

# Five-Axis Plunge Milling Tool Path Generation of Integral Impellers

An Luling, Wei Wei, Zhuang Shudong, Qi Jialiang

**Abstract**—The structures of the integral impellers are analyzed. Blade bending and twisting degree which affect the machinability are assessed. Rough machining process is researched. Plunge milling as a reasonable rough milling strategy is proposed. A new method to obtain the envelope straight lines on one side of the free-form curves is presented, so that the contour curves are totally enveloped on one side by the lines. Then the algorithm for tool path generation of plunge machining are designed and implemented. At last calculation example is given.

**Keywords**—rough milling, tool path, integral impeller, CAM

## I. INTRODUCTION

AS the kernel part of aero-engine, the machining quality of the integral impeller directly affects the performance of the engine. With the rapid development in design and manufacturing of aero-engines, the thrust-to-weight ratio continuously increases, the blade shape and the structure of the integral impeller are of increasing complexity, and its machining accuracy and quality requirements have become more sophisticated. In rough machining of integral impellers, material removal reaches the largest, and the precision and quality of rough machining have direct influence on the subsequent finishing. In this paper, firstly, based on analyzing the structure of the integral impeller, roughing machining process is researched; and the machinability of impeller are assessed. Reasonable rough machining strategy is given, and the tool parameters and processing parameters are determined. Secondly, a new method to obtain the envelope straight lines on one side of the free-form curves is presented, so that the contour curves of the blade are totally enveloped on one side by the lines. Based on the solution of the envelope lines, the machinable areas for radial plunge machining and for bilateral plunge machining on the inlet/outlet are given

. An Luling is with Nanjing University of Aeronautics and Astronautics, Nanjing, China

Thirdly, the algorithm for tool path generation of plunge machining are designed and implemented. Based on the error analysis of plunge machining, the step length and spacing are deduced, and the cutter location (CL) and tool axis vector are calculated.

### A. Rough Machining Process Analysis Of Integral Impeller

Because of the complex structure, bending and twisting shape of blade, poor openness, it is generally difficult to apply suitable tool parameters and machining scheme in machining process planning. The interference and collision between the tool and workpiece easily occur, or there are areas where the tool can not reach. Therefore it is necessary to analyze the machinability of the passage of integral impeller.

The main task to analyze the machinability of the integral impeller is to determine the degree of difficulty and the largest tool diameter allowed with NC milling. The assessment of machinability includes calculation of blade bending and twisting degree, passage depth and width, and analysis of the boundary surfaces, etc.

### B. Bending and twisting assessment of blade

Twisting degree is measured with the twisting angle of the blade type lines. Bending degree is measured by the distance between the line to connect the upper and bottom cross-section centers, and the center of the other cross-sections of blade, which can directly reflect the openness of the area to be machined.

The twisting degree is assessed by calculating the largest angle between blade chord vector and impeller axis. The detailed calculation method is as follows. The blade surface is parameterized, as shown in Fig. 1(a). A series of  $v$  parameter lines from inlet side to outlet side are constructed. The point with the largest curvature on these lines are found out, i.e.  $P_{mi,i}$ , which splits the line into two segments. Two  $u$  chord vectors are obtained with connecting  $P_{0,i}P_{mi,i}$

and  $P_{mi,i}P_{1,i}$ . Angles  $\varphi_i$  and  $\varphi'_i$  are determined respectively and the larger one is the twisting degree on the parameter line. The largest twisting degree is determined through the calculation and comparison.

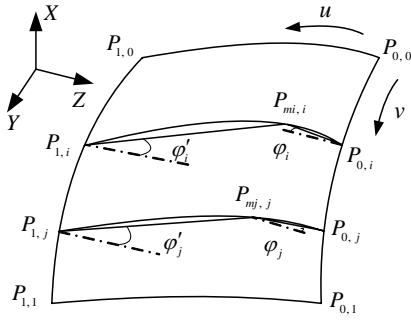


Fig.1 Twisting degree calculation

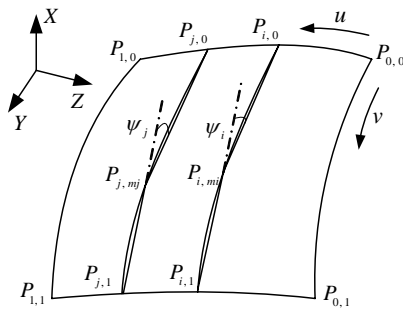


Fig.2 Bending degree calculation

The bending degree is assessed by calculating the angle between the radial chord vectors of the blade. A series of  $u$  parameter lines are constructed from the upper side to bottom side after parameterization of blade surface, as shown in Fig.2. Point  $P_{j,mj}$  with the largest curvature on parameter line is obtained. Two  $v$  chord vectors are obtained by connecting  $P_{j,0}P_{j,mj}$  and  $P_{j,mj}P_{j,1}$ , and the angle  $\psi_j$  is calculated. Similarly, the largest angle is finally determined.

