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ORIGINAL ARTICLE

Geometric modeling and tool path generation of model propellers with a single setup change

Cheol-Soo Lee · Jae-Hyun Lee

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Abstract A model propeller plays important roles in the design of the marine vehicles. The cavitations, the erosion, the pressure fluctuation, and the flow are measured by the model propeller. These measurements help to create the actual marine propeller. In this paper, geometry modeling and tool path generation for a model propeller are proposed, and the hub surface and lateral surface of the wing surfaces are generated by the proposed method. Considering the characteristics of the model propeller, efficient Cutter Location (CL) data are proposed: (1) the finish machining is completed with one setup posture. (2) A four-axis machining algorithm is proposed that makes it possible to the propeller with one setup and that minimizes machining error. (3) To minimize the maximum machining load, zigzag machining and an outside-to-inside tool path are introduced. A tilting guide curve is proposed to determine the tool axis vector. A smoothly changing tool axis vector is obtained through this curve, and the calculation is simple and fast. The results demonstrate that the proposed method is useful for the manufacturing of model propellers.

Keywords Marine propeller · Geometric modeling · Five-axis machining · Four-axis machining · Tool axis vector

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C.-S. Lee (✉)
Department of Mechanical Engineering, Sogang University,
1, Shinsu-dong, Mapo-gu,
Seoul 121-742, South Korea
e-mail: cscam@sogang.ac.kr

J.-H. Lee
CSCAM Co Ltd, Technology Research Center,
Ok-dong 1235-10, Gwangsan-gu,
Gwangju 506-500, South Korea
e-mail: jhlee@cscam.co.kr

1 Introduction

1.1 Model ship and model propeller

A model ship carries out experimental analysis to improve the propulsion and maneuvering performance of marine vehicles (see Fig. 1a). Based on these types of analyses, actual marine vehicles are designed and built. A model propeller plays important roles in the design of the marine vehicles. With the model propeller, the cavitations, the erosion, the pressure fluctuations, and the flow are measured. These measurements help to construct an actual marine propeller.

Figure 1b shows cavitations on the rudder surfaces. Cavitations on propeller blades and rudder surfaces can cause erosion at the local part where the cavities collapse. They can also lead to vibration and noise in the hull of the ship. Therefore, it is necessary to develop reliable analysis tools that can predict the formation of cavitations. From these types of analyses, an optimal propeller shape can be created. The designed shape of a propeller should be tested before it is manufactured. In this case, a model propeller is utilized to test and measure the performance of a propeller in a scaled environment.

1.2 Manufacturing of a model propeller

A model propeller is generally made from cylindrical aluminum alloy. Conventionally, it is manufactured by a manual method: (a) drilling at the check points of wing surfaces, (b) hand-finishing by grinding to those points. This method is time-consuming to build a model propeller accurately. Moreover, as this method depends simply on the skill of the craftsmen, the results may be imprecise and out of balance, which can cause the vibration and noise.

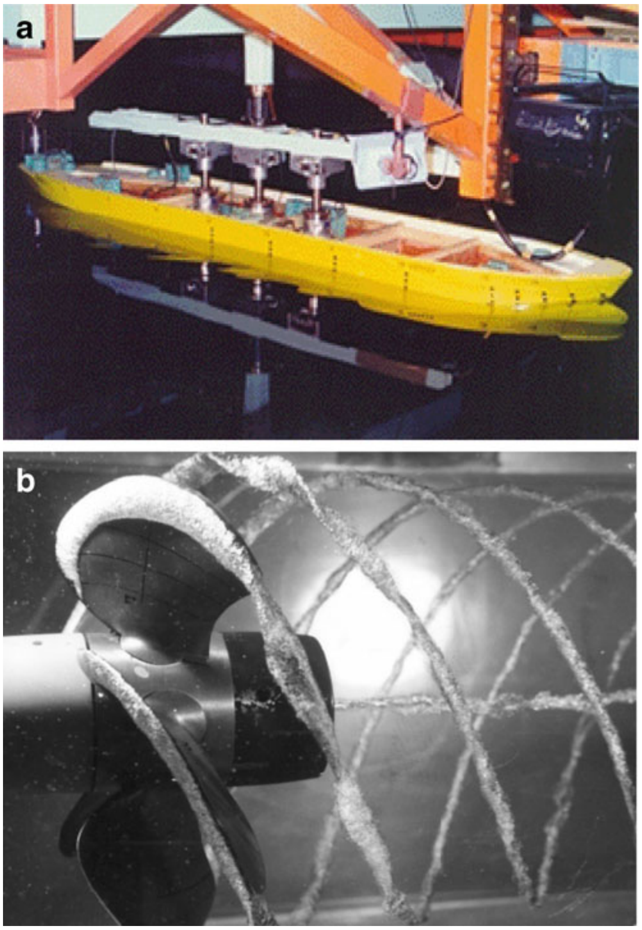


Fig. 1 A model ship (**a**) and a model propeller (**b**)

Currently, to improve the quality of a model propeller, a five-axis Numerical Controller (NC) machining is utilized. The procedure of the five-axis NC machining of a model propeller is given below.

(1) Set up the raw material as shown in Fig. 2a.
(2) Cut the upper side of the propeller via five-axis machining (see Fig. 2b).
(3) Turn over the work piece.
(4) Cut the other side of the propeller via five-axis machining (see Fig. 2c).

This method can cut clearly the narrow spaces as well as the uncut volumes in three-axis machining or by drilling. The machining quality and productivity is also superior to conventional methods. This method, however, can reduce the level of accuracy on account of setup errors that occurred during the turning over of the part. When the work piece is turned over manually, it is difficult to guarantee that tolerance is maintained at or below 0.01 mm. Hence, it is necessary to develop a method that does not require turning over the part.

