

Research on Path Planning for Residual Areas in Complex Milling

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Abstract: Residual areas with freeform border are commonly exist in milling workpiece with complex structures in aerospace, mold, automobile, shipbuilding and other industries. The method of path planning for machining these areas is elaborated to improve the efficiency. A method based on principal component analysis (PCA) and gridding method is proposed to create cutting field model. The cutting field model simplifies the residual area on the premise of avoiding overcut. The cutting path which combines contour-parallel mode with zigzag mode is finally generated based on the cutting field model. With the optimization of cutting width, feed rate, rapid traverse rate and tool lift time, the machining path with minimal time will be acquired.

Keywords: residual areas, complex milling, gridding method, principal component analysis, path generation.

1. Introduction

Nowadays, more and more parts with complex border are machined by CNC machine tools in the aerospace, mold, automobile, shipbuilding and other industries [1]. In order to improve the efficiency, the tool with larger radius is often used in rough machining. However, there are lots of corners and islands in these parts, which will lead to the irregular shape in the remained areas [2]. As shown in Fig.1, the shaded areas are two typical residual areas. The complexity and uncertainty of these remained areas raises new challenges to the high efficiency NC machining.

The existing methods about removal of the residual areas can be divided into two categories: supplement tool path to the original path [3, 4] or remove residual areas after original machining [5-7]. The former one can only solve the residual areas caused by the corner of tool path, but cannot deal with the residual areas caused by other factors such as the corner of workpiece. Thus, it is also necessary to remove residual areas after previous machining process. The aim of this paper belongs to the study for the residual areas that cannot be removed in the first machining.

In general, residual area will be machined as a new machining area. The border of residual area will be regarded as indestructible. Since the border of residual area is often described by freeform curve, it will increase difficulty to generate NC program by general CAM software for the parts. Actually, the border of residual area can be divided into two categories, one is a part of the workpiece border and the other will not exist after the whole machining process, such as the border contained in the red circles in Fig.1. This kind of border can be traversed by the tool, and then the path planning will be easier and more efficient. Based on this idea, a cutting field model is proposed in this paper to simplify the residual areas.

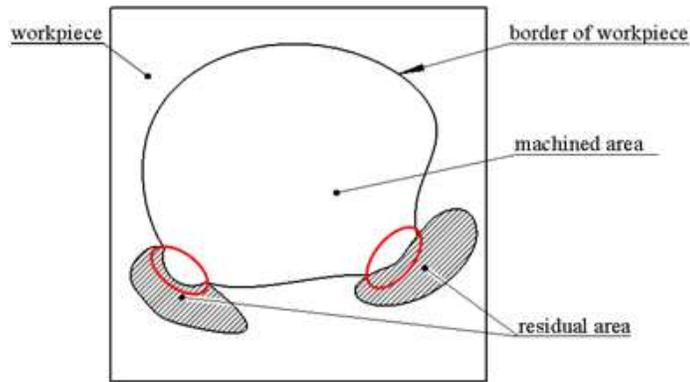


Fig.1: An example of residual areas in complex milling
 Generally, there are 3 types of tool path [8, 9] when planning the tool path, see Fig. 2

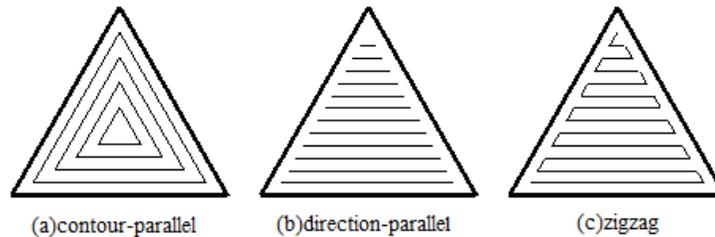


Fig. 2: Common tool path mode

- 1) Contour-parallel: Contour-parallel is one of the most available tool path modes. This kind of tool path can acquire a better surface quality and smoother border. It also has the characteristics of continuous path and less cutter lifting. However, tool moves between the lines in the machining process. The tool path is outside in according to the contour shape.
- 2) Direction-parallel: It also can get good surface quality. However, the efficiency of this method will be reduced because of the frequent tool lifting in this mode.
- 3) Zigzag: Due to the less tool lifting, efficiency can be markedly improved in this mode. Tool vibration will exist because climb milling and conventional milling occur alternately. It will influence the machining quality.

As described above, each tool path strategy has some disadvantages. When the residual areas do not have the border of workpiece, they can be removed quickly with zigzag mode. If the residual areas contain the border of workpiece, contour-parallel milling is firstly used to ensure the quality of the border, and then the remained areas are removed by zigzag tool path. So the method for cutting path planning contains contour-parallel path and zigzag path.

