi(d_i(t), d_j(t)) \zeta(t) < 0 \]  \hspace{1cm} (10)

When machining channel parts with complex surfaces, both the surface to be machined and its adjacent surfaces may constrain the movement of the cutter shaft. The feasible tool axis space is calculated as:

\[ X_{bl} = R \times \theta_{ul} \]  \hspace{1cm} (11)
After the feasible range of the pendulum cutter is discretized, the rotation coordinate system of the three-axis machining feed path is obtained as follows:

\[
\begin{align*}
X_{RR} &= R \times \theta_{RR} \\
X_{RL} &= X_{RR} + D \times \delta \\
X_p &= X_{RM} + L \sin \theta_p \\
X_p &= \theta_p L \cos \theta_p + X_{RM} \\
Y_p &= L \cos \theta_p \\
Y_p &= -\theta_p L \sin \theta_p \\
X_{RR} + X_{RL} &= 2X_{RM}
\end{align*}
\]  

(12)  
(13)  
(14)  
(15)  
(16)  
(17)  
(18)  

In the above coordinate system, the solution of the critical tool axis constraint will be transformed into the solution of the critical point on the intersection curve between the interference surface and the current pendulum cutter plane, and the calculation of the critical constraint on the cutter axis on the surface to be processed is to obtain the critical constraint between the surface to be processed and the moment. The process of critical points on the intersection curve of the front pendulum cutter is shown in figure 2.

Fig. 2 Calculation of critical point of surface to be machined

3. Optimization of oscillating constant stability control in triaxial machining

3.1 Surface decomposition of feasible pendulum cutter

On the basis of the geometric constraint model of triaxial machining tool motion, the oscillating constant stability control of triaxial machining tool is carried out. In this paper, a new method is proposed. This paper presents a control method of oscillating constant stability in triaxial machining based on surface decomposition. The tool length studied in this paper is obtained by optimizing the cutter axis vector in the feasible pendulum cutter region under the condition of determining the tool diameter. The expression of coordinate transformation for surface discretization is:

\[
\begin{bmatrix}
  x_1(t) \\
  x_m(t)
\end{bmatrix} =
\begin{bmatrix}
  a_{11} \\
  a_{mn}
\end{bmatrix}
\begin{bmatrix}
  s_1(t) \\
  s_n(t)
\end{bmatrix} +
\begin{bmatrix}
  a_{1m} \\
  a_{mn}
\end{bmatrix}
\begin{bmatrix}
  t \\
  t
\end{bmatrix}
\]

(19)  

Multi-axis machining can complete the multi-face of parts through a multi-axis joint feed. In the homogeneous coordinate system constructed above, the calculation of the tool length corresponding to each cutter axis vector in the feasible pendulum cutter region is taken as the basic operation. In order to select the machining tool correctly, the cutting parameters are reasonably set up, and the cutting parameters are constructed. Tool feed time control shaft is:

\[
x(t) = [x_1(t), x_2(t), K, x_n(t)]^T
\]

(21)  

Follow errors of X axis and Y axis are calculated, due to the point of the cutter radius determined by \(R_{i+1}\) domain is a subset of feasible pendulum knife tool radius is \(R_i\), three-axis cutter swing domain surface composed of parametric curve and surface decomposition based on the relation of three-axis machining ball cutter radius and feasible is obtained, as shown in Figure 3.
Fig. 3 Discrete decomposition process of curved surface in oscillating field of triaxial machining tool

According to the discrete decomposition process of curved surface in Fig. 3, all the cutter axis vectors are obtained, and the oscillating constant stability control of triaxial machining is carried out in the feasible pendulum cutter region.

3.2 Control and correlation analysis of oscillating constant Stability in triaxial machining

The tool length corresponding to each tool axis vector in the feasible pendulum cutter domain is calculated. The parameter correlation analysis is carried out according to the surface formed by the number curve, and the gain is adjusted by the isometric surface control method. The inertia torque of the cutter shaft is \( T = N l_1 \), at the potential interference surface \( r \).

Through the isometric transformation of the source surface, the correlation coupling gain is obtained. It is obtained that all the parametric curves made up of the feature point set must also be machined, and the surfaces formed by the parametric curves are machinability.