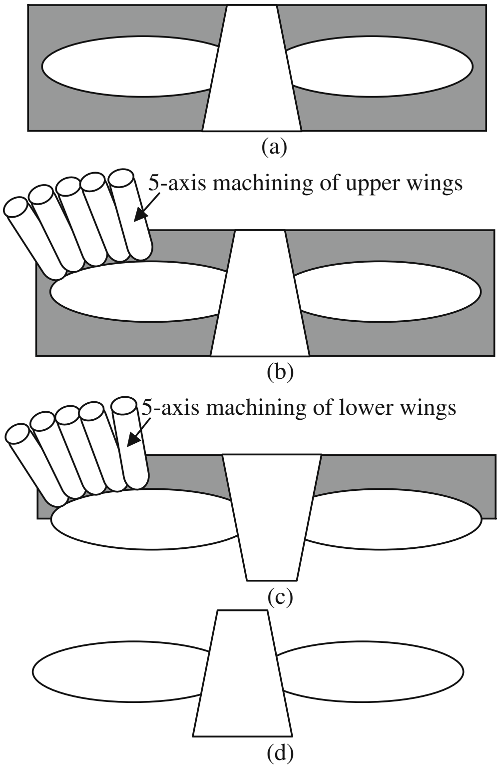


Fig. 2 A five-axis machining of a model propeller: **a** setup, **b** machining of upper wings, **c** machining of lower wings, **d** the completed propeller

This paper proposes a method that cuts a model propeller without the turnover. This means that the model propeller must be machined with a single setup, which can remove the error source caused by the turnover.

1.3 Literature survey

One of the earliest (1970) and still very useful introductions to five-axis milling was given by Baughman [1] clearly starting the applications [2]. This paper classifies the possible conceptual designs and actual existing implementations based on the theoretically possible combinations of the degrees of freedom. Some useful quantitative parameters, such as the workspace utilization factor, machine tool space efficiency, orientation space index, and orientation angle index are defined. The advantages and disadvantages of each concept are analyzed.

In the last decades, advances in machine tool and CAD/CAM technologies have made it more convenient to machine complex shapes. There have been many studies of five-axis machining. One concerns tool path and NC code generation, and another is in relation to interference checks and removals [3]. In the tool path generation, a surface base approach is used for rapid calculation at simple shaped work part. Recently, the polyhedral model of a sculptured surface is wildly researched [4–9]. And the researchers are concentrated on the regulation of the cutting load of tool and the tool path for high speed machining [10].

For the detection and removal of interference, the visibility cone, which played an important role in generating the CL data of the multi-axis machining [7], is calculated in each tool position. Then the optimized interference-free tool vector is obtained from the vectors of feasible range. In general approach, the determination of tool vector is time-consuming [3–6]. And the requirements and constraints of machining are different, at the work part and the used tool. Thus, there were practical approaches of turbine blade, impeller, tire, and propeller.

In the case of turbine blade, the projected visibility arc is proposed to simplify the range of feasible tool vector [11]. Then the optimized heel angle of flat-end mill is calculated for the machining condition. And the efficient method of generating five-axis rough machining is suggested by using the characteristic shape of centrifugal impeller [12]. And GPU-based five-axis finish machining of impeller with a ball-end cutter was introduced [22]. In the large marine propeller, the face-milling cutter is used, and the tool vector is optimized to reduce the scallop height of the adjacent paths [13]. Generally, the wing supporter is used to endure the machining pressure. In the small marine propeller, the wing supporter is not used. Thus, it is required to consider the machining pressure and to machine the narrow and deep valley of adjacent wing by one setup. In the previous research, the efficient tool path pattern considered the machining pressure is introduced. And the interference-free tool path of ball-end cutter is generated by check vectors of adjacent wing [17]. Recently, the cylindrical cutter is used to improve the machining quality. In this method, the cylindrical cutter and the machined surface can keep line contact. Thus, the scallop height is smaller than the ball-end cutter [18].

Generally, generating the interference-free tool path requires lots of time and efforts. At all tool positions, the feasible tool vectors are calculated and smoothly connected to minimize the dramatic change.

In this paper, a tilting guide curve is proposed to determine a tool axis vector, as shown in section 4.2. At the first tool path, a proper tilting guide curve is calculated, and the offset distance is determined. Then, at the next tool path, the tilting guide curve is determined by the offset distance. And by connecting these two curves at each tool position, the smoothly changing tool vectors are obtained. Thus, by one determination of offset distance, the feasible tool vectors and their smooth connection of all tool paths can be calculated in simple way. But, in check vector method [17], this calculation is required at all tool paths. By this method, a small marine propeller is machined by four-axis machining with a ball-end cutter at one setup efficiently.

The special case of propeller, which is not reachable by a tool to the inner hub area, as shown in section 3.1, is not machined by proposed four-axis method, though the global interference checking is possible. In that case, the interference-free tool paths are calculated by the general method of five-axis machining [19–22]. And the proposed idea can be applied to by a manual operation. The tool axis vector is dependent on the tilting guide curve at the proposed method. Thus, by manually editing the tilting guide curve, the interference-free tool path can be acquired.

2 System overview

2.1 Procedure

The overall procedure for the geometric modeling and tool path generation of a model propeller is given below:

(1) Set up the work piece (see Fig. 3a).
(2) Machine the 2D boundary of the model propeller via contour milling.
(3) Cut the lower side of the model propeller roughly using three-axis machining (see Fig. 3b).
(4) Turn over the work piece.
(5) Cut the other side of the model propeller roughly using three-axis machining (see Fig. 3c).
(6) Using four-axis NC machining, precisely cut the model propeller without a setup change (see Fig. 3d, e).

Steps (1) to (5) represent the processes of rough milling. When rough milling, the machining allowance remains for the finish cut. After the rough cut, the model propeller is cut precisely during the finish machining process. Even if it is necessary to turn over the part during rough machining, this does not influence the ultimate accuracy of finish cut. In the finish cut of small model propeller in step (6), the determination of tool axis vector of deep valley of wings is important. That requires lots of calculation in the general five-axis machining method. But, that can be calculated easily in four-axis machining. For the efficiency, we divided the wing path to the lower and the upper for four-axis machining and introduced the tilting guide curve.

The proposed procedure of tool path generation for a model propeller is presented as shown in Fig. 4.

(1) Create the surface model of a model propeller.
(2) Convert the surface model to a polyhedral model via tessellation.
(3) Generate the tool path of the cutter center.
(4) Generate the tilting reference curve.