2. Create Cutting Field Model

A method based on principal component analysis (PCA) [10] and gridding method is proposed to analyze each region and create cutting field model of the machining path.

2.1. Principal component analysis

A workpiece usually is machined by several steps, and it has several residual areas after first machining step, as shown in Fig.1. In order to machining these areas as quickly as possible, it is expected that the length of the tool path is as short as possible. Since the shape of these areas is different from each other, the machining direction of zigzag mode is also different.

As shown in Fig.3, if the area is machined horizontally or vertically under the coordinates of tool machine, the tool path will have many corners which are inefficient for machining. Thus, the residual border is analyzed with PCA method in order to get the efficient machining direction for zigzag mode.

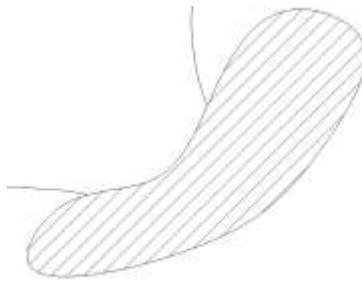


Fig.3: A residual area in the coordinates of machine tool

The first principal component vector of the residual area is calculated by PCA method. Assuming that the first principal component vector is (m, n) , then a rotation matrix can be established as follow:

$$\text{ROT} = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \quad (1)$$

where, θ is the angle between first principal component vector and the positive direction of X-axis. $\theta = \arctan(n/m)$.

Multiply the border points (X_i, Y_i) of the residual area by the rotation matrix ROT,

$$(PX_i, PY_i) = (X_i, Y_i) \times \text{ROT} \quad (i=1, 2, 3\dots) \quad (2)$$

Then the border points (PX_i, PY_i) in the coordinate with the first principal component vector (m, n) as X-axis are got. As shown in Fig.4, PCA method actually rotates the residual area, make the machining direction accord with the first principal component direction. In this way, the workpiece can be removed more efficiently with zigzag path.

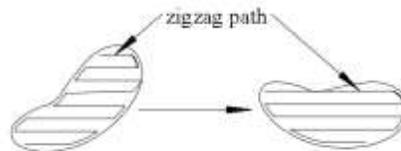


Fig.4: Border of residual area after PCA

2.2. Mesh the residual area

To simplify the residual area, meshing the residual machining area will generate lots of grids, which is illustrated in Fig.8. Traverse through all the grids which contain machining area so that the machining can be completed. The gridding method is as follows:

- 1) At first, the grid width should be determined by the diameter of the tool. As shown in Fig.5, the projection of tool is the excircle to the grid so that the area in grid is removed completely. So, the width of grid can be calculated by:

$$b = Dt / \sqrt{2} \quad (3)$$

Fig.5: The relationship between grid width and tool diameter

- 2) Calculated the distance from the points on the border of residual area to the border of workpiece. If the shortest distance is greater than the tool diameter, then go to step 3. Otherwise, find all the points on the border of workpiece whose distance to residual area is less than the tool diameter. Machining the residual area along the workpiece border that these points locate in with contour-parallel mode. As shown in Fig.6, it is the machining result of the residual area which is shown in Fig.3. After that, all border of residual area is the border which can be destroyed and tool can traverse the border but will not damage the border of

workpiece.

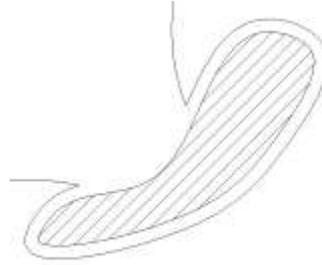


Fig. 6: A residual area after contour-parallel processed

- 3) The points (PX_i, PY_i) ($i=1, 2, 3\dots$) on the border of residual area after step2 in the new coordinate are got. Assuming that the coordinate values (NX_0, NY_0) of the grid which (PX_0, PY_0) locates in equal to $(0, 0)$. In order to determine the location of (PX_i, PY_i) , parameters dx_i, dy_i need to be calculated first, which are the distance between each point in x direction and y direction.

$$\begin{aligned} dx_i &= PX_{i+1} - PX_i \quad (i=1, 2, 3\dots) \\ dy_i &= PY_{i+1} - PY_i \end{aligned} \tag{4}$$

Then Dx and Dy can be calculated by:

$$\begin{aligned} Dx &= \sum_i dx_i \\ Dy &= \sum_i dy_i \end{aligned} \quad (i=1, 2, 3\dots) \tag{5}$$

Thus, whenever $Dx > b$ (b is grid width), it illustrates that the next point (PX_{i+1}, PY_{i+1}) locates in the grid which is on the right of the current grid. Set abscissa of grid that next point (PX_{i+1}, PY_{i+1}) locates in as $NX_{i+1} = NX_i + 1$. The number of grids adds one. Meanwhile, set $Dx = Dx - b$. Then continue to process the next point.

