Springer

KSME

Journal of Mechanical Science and Technology 33 (1) (2019) 315~322
www.springerlink.com/content/1738-494x(Print)/1976-3824(Online)
DOI 10.1007/s12206-018-1233-2

Morphing technology for generating intermediate roughing models in multi-axis machining for complex parts †

Han Feiyan*, Wei Juan, Zhang Chuanwei and Peng Xianlong

College of Mechanical Engineering, Xi'an University of Science and Technology, Xi'an Beilin District Yanta Road No. 58, 710054, China

(Manuscript Received February 13, 2018; Revised July 28, 2018; Accepted August 18, 2018)

Abstract

In multi-axis milling of the aviation complex parts, establishing accurate machining process model is a key technology to realize intelligent processing. In order to obtain accurate machining process model of the aviation complex parts, a method based on morphing technology to construct intermediate process models of multi-axis roughing is proposed. Firstly, the theoretical basis for morphing technology is introduced, and the mathematical model of three hermite transfinite interpolation for morphing technology is established. Then the process constraint which impacts the geometry of the intermediate process model is analyzed in morphing technology. According to the analysis of the process constraint to design the process parameters, and the process parameters with constraints are introduced to the morphing technology to construct the process models. Finally, a validation is conducted on a complex aviation parts. The example shows that the method can able to construct the intermediate process models of complex structure parts for multi-axis rough machining under the condition of controlling the machining allowance, and also can shorten the total processing time of the complex parts, to a certain extent, the processing efficiency is improved.

Keywords: Complex parts; Muti-axis machining; Morphing technology; Transfinite interpolation; Intermediate process model

1. Introduction

Multi-axis CNC milling is a typical method for processing difficult to be machined parts such as complex aviation parts. At present, the multi-axis CNC machining usually consists of three processing stages, namely roughing, semi-finishing and finishing, each processing stage corresponds to a process surface on which the tool path is planned, and these process surfaces are usually obtained by the process of theoretical surface equidistant deviation and transformation, that according to the machining tolerance and the requirement of error compensation. The biggest drawback of this traditional machining model is that the machining process cannot be predicted, and the current machining allowance cannot be accurately understood. For the complex parts, the most of allowance has to be removed in the roughing stage, its traditional process model may have the possibility of exist uncertainty allowance distribution or unevenly allowance distribution, which will result in empty cutting or cutter collision, thus affecting the processing quality and efficiency. Therefore, in the multi-axis CNC machining of such parts, it is very important to study the establishment method of the process surface model and to improve the processing quality and efficiency of those parts.

A lot of research work of establishment the process surface model in multi-axis milling has been done by the scholars. Duncan and Mair [1] proposed a planar sheet discrete machining model, which first discretizes the surface into a quadrilateral or triangular piece, and then calculate the tool path in NC machining. Farouki et al. [2-4] proposed that the offset distance must be greater than the curvature radius of the principal curvature, otherwise, the offset surface may produce self-intersecting or surface crack. Saito and Takahashi [5] proposed the Z-map model, using a large number of Z-map points to form the machining model, but the discrete expression of the geometry will lose its geometric accuracy. Choi et al. [6, 7] proposed an E-Zmap model with an equal step length, but the E-Zmap points of the step length cannot actually reflect the boundary and the corner information of the surface.

The above-mentioned process surface models which are constructed from the view of tool path calculation, that take the allowance as the basis of the part machining, and ignoring the size of cutting amount in actual machining, it may lead to empty cutting or strong vibration when the cutting amount is too large, and even occurrence the phenomenon of tool breakage, and so on. The new intelligent machining must use the new process surface model. Chen et al. [8] proposed a new method to build the process surface model based on the Z-