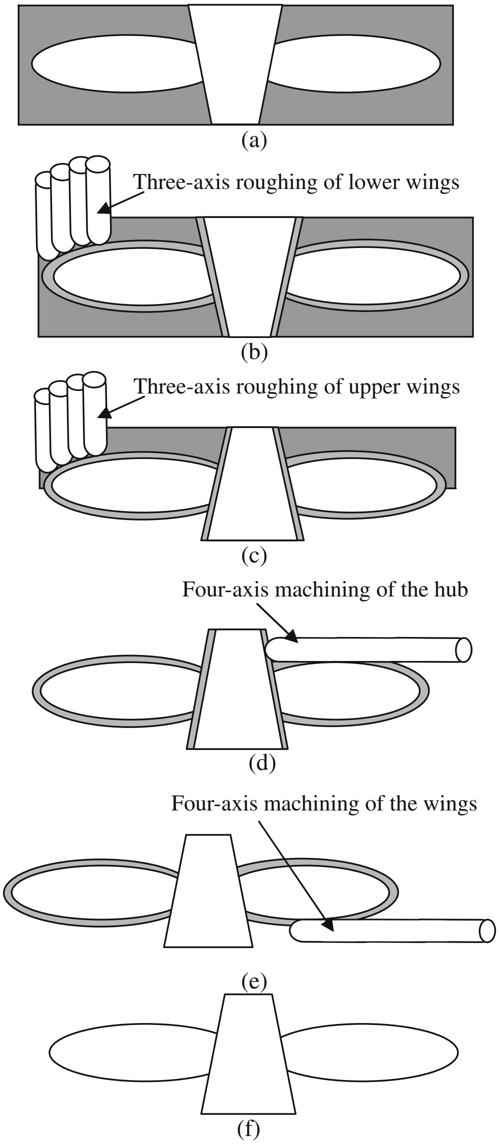


Fig. 3 The procedure for the machining of a model propeller: **a** setup, **b** rough cut by three-axis machining, **c** turnover and rough cut of the other side, **d** the four-axis machining of the hub, **e** the four-axis machining of the wing surfaces, **f** the completed model propeller

(5) Calculate the tilting angle of the cutter (the tool axis vector).
(6) Generate the NC code by post-processing.

A geometric model of an actual propeller is generated after an analysis and experimental efforts of hydromechanics. Data for the wing of the propeller are represented by a point list. These point data are only for the face of wings, implying that the lateral surface of the wing should be created properly.

To generate the tool path, the surface model should be tessellated to a polyhedral model. First, the offset tool path is calculated. This lies in the center of the ball-end mill. Some points should be inserted into the path, and the intersected loops should be removed to avoid interference. This modification is done automatically. At this point, it is necessary to calculate an interference-free tool axis vector. To generate the tool axis vector, this paper proposes the tilting guide curve. Using this curve, a proper tool axis vector can be generated, and the tool axis vector changes smoothly along the path.

2.2 Characteristics of the machining of a model propeller

Compared with conventional five-axis machining, there are a number of characteristics to be considered when machining a model propeller.

(1) In machining a propeller, a setup change during the rough machining process does not affect the accuracy. The setup change during the finishing, however, causes serious errors in the final result because the machining tolerance is very tight, i.e., 0.01 to 0.02 mm.
(2) There is no place except at the center of the hub to fix the model propeller during the machining. It is unstable, however, if the work piece is fixed at the center of the hub. Hence, a proper tool path should be generated to maintain the balance of the wings. If the wing is machined in one direction of rotation, balance of wings can be lost. This causes

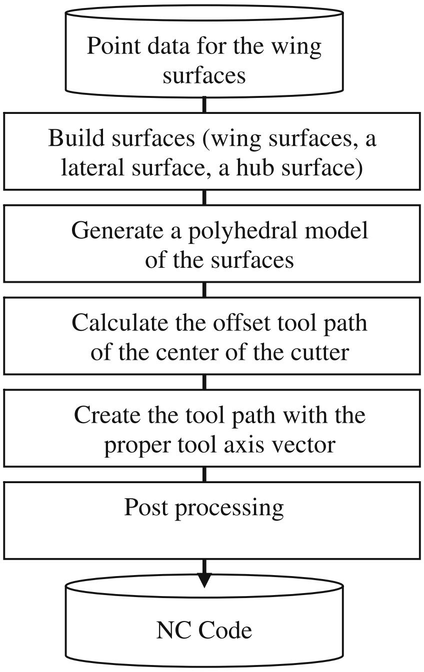


Fig. 4 The procedure of geometric modeling and the tool path generation of a model propeller

vibration of the propeller and reduces the total power output.

(3) The outside of the wing is thinner than the inside. If the wing is machined from the inside to the outside, the wing is easily deformed by the machining load. If the wing is machined from the outside, the amount of deformation can be reduced.

Considering these characteristics, the proposed tool path of a wing uses a zigzag pattern rather than a one-way pattern. And to reduce the pulling of a wing by machining pressure, it starts from the outside to the inside of the wing, from biggest radius path to smaller one. The most important feature of the proposed tool path is that it is not necessary to change the setup.

3 Geometric modeling of a model propeller

3.1 Generation of the wing surface

The geometry of the wing of an actual marine propeller is determined through different studies and experiments. A model propeller is designed by miniaturizing the actual propeller. The shape of wing surface, as shown Fig. 5, is characterized by the skew angle and the rack angle. These angles are related with the noise of propeller and resistance of water. To design the total wings of propeller, a wing surface is copied by rotation at the center point of hub. If the skew angle and the number of wings are bigger, the space of adjacent wings for machining of hub is smaller.

The interference-free tool path cannot be created; in the case of a four-axis, cutting tool cannot reach to the inner wing and hub area; the space of adjacent wings is too small to reach to the hub area by a four-axis tool or blocked by bended special shape of wings.

3.1.1 Upper and lower surfaces of a wing

The geometric data of the wings are represented by the point lists that lie on the concentric circles of the hub. Each point list is described by the radius of concentric circle (r), the angle between the y-axis, and the line from the origin to a point, the distance from the upper limit to the upper surface, the thickness of the wing, and the distance from the lower limit (usually $z=0$) to the lower surface, as shown in Fig. 6. The Cartesian coordinate values are obtained by the following equations.