Whenever $Dx < 0$, it illustrates that the next point (PX_{i+1}, PY_{i+1}) locates in the grid which is on the left of the current grid. Set abscissa of grid that next point (PX_{i+1}, PY_{i+1}) locates in as $NX_{i+1} = NX_i - 1$. The number of grids adds one. Meanwhile, set $Dx = Dx + b$. Then continue to process the next point.

Similarly, whenever $Dy > b$, it illustrates that the next point (PX_{i+1}, PY_{i+1}) locates in the grid which is above the current grid. Set ordinate of grid that next point (PX_{i+1}, PY_{i+1}) locates in as $NY_{i+1} = NY_i + 1$. The number of grids adds one. Meanwhile, set $Dy = Dy - b$. Then continue to process the next point.

Whenever $Dy < 0$, it illustrates that the next point (PX_{i+1}, PY_{i+1}) locates in the grid which is below the current grid. Set ordinate of grid that next point (PX_{i+1}, PY_{i+1}) locates in as $NY_{i+1} = NY_i - 1$. The number of grids adds one. Meanwhile, set $Dy = Dy + b$. Then continue to process the next point.

Fig.7 is an example of meshing the residual area. The width of grid is b . When $i=6$, $Dy > b$, it illustrates that the point (PX_7, PY_7) locates in the grid which is above the current grid. Then the coordinate values (NX_i, NY_i) ($i=0\sim6$) of the grid which (PX_i, PY_i) ($i=0\sim6$) locate in is $(0, 0)$. And (NX_7, NY_7) is $(0, 1)$.

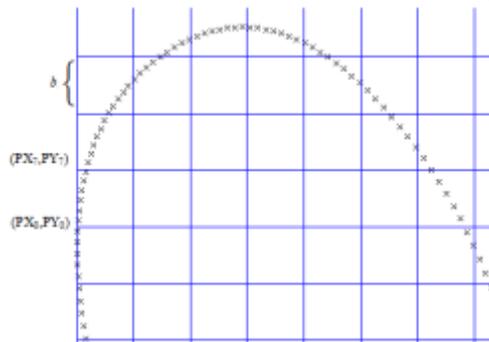


Fig.7: An example of meshing the residual area

When all the points on the border are processed, the number of grid is recorded.

- 4) After step 3, the result of grid may not be the best. Change the initial value of Dx and Dy , then the position

of the points of the border in the grid will be changed. Actually, Dx and Dy decide the position of the first point in the starting grid. Thus, change Dx and Dy from 0 to b respectively and record the number of grid after each change. Comparing all results, choose the situation with least grids. Then the meshing is optimized. Then the original residual area has been converted to a grid area. The cutting field model has been created.

2.3. Criteria of Machining Path Judgment

Through meshing the residual area, the original residual area is changed to some grids. So the judgment criteria of processing path can be described by:

$$T = (\sum_{i=1}^n CP_i + \sum_{j=1}^m ZZ_j) / v_w + \sum_{k=1}^l QM_k / v_q + 2lt_l \tag{6}$$

where T is machining time; $\sum_{i=1}^n CP_i$ is the sum of the distance with contour-parallel machining; $\sum_{j=1}^m ZZ_j$ is the

sum of the distance with zigzag machining; v_w is the machining speed; $\sum_{k=1}^l QM_k$ is the sum of distance with

rapid motion and v_q is speed of rapid motion. l is the times of lifting tool; t_l is the time spent for lifting tool, including lifting tool and dropping tool;

From (5), there are several factors to influence the machining time. Among these factors, v_w, t_l, v_q are technological parameters that cannot be improved by algorithm. $\sum_{i=1}^n CP_i$ also cannot be changed. Then the

parameters that can be optimized are distance with zigzag machining $\sum_{j=1}^m ZZ_j$ and times of lifting tool l . Thus, searching for the shortest path though these grids and lift tools is the key to improve efficiency.

3. Algorithm Of Path Planning

The algorithm of path planning is based on zigzag mode for the remained area. As shown in Fig.8, there is a meshed machining area, and the red grids represent the machining area.

Then extract two ends of continuous grids in each line, just as red grids that are shown in Fig.9. Both ends of continuous grids (G11, G12, G21...) are called as "endpoints grid". Between endpoints grids, there is the path for line cutting.