C. Calculation of passage depth and width

First the upper and bottom curves of the blade basin and back are parameterized respectively to obtain four curves. Then they are replaced with discrete points. The distance between the corresponding discrete points on upper curve and bottom curve are calculated and the largest value is taken as the largest height of the blade, i.e. the depth. The blade basin

and back surfaces within the same passage are parameterized and discretized in terms of precision requirements. The distance between the corresponding discrete points on upper curve and bottom curve are calculated and the smallest value is taken as the smallest width of the passage, and the largest value is taken as the largest width of the passage.

D. Assessment of tool reachability for passage machining

For integral impeller, the passage is constrained by the surfaces of blade basin, back and hub. When machining, the interference between tool and surface of workpiece easily takes place. In assessment of tool reachability, blade surface is offset toward the inner side of the passage with the distance of tool radius, so that the assessment model can be simplified. If the integral impeller is milled on one side and there is area where the tool can not reach, it may be the bending degree or twisting degree of the blade is too big.

E. Rough milling strategy

Since the deep and narrow passage of blade with big bending and twisting degree, slender tool is needed to machine the integral impeller. Through analyzing the structure of the integral impeller and the properties of various milling methods, it follows that plunge milling (Fig.3) is suitable for the rough machining of the integral impeller. To achieve uniform margin, side milling is carried out after plunge milling.

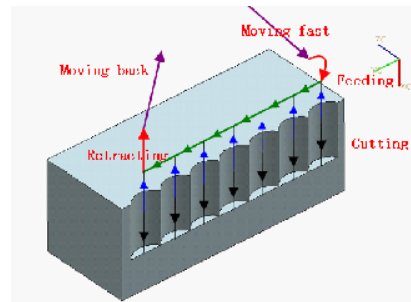


Fig.3 Plunge milling

II. PLUNGE MILLING TOOL PATH GENERATION OF INTEGRAL IMPELLER

Plunge milling has the advantages of small radial cutting force, steady milling performance, and high machining efficiency. It is widely applied to removing blank material in rough machining stage. Nowadays, there are plunge milling programming modules in UG, CATIA and MASTERCAM. However these modules are used in three-axis machining. In

this paper, tool path generation algorithm for 5-axis plunge milling is researched. First a type of new method for solving one-sided envelope lines of the free-form curve is presented. The division method for passage area of machining is designed. Then the machinable area of the passage is defined to avoid the interference. The tool path generation procedure is shown in Fig.4. For plunge milling, the cutting is along the tool axis direction. Therefore the machined boundary surfaces are ruled surfaces. On the other hand, in general the blade surface is free-form and is not ruled surface. To raise rough milling efficiency, ruled surface is used to approximate the blade surface. And the spatial sweeping surface for tool axis is the offset of the workpiece surface. The procedure for solving offset envelope ruled surface is as follows:

- (1) Solving  $n + 1$   $u$  parameter lines  $C(u_i, v)(i = 0, 1, \dots, n)$ , as shown in Fig.5 (a);
- (2) Calculating the envelope ruled generating lines which lie on one side.