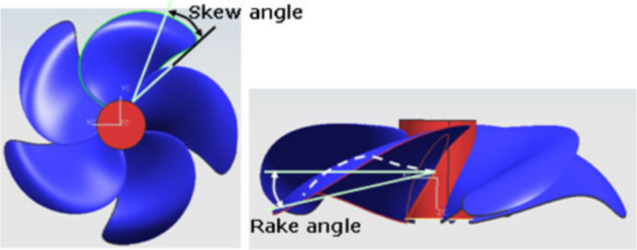


Fig. 5 The example of model propeller

$$x = r\sin(\theta) \tag{1}$$

$$y = r\cos(\theta) \tag{2}$$

$$z_f = b + c \tag{3}$$

$$z_b = c \tag{4}$$

where

r is the radius of the concentric circle of the point list.
θ is the angle between the y-axis and the line from the origin to a point.
b is the thickness of the wing at a point.
c is the height of a point on the lower wing.
z_f is z value of a point on the upper wing.
z_b is z value of a point on the lower wing.

The numbers of points of the point list are not identical because the points are sampled according to the angle. To generate a Bezier surface of order (4, 4), the point list is adjusted to have the same number of points as other point lists, and the points are spaced evenly. Using these point lists, a Bezier composite surface of order (4, 4) can be created easily. There are many studies on this topic [14]. Figure 7 shows a surface model of the upper and lower surfaces of a wing.

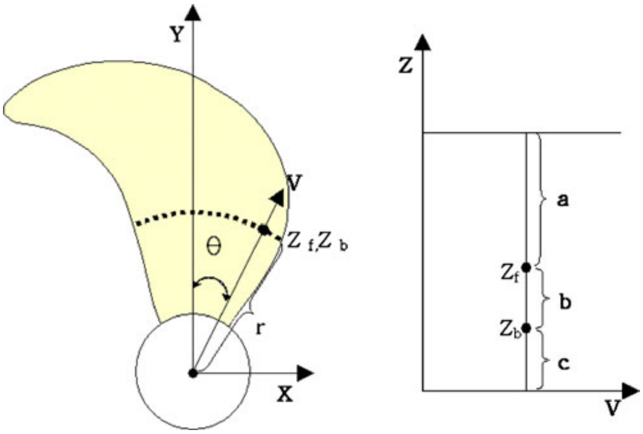


Fig. 6 Geometric data of a wing

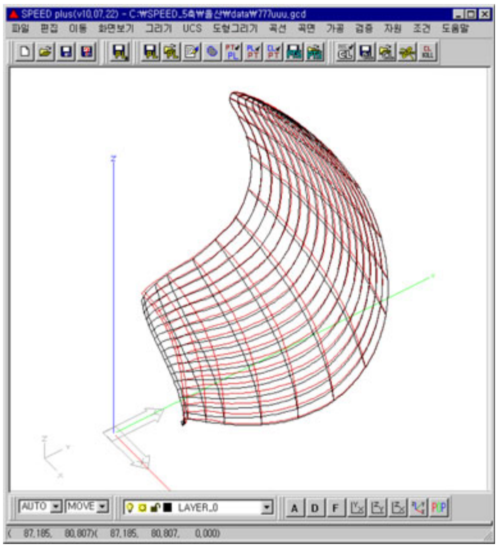


Fig. 7 A wing surface of a model propeller

3.1.2 *A lateral surface of a wing*

It is necessary to create a lateral surface to connect the upper and the lower surfaces smoothly. This surface should be generated by the system automatically rather than by the designer of a propeller. Using two points of the upper and lower wing surfaces (*F*, *B*), the tangent vectors at the points (V_f, V_b) and the end point of a wing (*E*), a sectional curve (CV_{sec}) can be created, as shown in Fig. 8. These sectional curves can be created along the boundary curve (CV_{bnd}). Using these sectional curves and the boundary curves of the upper and lower surfaces, a lateral surface is generated.

As the tangent vectors of the upper and lower surfaces are used to generate the lateral surface, continuity (G^1) is guaranteed only at the point where the sectional curves are placed. G^1 continuity is not guaranteed at the other boundary points. When the tool path is generated by offsetting method, the gaps of wing surfaces and lateral surface are enlarged, especially at the end part of the wing. This drawback must be considered when the tool path is generated.

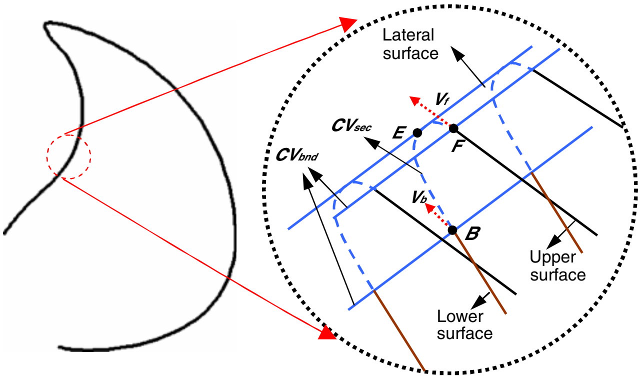


Fig. 8 Creation of the lateral surfaces

3.1.3 *A hub surface*

A hub surface can be created using rotating the cross-sectional curve that is represented as a list of the height (H_{i}) and its radius (R_{i}), as shown in Fig. 9. By rotating the cross-sectional curve, a hub surface can be created easily.

4 Tool path generation

4.1 Tool path of the cutter center

Surfaces representing the model propeller should be tessellated to create a polyhedral model. In this paper, the polyhedral model consists of triangles that have three vertices and normal vectors. As surfaces used in this paper are smooth, the sampling intervals (Δu, Δv) are easily calculated, which satisfy the given tolerance. All triangle points on the aforementioned surfaces can be obtained using the (Δu, Δv). A polyhedral model is constructed by the sampled points of wing surfaces, hub surface, and lateral surfaces.

As a ball-end mill is used to cut the model propeller, these triangles should be offset by the radius of the cutter. The tool path of the cutter center can be calculated by intersecting the offset polyhedral model and a plane or a cylinder. To avoid interference with the wings and the cutter, a proper tool axis vector should be calculated.