*Corresponding author. Tel.: +86 2985583159, Fax.: +86 2983856323
E-mail address: hanfeiyan@126.com
† Recommended by Associate Editor Wonkyun Lee
© KSME & Springer 2019

direction stock-remaining, which is only suitable for three-axis machining. The normal-direction stock-remaining method can be used for multi-axis machining, but the Normal-direction stock-remaining method need to calculate the normal vector of each point, but the normal vector is difficult to solve. In addition, the morphing technology is a special method of constructing the intermediate process models. Douglas [9] and Lazarus [10] firstly studied the morphing technology. Lefebvre and Lauwers [11] using the morphing technology to construct the multi-axis roughing process surface model of a simple cavity parts for the first time, and then planning the tool path in 3D machining, compared with the conventional 2.5D and 2D tool path generation method, the presented method makes the workpiece surface no staircase-like residual, but the algorithm is limited to a cavity model that its shape simply changes along the depth direction of the cavity. Han et al. [12, 13] applied the morphing technology to some parametric surfaces to generate process surfaces in three-axis NC machining. However, the process surface is only valid in a simple model which has the unidirectional free-form surface. On this basis, Huang [14] proposed a boundary-consistent implicit model entity parameterization method (PISM) to generate the process surface in five-axis machining. The advantage of this method is that the surface generated by the Laplace-based PISM method cannot produce self-intersection and redundancy. The disadvantage is that the Laplace-based PISM method has a slow convergence rate, and the solution time becomes longer as the grid number increases.

However, for CNC machining of complex parts, in addition to determining the process surfaces of the machining process, the planning of the tool path on those process surfaces is equally important. There are many ways to plan the tool path of complex parts, for example, Lin et al. [15] proposed an accurate and efficient method for five-axis CNC machining of free-form surfaces. In their algorithm, the best tool is selected, the tool path autonomously is planned using curvature matching and integrated inverse kinematics of the machine tool. It uses the real cutter contact tool path generated by the inverse kinematics. Can et al. [16] proposed a novel iso-scallop tool path generation strategy for the efficient five-axis machining of free-form surfaces. In this method, the cutter paths were scheduled so that the scallop height formed between two adjacent machining paths was constant. Meanwhile, a new tool path generating methodology for five-axis machining of 3D curves that are projected from 2D planes onto free-form part surfaces was presented by Can et al. [17], and a Windows® based software has been developed according to the presented algorithm, cutter contact (CC) data and surface normals for CC points were obtained with this software. Lee et al. [18] presented an interference-free tool path generating method for semi-finish and finish machining of the helical milling cutter. The method for machining the helical milling cutter is established based on the differential geometry and the enveloping theory. Besides, Jeon et al. [19] proposed a touch-probe path generation method using similarity analysis between the feature vectors of 3D shapes for the OMM. A computer-aided inspection planning system are developed that can correct non-applied measuring points and generate the final touch-probe path.

Therefore, based on the above-mentioned literatures, a method for generating process surfaces is proposed for complex surfaces, here the process surfaces are some parameterized surfaces. In this paper, the influence of workpiece geometry on the machining process is further considered, and the process parameters that affect the geometry of the process model is designed through process constraint analysis. Finally, the process parameters with constraints are introduced to the morphing technology to build the process surface of complex parts. After obtaining the process surface, the isoparametric curve can be regarded as the roughing tool path of parametric process surface. So the roughing tool path can be obtained easily while determining the process surface. The method presented in this paper can control the current machining allowance according to the actual cutting depth of the cutter, overcome the shortcomings of the traditional process model, convenient the tool path calculation, and can shorten the total machining time of the complex parts, finally improve the machining efficiency.

2. Establishment of morphing technology model

2.1 Morphing technology

The morphing technology refers to a continuous, smooth, and natural transition from one object to another object. If the morphing technology is applied to the establishment of the process model in multi-axis roughing, the source object refers to the rough surface before milling, and the target object refers to the final finished shape. The rough surface and the finished shape directly control the shape of intermediate surface model during the morphing process.

The morphing technology can be implemented by the internal parameterization of the three-dimensional entity. Once an arbitrary shape of the three-dimensional entity is parameterized, its internal point can be described by a ternary parameter, and the intermediate process surface can be obtained by fixing one of the parameter with a constant value in the depth direction. This method of vectorization needs to be achieved by grid generation techniques. However, the transfinite interpolation is a kind of algebraic grid generation method which is widely used, through the transfinite interpolation processing, the grid which satisfies the specified boundary requirement can be obtained, and the grid space can be directly controlled.

