Efficient Algorithm for Sidewall Machining of Aircraft Structural Part

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Abstract. Traditionally, the boundaries of the pocket bottom face are often used as the guide elements of the machining process of sidewall machining. However, for complex pocket, overcutting often occurs due to the incorrectness of the guide elements. To solve this problem, the sidewall machining model is presented at first. Then, terms such as rim convex edge and visible property are introduced in detailed. Finally, the rim convex edges are projected onto the bottom face and the visible guide lines are constructed by sub-lines selection based on the visible property. At last a case study is given to verify the feasibility and effectiveness of the proposed algorithm. The result shows that the algorithm can avoid overcutting for complex pocket.

1. Introduction

Sidewall machining is one of the most common and important machining stage in the aircraft fabrication process of structural parts and turbines which have high accuracy requirements and are easy to deform [1]. Since most sidewall faces of aircraft structural part are ruled faces, 3-axis flank machining [2] is still widely adopted in the finishing machining process. Moreover, for the complex pocket composed of inclined faces, 3-axis flank machining is often used to remove the residual material left by rough machining before 5-axis flank machining [3-6]. Generally, 3-axis sidewall machining uses the offsetting curves of the boundaries of the related bottom face as the tool-path elements [7]. The 2D-curve offsetting problem has been regarded as the key issues for tool-path generation of sidewall machining [8,9]. However, under the shelter of the inclined faces, some boundaries are invisible along the opposite direction of the machining direction. Therefore, interference occurs when the cutting tool locates in the invisible area.

The research reported in this paper is motivated by the above observation. The objective of this work is to provide an efficient algorithm that can receive precise machining region for sidewall machining process, which would avoid overcutting in the machining process. In other word, the main task of the current work is to define machining region from the perspective of geometry, therefore machining parameter is not considered here. Section 2 describes the proposed algorithm in detailed and the section 3 presents the case study. Conclusions are given in Section 4.

2. The proposed algorithm

2.1 Machining model
Sidewall machining is used to remove the radial allowance left by rough machining process, and the machining model of 3-axis sidewall machining can be expressed as follows:

\[ MV = (d_r, C, H_b, H_t) \]
\[ TP = f(MV) \]

Where \( MV \) is a single machining volume that can be described by the four parameters. \( d_r \) represents the radial allowance, \( C \) means the guide line that limits the movement range of the machining tool, \( H_b \) and \( H_t \) are the bottom and top height of the machining volume. In this paper, the end-milling cutter is used to generate the tool path \( TP \), which can be generated by the tool path generation function \( f \), and the main task of the function is to compute the offsetting curve of the guide curve.

Fig. 1 shows the machining model of a simple pocket, where \( m \) is the machining volume and \( C \) is the guide line. Generally, the boundaries of the bottom face are regarded as the guide lines for the sidewall machining volume. However, for complex pocket composed inclined faces, part of the bottom face is inaccessible for the cutting tool. Since the cutting tool direction is often fixed during machining time, overcutting often occurs during the machining process. Therefore, in order to avoid overcutting phenomenon, the guide line should be visible.

2.2 The proposed method

Base on the machining model, the most important task is to compute the precise guide line. Fig. 2 presents the flowchart of the proposed algorithm.

2.2.1 Rim convex edge extraction. Rim convex edge. Rim convex edge (RCE) is the convex edge that is visible along the opposite direction of the machining direction (z-axis), and it can be extracted from CAD model by the following rule.
Rule 1. Suppose $e$ is a common convex edge of face $f_1$ and $f_2$, $\vec{n}_1$ and $\vec{n}_2$ are normal vector of face $f_1$ and $f_2$ respectively, which point out of the volume. $\theta_1(\theta_2)$ is the angle between $\vec{n}_1(\vec{n}_2)$ and z-axis. If $\theta_1 \geq 90$ & $\theta_2 \leq 90$ or $\theta_1 < 90$ & $\theta_2 \geq 90$, then $e$ is a RCE.

2.2.2 Visible property initialization. Traditionally, the edges of out loop on the inclined faces are projected onto bottom face to construct precise guide line[7]. However, for complex pocket, the number of projection lines may be large and the relationships between each other are complicated, as shown in Fig. 3.