4.1.1 *Tool path generation to cut a wing surface*

The tool path to cut the wing of a model propeller is generated by calculating the intersection curve between the

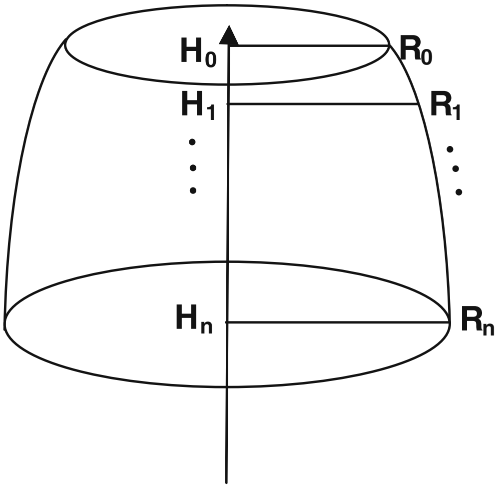


Fig. 9 A hub surface

offset polyhedral model and a cylinder, as shown in Fig. 10. The cylinder and the hub surface are concentric. When calculating the intersection, the intersection point and the normal vector at the point are saved. If the normal vectors of each vertex of a triangle change suddenly, the cutter (ball-end mill) may over-cut its own triangle. In Fig. 11, the offset triangle is more expended than the original one. Thus, it is necessary to insert points between the end points of $p1$ and $p2$.

There are three polyhedral models that represent a wing: the upper surface, the lower surface, and the lateral surface. If calculating the intersection curves, there are four curves: an intersection curve on the upper surface, an intersection curve on the lower surface, and two intersection curves on the lateral surface. These four curves must be connected to one curve. At this point, two types of problems can occur. The first of these involves intersection curves that are overlapped, and the second involves intersection curves that are apart from each other.

If overlapping occurs, it is necessary to calculate an intersection and join the two curves at that point, as shown in Fig. 12a. To remove overlapped points, intersection points must be calculated between the normal vector line and curves from the lateral surface and wing surface. If there are two intersection points (this means "overlapping"), the outer point (mark ○) of two points should be selected as a point of tool path. If the curves are apart from each other, additional points must be inserted using the cutter radius and the normal vectors of the end point, as shown in Fig. 12b.

4.1.2 Tool path generation to cut a hub surface

As the hub surface is created by the surface of the revolution, the section curve at the height becomes a circle. A good tool path is created when cutting the hub with circular arcs. The first step when calculating the tool path involves generating the intersection curve between the offset hub surface and a plane parallel to the *XY*-plane. This intersection curve is a circle that should be bounded by the wing surfaces. By calculating the intersection points between the circle and a polyhedral model of wing surfaces, the circle from the offset hub surface becomes a circular arc. Fig. 13 shows a side view of a tool path that can be used to cut the hub.

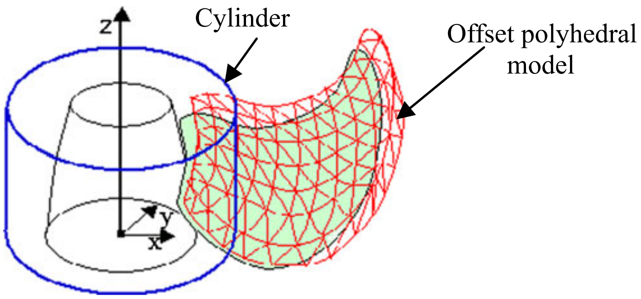


Fig. 10 Tool path generation by calculation of the intersection curve between a cylinder and the offset polyhedral model

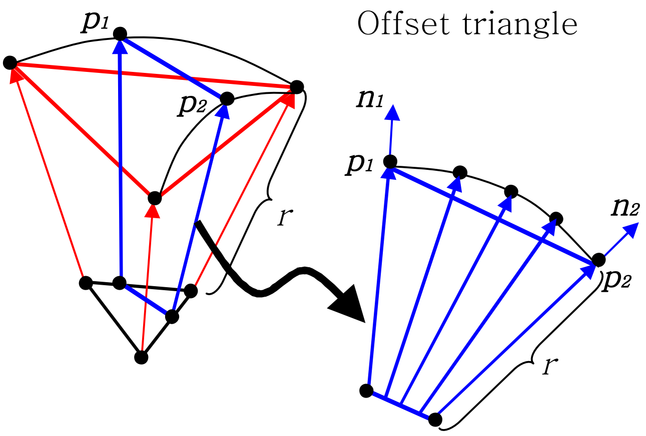


Fig. 11 Tool path creation of the offset triangle

4.2 Determination of a tool axis vector

4.2.1 A tool axis vector

In five-axis machining, the tool posture is determined in the following procedure [7]:

(1) Visibility computation: To generate the tool axis vector, an access volume should be calculated. The access volume is a space in which the tool can approach a point of the tool path without interference. The access volume is cone-shaped in the case of five-axis machining. In the case of four-axis machining, the access volume is a triangle, that is, a planar space [5, 7].

(2) Definition of the tool posture: The tool axis vector is determined by selecting an axis vector in the cone (the

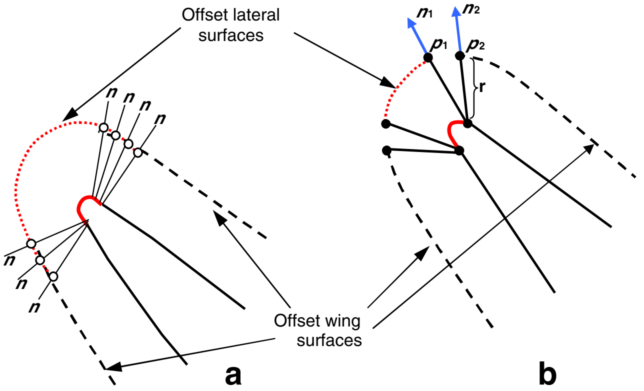


Fig. 12 Connection of the tool path

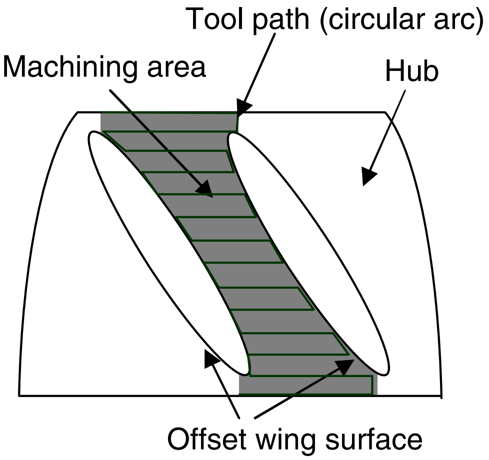


Fig. 13 Tool path of a hub surface

access volume), as shown in Fig. 14a. Then, the vectors of adjacent position are connected smoothly. Considering the shape of wing, the propeller can be machined by five-axis or four-axis machine. In five-axis machining, various postures are possible, but the calculation of tool axis vectors is time-consuming and smooth change of the vectors is difficult [15, 16]. With the four-axis machining, these works can be finished with little effort.