2.2 The hermite transfinite interpolation

Since the hermite interpolation method combines the derivative values of the function, the accuracy of the interpolation is improved. If the basic function of the hermite polynomial interpolation is used as the basis function of the transfinite interpolation algorithm, the transfinite interpolation is

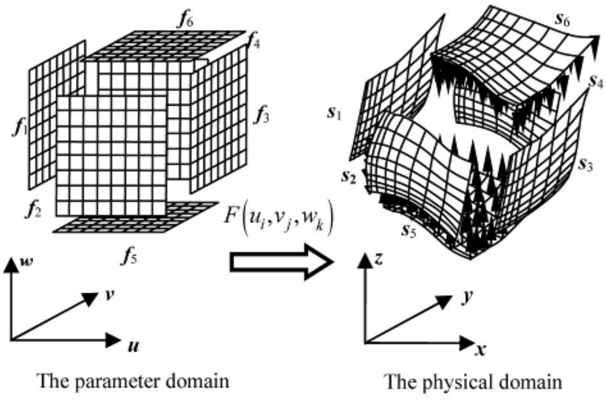


Fig. 1. The Hermite transfinite interpolation.

called the three hermite transfinite interpolation. As shown in Fig. 1, the *xyz* coordinates in the physical domain correspond to the *uvw* coordinates in the parametric domain. The surfaces s_1, s_2, s_3, s_4, s_5, s_6 in the physical domain is corresponded to parametric surfaces $f_1, f_2, f_3, f_4, f_5, f_6$ in the parametric domain.

In the transfinite interpolation algorithm, if the normal vector of the points which located on two corresponding surface along the z coordinate direction in the physical domain is known, the three hermite transfinite interpolation can be used in the $\boldsymbol{z}$ coordinate direction. Then, the function of the univariate three hermite interpolation in $\boldsymbol{z}$-direction is as follows:

$$\begin{aligned} F_w(u,v,w) &= \sum_{k=1}^{2}\sum_{l=0}^{1}\gamma_k^l(w)\frac{\partial^l F(u,v,w_k)}{\partial w^l} \\ &= \gamma_1^0(w)F(u,v,w_1)+\gamma_1^1(w)\frac{\partial F(u,v,w_1)}{\partial w} \\ &\quad +\gamma_2^0(w)F(u,v,w_2)+\gamma_2^1(w)\frac{\partial F(u,v,w_2)}{\partial w} \end{aligned} \tag{1}$$

where $\gamma_1^0(w)$´ $\gamma_1^1(w)$´ $\gamma_2^0(w)$´ $\gamma_2^1(w)$ refer to the interpolation basic function, $\boldsymbol{F}$ is the function of morphing technology. And then,

$$\begin{aligned} \gamma_1^0(w) &= \left(1+2\frac{w-w_1}{w_2-w_1}\right)\left(\frac{w-w_2}{w_1-w_2}\right)^2 \\ \gamma_1^1(w) &= (w-w_1)\left(\frac{w-w_2}{w_1-w_2}\right)^2 \\ \gamma_2^0(w) &= \left(1+2\frac{w-w_2}{w_1-w_2}\right)\left(\frac{w-w_1}{w_2-w_1}\right)^2 \\ \gamma_2^1(w) &= (w-w_2)\left(\frac{w-w_1}{w_2-w_1}\right)^2 \end{aligned} \tag{2}$$

where w_1 and w_2 represent the parameter values of the two corresponding surfaces $F(u,v,w_1)$ and $F(u,v,w_2)$ in the $\boldsymbol{w}$ direction, and the surfaces $F(u,v,w_1)$ and $F(u,v,w_2)$ correspond to the surfaces $\boldsymbol{s}_5$ and $\boldsymbol{s}_6$ in Fig. 1. The partial derivative direction of $F(u,v,w_1)$ and $F(u,v,w_2)$ in the $\boldsymbol{w}$ direction can be determined by the intersection of the corresponding points on the surface in the $\boldsymbol{u}$ direction and the $\boldsymbol{v}$ direction. The partial derivative of the $\boldsymbol{w}$ direction will be perpendicular to the surfaces $F(u,v,w_1)$ and $F(u,v,w_2)$. Then the partial derivative on the $\boldsymbol{w}$ direction is calculated as:

$$\begin{aligned} \frac{\partial F(u,v,w_1)}{\partial w} &= \left[\frac{\partial F(u,v,w_1)}{\partial u}\times\frac{\partial F(u,v,w_1)}{\partial v}\right]\psi_1(u,v) \\ \frac{\partial F(u,v,w_2)}{\partial w} &= \left[\frac{\partial F(u,v,w_2)}{\partial u}\times\frac{\partial F(u,v,w_2)}{\partial v}\right]\psi_2(u,v). \end{aligned} \tag{3}$$