The \( S \theta \) trajectory tracking search surface is defined as:

\[
A_\theta = \pi l_\theta (2r_\theta + 2l_g + l_\theta)
\]

The control gain of each offset surface is obtained as follows:

\[
N I = \pi l_\theta (2r_\theta + 2l_g + l_\theta) J_{r_\theta} \theta_r \theta_c
\]  (22)

The intersecting curve equation between the plane of the pendulum cutter and the potential interference surface in triaxial machining is shown as follows:

\[
\begin{align*}
C_\alpha \frac{dV}{dt} & = l_\alpha - g_m m h (V - V_m) - g_r (V - V_r)
\end{align*}
\]

\[
\begin{align*}
\frac{dm}{dt} & = \alpha_r (V) (1 - m) - \beta_r (V) m \\
\frac{dh}{dt} & = \alpha_r (V) (1 - h) - \beta_r (V) h \\
\frac{dn}{dt} & = \alpha_r (V) (1 - n) - \beta_r (V) n
\end{align*}
\]  (23)

Several feature points are selected on the surface to be processed, and the multi-peak Gaussian curve fitting is carried out at each feature point \( \mathbf{Df}/k \). Thus, the oscillating constant stability control of triaxial machining is realized, and the optimal state control equation is obtained as follows:

\[
\begin{pmatrix}
X_{\alpha M} \\
V_{\alpha M} \\
\delta_r \\
\omega_r \\
\delta
\end{pmatrix}
= \begin{pmatrix}
0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & A_{23} & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & A_{23} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}
\begin{pmatrix}
X_{\alpha M} \\
V_{\alpha M} \\
\theta_r \\
\omega_r \\
\delta
\end{pmatrix}
+ \begin{pmatrix}
0 & 0 \\
B_2 & B_2 \\
0 & 0 \\
B_4 & B_4 \\
0 & 0
\end{pmatrix}
\begin{pmatrix}
C_\alpha \\
C_r
\end{pmatrix}
\]  (24)

Wherein:
According to the optimal design of the control law above, every critical cutter axis unit vector \( T \) is mapped to Gaussian sphere, and the feasible pendulum tool field \( G \) is obtained. The parameter correlation analysis is carried out according to the curved surface formed by the number curve, and the control of constant stability of three-axis machining oscillating is realized.

### 4. Simulation experiment and result analysis

In order to verify the correctness and validity of the research method in the control of three-axis machining oscillating constant stability, taking the integral impeller passage as an example, the NC machining code is generated by using the CAM module in UG software, and the NC machining code is added into the VERICUT software. In the experiment, the tool size parameters are chosen as follows:

- narrowest width \( C_{w} = 1.44 \), feed rate \( C_{v} = 1.92 \), single point processing line width \( C_{\mu} = 0.09 \), total length of cutter contact track \( \sigma_{t} = 1.0 \), tool diameter \( \sigma_{e} = 1.3 \).
- The switching errors of the tip point and the cutter shaft are respectively 0.1 mm and 0.1°, maximum tangential transition \( J_{\text{max}} \) is 250 mm/s², machine tool translational shaft \( X, Y, Z \) are 200 mm/s, 1000 mm/s², according to the above simulation environment and parameter setting, the oscillating constant stability control of triaxial machining is simulated, and the three-axis machining feed path for simulation is shown in figure 4.

![Figure 4 Three-axis machining feed path for simulation](image)

According to the feed path given in figure 4, the weight diversity of three-axis machining pendulum cutter region is carried out. In order to verify the influence of different tool diameters on machining results, the unoptimized tool diameter of 10 mm and the optimized tool diameter of 10 mm are adopted in this paper. The machining path is planned for 14mm, and the surface decomposition of the feasible pendulum cutter field for triaxial machining is obtained. The result is shown in Fig. 5.
Figure 5 shows that the stability of tool locus trajectory is good, the path length is shortened by 145.4 mm and the tool swing amplitude is reduced by 14.11 mm, which is beneficial to improve the stability of the three-axis machining feed process. In order to compare performance, the deviation between linear and nonlinear parameters of three-axis machining oscillating constant stability control is measured by using this method and traditional method as shown in Fig. 6.

The analysis of Figure 6 shows that the deviation of this method is small and the tool dimension parameter value is optimal, which is helpful to improve the stability of triaxial machining swing control, and proves the correctness and effectiveness of this method.

5. Conclusions
In this paper, in order to reduce the swing and reduce the machining error, a three-axis machining swing constant stability control method is proposed based on surface decomposition. The geometric constraint model of tool movement in triaxial machining is established. According to the geometric constraint of tool motion described, the critical cutter axis vector at a single tangent contact is solved, and the constraint parameter model of tool axis swing control in triaxial machining is analyzed. According to the relation between the radius change of the three-axis machining ball head cutter and the feasible pendulum cutter field, the surface decomposition is carried out, all the cutter axis vectors are obtained, and the tool length corresponding to each tool axis vector in the feasible pendulum cutter field is calculated. According to the parameter correlation analysis of the curved surface formed by the number curve, the steady stability control of the three-axis machining swing is realized. The simulation results show that the stability of the tool can be improved by using this method to control the oscillating stability of the tool. The optimization of tool size parameters is helpful to improve the process stability. It has good application in three-axis machining.

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