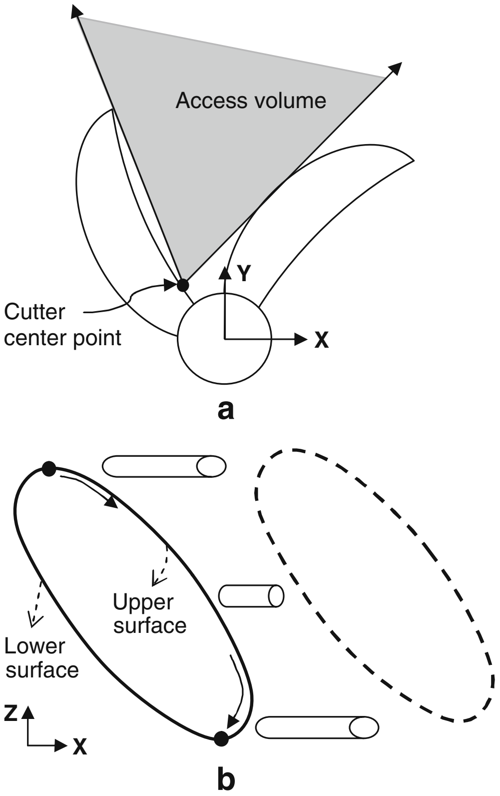


Fig. 14 The tool axis vector of a propeller. **a** An access volume of *XY* view. **b** A tool axis vector of *ZX* view

In the approach of four-axis machining, the path of a wing is divided to the upper and the lower surface tool path, as shown in Fig. 14b. The calculation of tool axis is simplified from the 3D space to the planer space. And this paper introduced a tilting guide curve to simplify more the creation of tool axis vector.

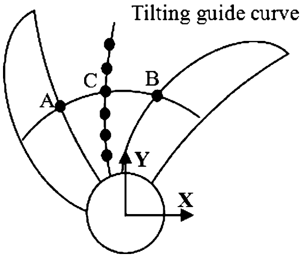
4.2.2 Generation of a tilting guide curve

A tilting guide curve is an intermediate curve of two intersecting curves of wing surfaces with a plane parallel to the *XY*-plane. Figure 15 shows the technique used to generate a tilting guide curve. The intersection curves between the offset polyhedral model of a wing and a plane should be calculated. By calculating intersection points between this intersection curve and a concentric circle, points A and B are obtained. Point C is an intermediate point between A and B. If the radius of the concentric circle changes from the radius of the hub to the end of the wing, a tilting guide curve can be generated at the height. The tilting guide curve should be generated at any height. For efficiency of the system, tilting guide curves are generated at sampled heights. In this paper, only 15 sampled heights are used to generate the tilting guide curves. At an intermediate height, the interpolated tilting guide curve can be utilized.

4.2.3 Determination of the offset distance

Using the tool path and the tilting guide curve presented at the previous stage, the tool axis vector can be determined. As shown in Fig. 16, P is a point on the tool path, and V_i is a tool axis vector. The first tool axis vector is a vector from point P to point Q_i on the tilting guide curve. With a tool axis vector, V_i, the interference check is processed with the tool holder and the work piece. If interference has occurred with the tool axis vector V_i, $V_{\mathrm{i}+1}$ is then considered as the next tool axis vector. This procedure is repeated until there is no interference. Then, the offset distance, the radius gap of a tool path and the searched tilting guide curve, is determined. At the first tool path, the offset distance must be calculated. But at the next tool path, a tilting guide curve is determined by using the offset distance easily. The check radius is the sum of radius of the tool path and the offset distance. Then, the tilting guide curve, which is the radius

Fig. 15 A tilting guide curve at a height



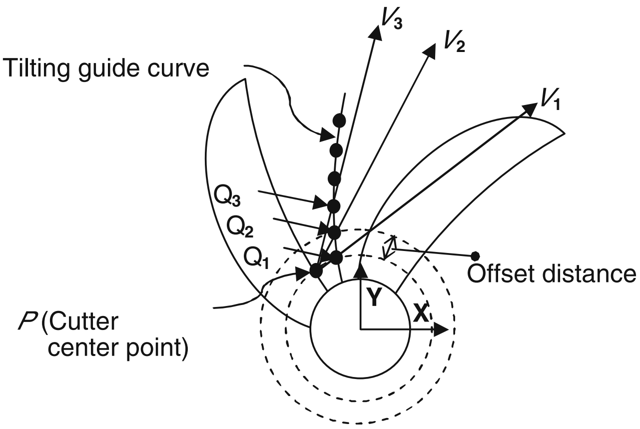


Fig. 16 Determination of a tool axis vector using the tilting guide curve

closest to the check radius, is selected. The space of adjacent wings at the next tool paths is wider than the first one. Thus, the recalculation of offset distance is not necessary. And by just connecting from the tool path to the tilt guide curve at each tool position, the smoothly changing interference-free tool vector is obtained.

The determination of a tilting vector in this manner leads to good results, such as surface finishing and the smooth motion of the machine tool, because the tool axis vector changes smoothly along the tool path. The index *i* is increased from the inside to the outside of a model propeller. If the index *i* is decreased, the interference check is processed from the outside to the inside with acceptable results. The tool position vector and tool axis vector are obtained in this manner. With these data, the four-axis CL data can be generated.

4.3 Post-processing for generation of NC code

To manufacture the model propeller, a conventional five-axis NC machine is utilized, which is attached to a tilting and rotating table (see Fig. 17a) on a three-axis NC machine. Although the five-axis machine is used, the four-axis machining method is utilized, as described in this paper. Four-axis machining has an advantage in that it can cut the model propeller without changing the setup.