Here $\psi_1(u,v), \psi_2(u,v)$ are two scalar functions, there are the scalar values of the partial derivatives of the surface $F(u,v,w_1)$, $F(u,v,w_2)$ in the $\boldsymbol{w}$ direction, respectively. This scalar value can be a constant or a function related to the surface information. It can be seen that the hermite transfinite interpolation method provides an additional control parameters of $\psi_1(u,v)$, $\psi_2(u,v)$ to the intermediate surface. However, the setting of these parameters need to attempt, if the value of $\psi_1(u,v)$, $\psi_2(u,v)$ is too large, the interpolation equation may be multi-valued, such as grid cross, but a bottom process surface which almost close to the theoretical surface can be obtained by a suitable value of $\psi_1(u,v), \psi_2(u,v)$. Therefore, the appropriate parameter value of $\psi_1(u,v), \psi_2(u,v)$ need to be set based on the geometry of different workpiece in the actual machining.

If the hermite transfinite interpolation is used in the $\boldsymbol{z}$ direction, the values of $\boldsymbol{w}$ parameter corresponding to the two faces in the $\boldsymbol{z}$ direction are $w_1 = 0$ and $w_2 = 1$, respectively. The linear transfinite interpolation is adopted in the other two directions of $\boldsymbol{x}$ and $\boldsymbol{y}$, then the univariate interpolation equation in the three parameter directions are as follows:

$$\begin{aligned} &F_u(u,v,w) = (1-u)F(0,v,w)+uF(1,v,w) \\ &F_v(u,v,w) = (1-v)F(u,0,w)+vF(u,1,w) \\ &F_w(u,v,w) = (2w^3-3w^2+1)F(u,v,0)+(-2w^3+3w^2)F(u,v,1) \\ &(w^3-2w^2+w)\left[\frac{\partial F(u,v,0)}{\partial u}\times\frac{\partial F(u,v,0)}{\partial v}\right]\psi_1(u,v) \\ &+(w^3-w^2)\left[\frac{\partial F(u,v,1)}{\partial u}\times\frac{\partial F(u,v,1)}{\partial v}\right]\psi_2(u,v). \end{aligned} \tag{4}$$

According to the recursive formula of the transfinite interpolation, the function of morphing technology $\boldsymbol{F}$ is as follows:

$$\begin{aligned} &F(u,v,w) = (1-u)F(0,v,w)+uF(1,v,w) \\ &+(1-v)\left[F(u,0,w)-(1-u)F(0,0,w)-uF(1,0,w)\right] \\ &+v\left[F(u,1,w)-(1-u)F(0,1,w)-uF(1,1,w)\right] \\ &+(2w^3-3w^2+1)\left[F(u,v,0)-F_2(u,v,0)\right] \end{aligned} \tag{5}$$

$$+\left(w^3-2w^2+w\right)\left[\left[\frac{\partial F(u,v,0)}{\partial u}\times\frac{\partial F(u,v,0)}{\partial v}\right]\psi_1(u,v)-\frac{\partial F_2(u,v,0)}{\partial w}\right]$$
$$+\left(w^3-w^2\right)\left[\left[\frac{\partial F(u,v,1)}{\partial u}\times\frac{\partial F(u,v,1)}{\partial v}\right]\psi_2(u,v)-\frac{\partial F_2(u,v,1)}{\partial w}\right]$$
$$+\left(-2w^3+3w^2\right)\left[F(u,v,1)-F_2(u,v,1)\right].$$

3. The parameter design of morphing model

In the actual machining, the appropriate value of the morphing model parameter $\psi_1(u,v)$ and $\psi_2(u,v)$ need to be set according to the geometry of different workpieces, so the morphing model parameters of $\psi_1(u,v)$ and $\psi_2(u,v)$ can be established related to the surface information. Therefore, the process constraints is analyzed firstly in this section, and then the process constraints are introduced to design the morphing model parameters $\psi_1(u,v)$ and $\psi_2(u,v)$.