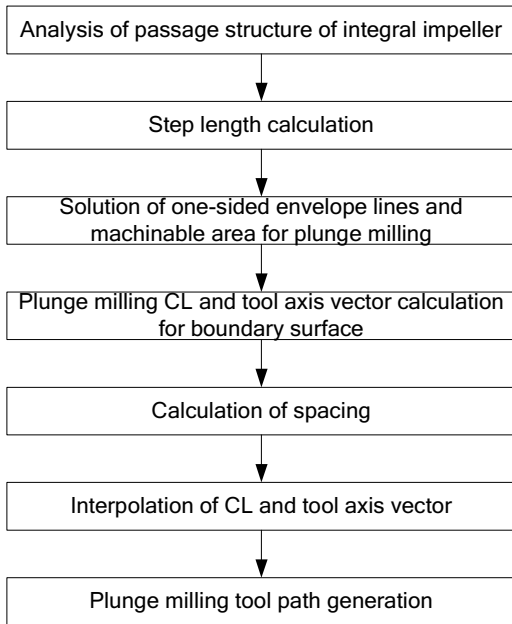


Fig.4 Tool path generation procedure

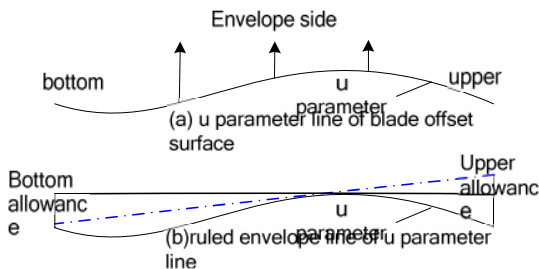


Fig.5 Solution of rule envelope surface

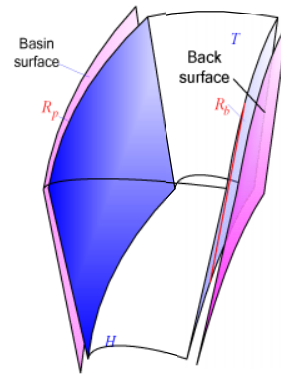


Fig.6 Rough machining area

The rough machining area of passage can be determined as shown in Fig.6.

As shown in Fig.7, the intersection curves between the offset ruled envelope surfaces of blade basin and back and the roof surface  $T$  are  $C_1(u)$  and  $C_2(u)$ , and the intersection curves with the bottom surface  $H$  are  $C_3(u)$  and  $C_4(u)$ . The step length can be determined in terms of the scallop height, and all of the CL points  $T_{3\_i} (i = 1, 2, \dots, n)$  on boundary curve  $C_3(u)$ . Make planes  $P_i$  perpendicular to impeller axis, and  $P_i$  intersects with  $C_1(u)$  at  $T_{1\_i}$ ,  $C_2(u)$  at  $T_{2\_i}$  and  $C_4(u)$  at  $T_{4\_i}$ . Link CL points  $T_{1\_i}$ ,  $T_{3\_i}$  and  $T_{4\_i}$  to construct approximately the generating lines of the ruled envelope surface. And  $\overline{T_{1\_i}T_{3\_i}}$  and  $\overline{T_{2\_i}T_{4\_i}}$  are the direction of plunge milling tool axis.

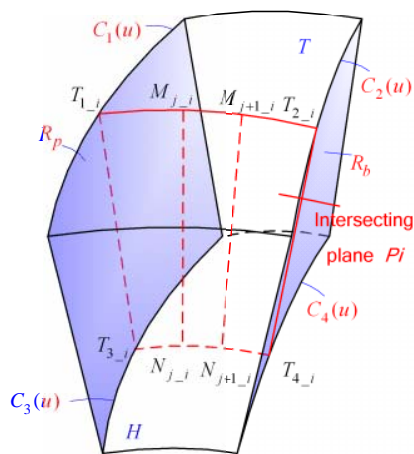


Fig.7 Tool path generating

Within the plane  $P_i$ , the tool axis vector is interpolated in terms of spacing interpolation boundary, and the passage tool axis vector  $\overline{M_{j-i}N_{j-i}}$  is obtained. Connect all of the tool axis vectors according to certain way, i.e. the plunge milling tool path for a passage. At last all plunge milling tool path of the passages can be obtained through arraying.

### III. CALCULATION EXAMPLE AND CONCLUSIONS

Fig.8 and Fig.9 show the plunge milling tool path axis vectors and simulation respectively.

The following conclusions can be obtained.

- (1) Bending and twisting degree can be used to assess the machinability of the integral impeller.
- (2) Plunge milling is an effective method to the rough machining of the integral impeller.
- (3) With the one-sided envelope straight lines of the free-form curves, the overcut can be avoided.

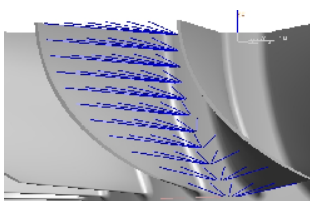


Fig.8 Tool path axis vectors

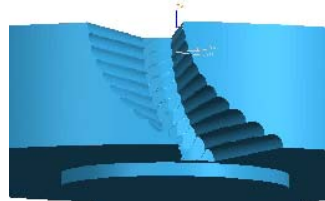


Fig.9 Cutting simulation

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