The kinematic structure is shown in Fig. 17b. Using the position data (P_x,P_y,P_z) and the tool axis vector (A_x,A_y,A_z), the absolute coordinate values to send to the NC machine are generated. The inverse kinematics can be calculated using the equations given below. (x, y, z) are coordinate values for the Cartesian coordinate system, and (a, c) represent angles of the rotational axes.

$$c = \frac{\pi}{2} - \arctan\left(A_y, A_x\right) \tag{5}$$

$$a = \frac{\pi}{2} - \arctan\left(A_z, \sqrt{A_y^2 + A_x^2}\right) \tag{6}$$

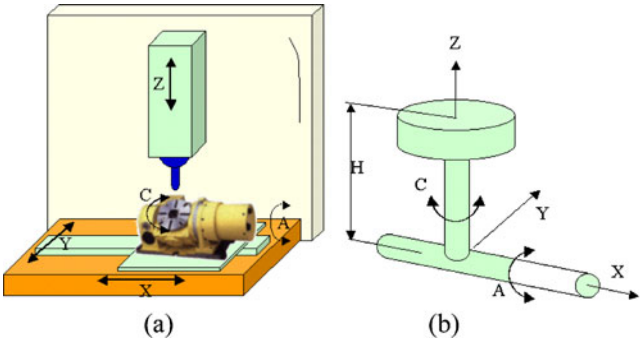


Fig. 17 A five-axis NC machine

$$(x,y,z,1) = \left(P_x,P_y,P_z,1\right)\begin{pmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&H&1\end{pmatrix}\begin{pmatrix}\cos(c)&\sin(c)&0&0\\-\sin(c)&\cos(c)&0&0\\0&0&1&0\\0&0&0&1\end{pmatrix}\begin{pmatrix}1&0&0&0\\0&\cos(a)&\sin(a)&0\\0&-\sin(a)&\cos(a)&0\\0&0&0&1\end{pmatrix}\begin{pmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&-H&1\end{pmatrix} \tag{7}$$

5 Implementation and the results

Figure 18 shows the CL data that are used to machine a model propeller. There are uncut volumes because the rough cutting is done by three-axis machining. These uncut volumes must be removed before the finish machining, as shown Fig. 18a. CL data for the finish machining of the wing surface are shown in Fig. 18b, c. CL data for the machining of the hub surface are shown in Fig. 18d.

The CL data for one wing surface are copied to formulate the CL data that are used to cut the other wing surfaces and the other parts of the hub surface. None of the CL data requires a setup change. Figure 19 shows an actual model propeller machined by the proposed method.

When the model is being tessellated, in this paper, the tolerance of polyhedral model is set to 0.005 mm. So, the tool path error should be less than it. But, there are machining errors caused by mechanical problems such as a tool chattering and accuracy of machine tool. With a conventional five-axis machining, the cutting accuracy was 0.08~0.15 mm. With the proposed method, however, the accuracy is improved to 0.02~0.04 mm because the proposed method cuts the model propeller without a setup change.

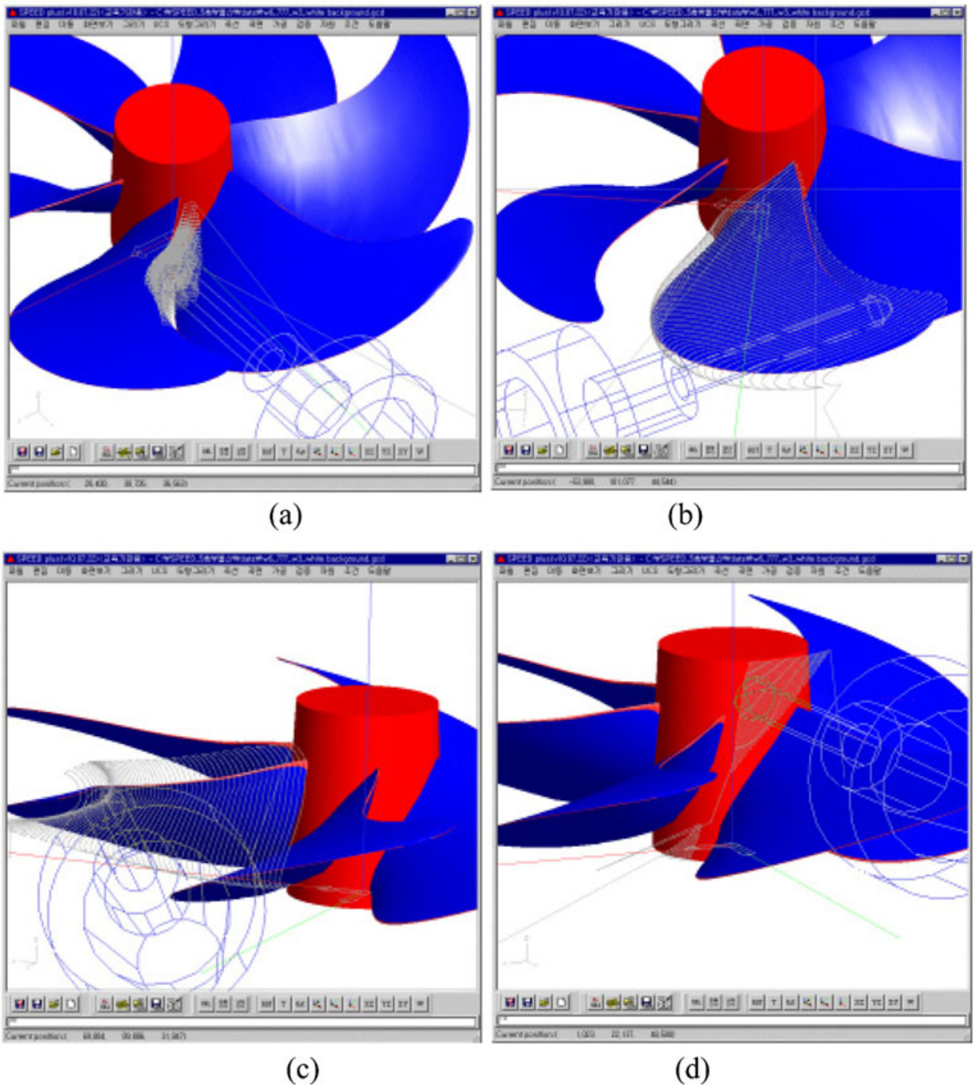

(a) (b) (c) (d)