3.1 The analysis of process constraints

In the method of the hermite transfinite interpolation multi-axis roughing proposed by Lefebvre [12], the scalar associated with the size of the surface normal vector is set to be a constant value, which makes the intermediate process surface adjacent to the target surface not well approach the target surface, even exist a certain distance, and the distribution of each intermediate process surface is not uniform, if such an intermediate surface is taken as a process model, there will appear uneven cutting phenomenon that is not conducive to the actual machining. Therefore, it is necessary to introduce the process constraints in the hermite transfinite interpolation to control the distribution of the generated intermediate surface in the cutting direction, only in this way that can make the generated intermediate surface is suitable to be machined in the actual machining.

In Fig. 2, P_i, Q_i is two corresponding points on the surface of s_5 and s_6, and ψ_1, ψ_2 is the size of normal vector at point P_i and Q_i. In order to obtain the process surface which meet the technological requirements of the machining process, the ideal distribution state of the intermediate process surfaces is usually obtained by changing the value of $\psi_1(u,v)$ $\psi_2(u,v)$ at present. That is because the distance between the intermediate process surfaces and the target surface will change with the values of $\psi_1(u,v)$ and $\psi_2(u,v)$. Therefore, the ideal distribution state of the intermediate surfaces is difficult to obtain and requires a lot of attempts.

In order to overcome this phenomenon, in this section, the actual technological constraints is combined with the hermite transfinite interpolation, and the morphing model parameters $\psi_1(u,v)$ $\psi_2(u,v)$ which related to the information of to be machined surfaces is designed reasonably, then the distribution state of the intermediate process surfaces can be controlled, which will make the intermediate process surfaces are evenly distributed in the cutting depth direction, and the intermediate surface adjacent to the theoretical surface is well approximated to the theoretical surface.

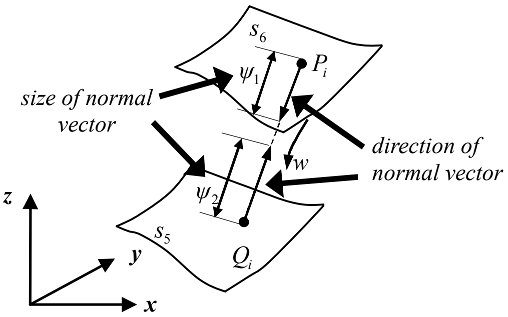


Fig. 2. The representation of surface normal vector corresponding to the morphing model parameter.

3.2 The design of morphing model parameter

The design of reasonable morphing model parameter is significant in the problem of the hermite transfinite interpolation. $\psi_1(u,v)$ and $\psi_2(u,v)$ are the morphing model parameters related to the normal vector information of the initial surface and the theoretical surface, respectively. As the initial surface corresponds to the rough surface, and the rough surface is generally a single plane or a complex shape curved surface. When the rough surface is a plane surface, the function value of $\psi_1(u,v)$ can be set to be a constant ***C***, and its normal vector is easy to calculate. It is only necessary to judge whether the direction of the normal vector is pointed to the target surface.

Assuming that the normal vector direction of a point P on the initial surface is P', and the normal vector direction of a point Q on the initial surface is Q', If the inequation $(P-Q)\cdot P'<0$ is satisfied, then the normal vector direction on the initial surface is pointed to the target surface. Since the initial surface is a plane surface, and the direction of normal vector on the plane surface is the same as each other, then the influence of $\psi_1(u,v)$ to the shape of obtained surface after the hermite transfinite interpolation is not large, therefore, the design of $\psi_1(u,v)$ cannot be considered. When the rough surface is a complex surface, it is necessary to adopt the same method as the theoretical surface in design of the morphing model parameter $\psi_2(u,v)$.

As the theoretical surface corresponds to the surface of the workpiece, and the surface of the workpiece is generally complex in shape, the direction of the normal vector at each point on the surface is different, and its normal vector size will also affect the distribution of the intermediate surfaces in the hermite transfinite interpolation. In this section, the morphing model parameter $\psi_2(u,v)$ related to the surface geometry information is established, which can automatically obtain the value of the normal vector at each point according to the surface information, that affects the distribution of the intermediate surfaces obtained in hermite transfinite interpolation.

Since the intermediate surfaces are distributed along the cutting direction, and the cutting direction is the depth direction of the initial surface to the theoretical surface, the

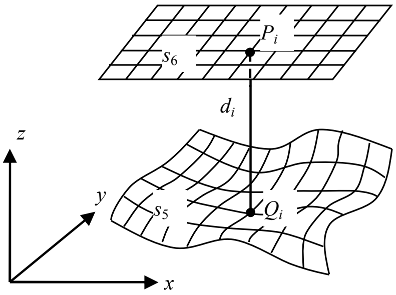


Fig. 3. The distance between the initial surface and the theoretical surface in the physical domain.