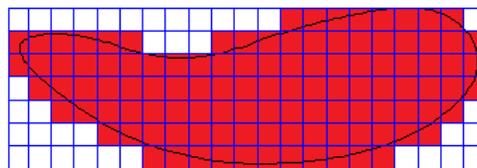


Fig.8: A meshed machining area

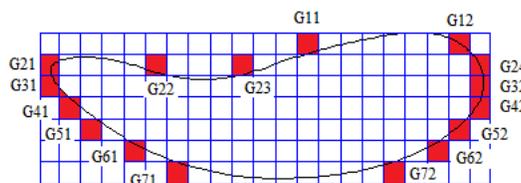


Fig.9: Extract both ends of continuous grids in each lines

Then we will give a definition of "chain". If a series of endpoints grids satisfy the following conditions:

- 1) These endpoints grids locate in the same border.

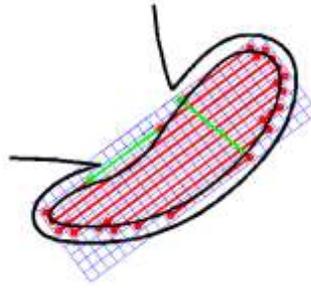


Fig.11 The machining path by the algorithms when set machining speed: $v_w = 10\text{mm/min}$

If we set the machining speed: $v_w = 10\text{mm/min}$, then the machining path is shown in Fig.11. Then the path is different from that is shown in Fig.10. Because the machining speed is too slow, lifting tools if necessary may improve the machining efficiency. Refer to (7), it takes 5104s to finish the machining with the path shown in Fig.10 and it takes 5096s to finish the machining with the path shown in Fig.11.

The machining simulation of the residual area in Fig.10 is shown in Fig.12. The residual area is shown as red part. The green part is the machined area. The simulation verifies the feasibility of the algorithm. Residual area is removed quickly on the premise of avoiding overcut.

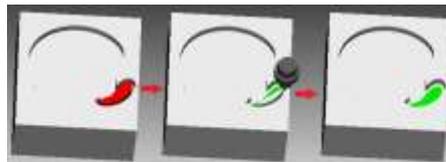


Fig.12: 3D machining simulation of the residual area in Fig.10

If the distance from the points on the border of the residual area to the border of workpiece is larger than the tool diameter, the contour-parallel mode can be directly used to remove the residual area. A larger diameter tool can be used to machining the residual area. An example is shown in Fig.13. The machining path by the algorithms is shown in Fig.14.

The machining simulation of the example shown in Fig.13 is shown in Fig.15. This example illustrates that larger diameter of tool can be selected only if the residual area is far enough from the workpiece border based on the algorithms. That is to say, the shape of residual area can be ignored if the residual area is far from the workpiece border. Just using a simple machining path with a large diameter tool, the residual area can be removed efficiently.

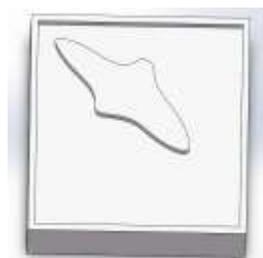


Fig. 13: An example that the distance from the points on the border of the residual area to the border of workpiece is larger than the tool diameter

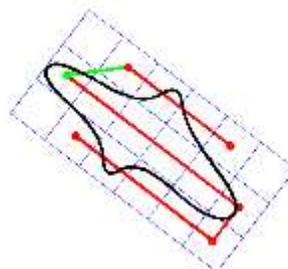


Fig. 14: The machining path of the residual area shown in Fig.13 by the algorithms

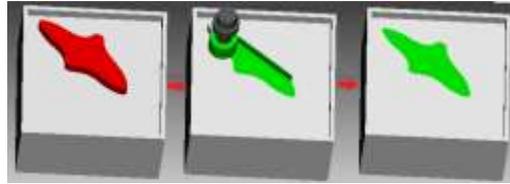


Fig. 15: 3D machining simulation of the residual area in Fig.13

5. Conclusion

The paper presented a cutting field model of tool path to remove the residual areas with freeform border. Through PCA method, a better machining direction was found. Gridding method simplified the path planning problem, converted it to a grid traversal problem. Then an algorithm of path planning is proposed to generate machining path for zigzag path. The algorithm extracts both ends of continuous grids in each line as "endpoints grids". "Chain" was elaborated. With the change of starting point, the path planning result is difference. The method to find the best result is based on the machining parameter including machining speed v_w , rapid motion speed v_q and time spent for lifting tool t_l . Through an example, the difference path planning because of the change of v_w can be seen. The residual area that is far from the workpiece border can be removed efficiently with a large diameter tool regardless of its shape based on the algorithm. The algorithm can be used in the development of CAM software and can be a reference to the layer machining efficiency.

6. Acknowledgment

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7. References

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