Fig. 18 Four-axis CL data to cut a model propeller: **a** rough machining of an uncut volume, **b** finish machining of the upper wing surface, **c** finish machining of the lower wing surface, **d** finish machining of the hub surface

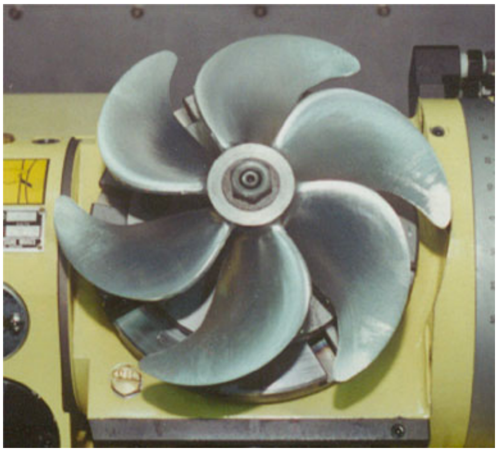


Fig. 19 A machined model propeller

6 Conclusions

In this paper, geometry modeling and tool path generation of a small model propeller are proposed. The geometry modeling of a model propeller can be created by the designed point data. A hub surface and a lateral surface of wing surfaces are generated by the proposed method. These surfaces are tessellated to create a polyhedral model that is utilized to calculate the CL data.

In the real-sized large propeller, the machining time is an important factor. So, the machining method is different. It is not necessary to generate the whole NC data at one time, and the flat-end mill is preferred. But, the main concern of the small propeller is to generate the whole finish machining data for a single setup. Considering the characteristics of the small model propeller, this paper proposed an efficient CL data: (1) finish machining is completed with one setup posture. (2) A four-axis machining algorithm is proposed, which makes it possible to machine the propeller with one setup and minimizes the number of machining errors. (3) To minimize the maximum machining load, zigzag machining and an outside-to-inside tool path are introduced. A tilting guide curve is proposed to determine the tool axis vector. Using this curve, a smoothly changing tool axis vector is obtained with a fast and simple calculation. The results demonstrate that the proposed method is useful for the manufacturing of a model propeller.

References

1. Bohez ELJ (2002) Five-axis milling machine tool kinematic chain design and analysis. Int J Mach Tools Manuf 42:505–520
2. Baughman JA (1970) Multi-axis machining with APT. In: Leslie WHP (ed) Numerical control user's handbook. McGraw-Hill, London, pp 271–298
3. Li SX, Jerard RB (1994) Five-axis machining of sculptured surfaces with a flat-end cutter. Comput Aided Des 26:798–803
4. Choi BK, Park JW, Jun CS (1993) Cutter-location data optimization in five-axis surface machining. Comput Aided Des 25:377–380
5. Elber G, Cohen E (1999) A unified approach to verification in five-axis freeform milling environments. Comput Aided Des 31:795–800
6. Rao A, Sarma R (2000) On local gouging in five-axis sculptured surface machining using flat-end tools. Comput Aided Des 32:416–420
7. Balasurimaniam M, Laxmiprasad P, Sarma S, Shaikh Z (2000) Generating five-axis NC roughing paths directly from a tessellated representation. Comput Aided Des 32:261–267
8. Le Z, Chen W (2005) The analysis of correlative error in principal axis method for five-axis machining of sculptured surfaces. Int J Mach Tools Manuf 45:1031–1036
9. Hosseinkhani Y, Akbari J, Vafaeesefat A (2007) Penetration-elimination method for five-axis cnc machining of sculptured surfaces. Int J Mach Tools Manuf 47:1625–1635
10. Lavernhe S, Tournier C, Lartigue C (2008) Optimization of 5-axis high-speed machining using a surface based approach. Comput Aided Des 40:1015–1023
11. Piao C-D, Lee C-S, Cho K-Z, Park G-R (2004) Automatic NC-data generation method for five-axis cutting of turbine blades by finding safe heel-angles and adaptive path-intervals. J Mech Sci Technol 18(5):753–761
12. Young H-T, Chuang L-C, Gerschwiler K, Kamps S (2004) A five-axis rough machining approach for a centrifugal impeller. Int J Adv Manuf Technol 23(3–4):233–239
13. Lo C-C (1999) Efficient cutter-path planning for five-axis surface machining with a flat-end cutter. Comput Aided Des 31:557–566
14. Piegl LA, Tiller W (1996) The NURBS Book. Springer-Verlag, New York
15. Agson Gani E, Kruth JP, Vanherck P, Lauwers B (1997) A geometrical model of the cut in five-axis milling accounting for the influence of tool orientation. Int J Adv Manuf Technol 13 (10):677–684
16. Huiwen Li O, Tutunea-Fatan R, Feng H-Y (2007) An improved tool path discretization method for five-axis sculptured surface machining. Int J Adv Manuf Technol 33(9–10):994–1000
17. Youn JW, Jun Y, Park S (2003) Interference-free tool path generation in five-axis machining of a marine propeller. Int J Prod Res 41(18):4383–4402
18. Cao L, Liu J (2006) An integrated surface modeling and machining approach for a marine propeller. Int J Adv Manuf Technol 35(11–12):1053–1064
19. Morishige K, Takeuchi Y, Kase K (1999) Tool path generation using C-space for 5-axis control machining. J Manuf Sci E-T ASME 121(1):144–149
20. Balasubramaniam M, Sarma SE, Marciniak K (2003) Collision-free finishing tool paths from visibility data. Comput Aided Des 35(4):359–374
21. Jun CS, Cha K, Lee YS (2003) Optimizing tool orientations for 5-axis machining by configuration-space search method. Comput Aided Des 35(6):549–566
22. Bi QZ, Wang YH (2009) Ding H, A GPU-based algorithm for generating collision-free and orientation-smooth five-axis finishing tool paths of a ball-end cutter. Int J Prod Res 99999(1):1–20