![Projection lines onto the bottom face](image)

**Figure 3.** Projection lines onto the bottom face

In order to simplify the guide line construction, a visible property is introduced to RCE. Before the property initialization, it is necessary to sort the edges on the inclined faces. The edges in outer contour loop of inclined faces are sequenced by the right-hand rule, while it is unnecessary to initialize the visible property for the edges in inner contour loop since the edges cannot limit the travel range of the cutting tool. Table 1 shows the detailed visible property values for different edges, where positive edge means the edge whose ending vertex is the vertex of next edge in the contour loop, else the edge is called negative edge.

| Belonging face | Edge type   | Visible property |
|---------------|-------------|------------------|
| Inclined face | Positive Edge | -1               |
|               | Negative Edge | 1                |

2.2.3 Visible guide line construction. Visible guide line. Set $C$ is a set of continuous lines on bottom face of the pocket, $C = (L_1, L_2, \ldots, L_n)$, $F$ is a set of inclined faces, $F = (f_1, f_2, \ldots, f_m)$. $\forall L_p$, $L_p$ is the z-ray on a random point of $L_i$, $L_i \in C$, if $\exists p, p = L_p \cap F$, and the point $p$ lies on an outer loop of the inclined faces, then $C$ is visible guide line.

Fig. 4 illustrates three types of two projection lines of RCEs. For the part intersecting and full intersecting case, sub-lines can be easily generated by the intersecting point and some of the sub-lines should be removed. The visible property of the RCE is used to remove the invalid sub-lines.

![Relationship between projection lines](image)

**Figure 4.** The relationship between projection lines

Take the full intersecting lines $L_1$ and $L_2$ for example, the steps to remove invalid sub-line are described as follows.

Step 1: Suppose $\vec{T}_1$ and $\vec{T}_2$ are two sub-lines of $L_1$, and $\vec{T}_2$ represents the vector from the starting point to the end point of $L_2$. 

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Step 2: Compute the vector $\overrightarrow{p_{st},p_{mid1}}$ and $\overrightarrow{p_{st},p_{mid2}}$, where $p_{st}$ is the starting point of $L_2$ while $p_{mid1}$ and $p_{mid2}$ are the middle points of $\overrightarrow{L_1}$ and $\overrightarrow{L_2}$ respectively. Then, compute the cross product $\overrightarrow{T_1} = \overrightarrow{p_{st},p_{mid1}} \times \overrightarrow{T_2} = \overrightarrow{p_{st},p_{mid2}}$.

Step 3: Set $\overrightarrow{\theta}$ means the angle between $\overrightarrow{T_i}$ and z-axis, $1 \leq i \leq 2$. When the visible property of value of $L_2$ is equal to 1, then $\overrightarrow{L_i}$ should be removed when $\overrightarrow{\theta} = 0^\circ$. Else, $\overrightarrow{L_i}$ should be removed when $\overrightarrow{\theta} = 180^\circ$.

As shown in Fig. 5, there are three projection lines on the bottom face, and $\alpha_1$, $\alpha_2$ and $\alpha_3$ are the visible property of $L_1$, $L_2$ and $L_3$ respectively. At first, we consider the intersecting lines $L_1$ and $L_2$, the sub-lines $\overrightarrow{L_i}$ and $\overrightarrow{L_j}$ can be removed by the method mentioned above. Then, $\overrightarrow{L_1}$ and $\overrightarrow{L_3}$ can be extracted and removed by the same method. For the open pocket, the visible guide line is an unenclosed loop and it is unnecessary to group the original boundaries of bottom face and the visible guide line. But, for the closed pocket, the visible guide lines are composed of valid projection sub-lines and the original bottom boundaries, as shown in Fig. 5(c).

Figure 5. Visible guide lines construction example

2.2.4 Tool path generation. Based on the sidewall machining model, the tool path can be easily generated after getting the precise guide lines. At first, the basic tool path elements are generated by the offsetting function[7]. Then, the axial passes number of the tool path is computed by the height of sidewall faces and the maximum axial cutting depth.

3. Implementation

To validate the feasibility and effectiveness of the proposed algorithm, a case study on a simple aircraft structural part is conducted on the platforms of Microsoft Visual Studio 2005 and CATIA. Fig. 6 shows the tool path comparison between the traditional method and the proposed method. By the original method, the bottom boundaries are used as the guide line for sidewall machining (see Fig. 6(b)), which induces the overcutting in the machining process, as shown in Fig. 6(c). By applying the proposed algorithm, three rim edges on the inclined faces are extracted, as shown in Fig. 6(a). Then, based on the precise guide line (see Fig.6(d)), the traditional tool path generation function[7] is used to generate the optimized tool path, as shown in Fig.6(e). The result shows that the proposed algorithm can avoid overcutting for complex pocket with inclined faces.
4. Conclusion

In this paper, to avoid the overcutting in the sidewall machining process of complex pocket composed of inclined faces, a novel efficient algorithm is proposed. The key of the algorithm is to generate precise guide lines that are visible along the opposite direction of the machining direction. Compared to the traditional tool path generation methods, the proposed algorithm focuses on the boundary correctness for the sidewall faces. Rim convex edge and the visible property are developed and used in the invalid projection line removal process, which deeply improve the efficiency and accuracy of guide line generation. Computer implementations are provided, and the results show that the proposed algorithm is feasible and efficient.

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