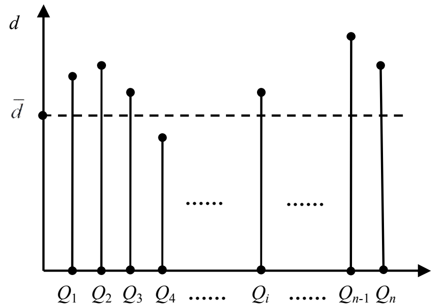


Fig. 4. The distance between the corresponding points of the initial surface and the theoretical surface.

morphing model parameter can be simplified to a scalar function $\psi_2\left(d_{s_5,s_6}\right)$ that related to the distance between the initial surface and the theoretical surface.

As shown in Fig. 3, assuming that the initial surface s_6 is a plane surface, the corresponding morphing model parameter can be set to a constant value, a series of ordered points on its surface is defined as $\{P_1,P_2,P_3,......,P_i,......,P_n\}$, and a series of ordered points on the theoretical surface s_5 is defined as $\{Q_1,Q_2,Q_3,......,Q_i,......,Q_n\}$, then the distance between the corresponding points which located on the initial surface and the theoretical surface is defined as $d=\{d_1,d_2,d_3,\cdots, d_i,\cdots,d_n\}$.

Let $d^*=\left\{\frac{d_1}{\bar{d}},\frac{d_2}{\bar{d}},\frac{d_3}{\bar{d}},......,\frac{d_i}{\bar{d}},......,\frac{d_n}{\bar{d}}\right\}$,

where $\bar{d}=\frac{(d_1+d_2+d_3+...+d_i+...+d_n)}{n}$, as shown in Fig. 4.

In this scalar function $\psi_2\left(d_{s_5,s_6}\right)$, the variable parameter d^* related to the distance between the theoretical surface and the initial surface is introduced as the control parameter. The following scalar function is defined as:

$$\psi_2\left(d_{s_1,s_2}\right)=d+\mathrm{sh}\left(a\left(d^*-1\right)\right) \tag{6}$$

where $\frac{d_{\min}}{\bar{d}}\le d^*\le\frac{d_{\max}}{\bar{d}}$, $a>0$, $\boldsymbol{a}$ is the adjustment factor, and the value of a can be adjusted according to the process requirements.

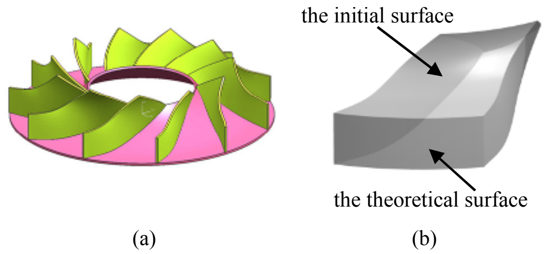


Fig. 5. Impeller part: (a) Impeller model; (b) the geometry to be machined.

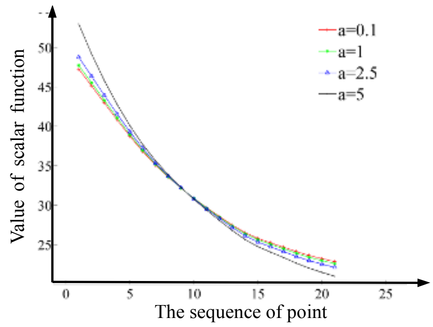


Fig. 6. Scalar chart under different regulatory factor.

4. Analysis of an example

In order to verify the correctness and effectiveness of the proposed method in this paper, a titanium alloy impeller parts is taken as an example for specific analysis, as shown in Fig. 5. Fig. 5 is the CAD model of the impeller part, the impeller with 11 blades, and the height is about 50 mm, the inner diameter is about 45.88 mm, outside diameter is about 111.5 mm, the narrowest width of impeller channel is about 24.185 mm, the blade surface is a free-form surface and the highest height of which is about 39.35 mm.

For impeller parts, there has 70 %~90 % allowance need to remove in impeller channel rough machining, so the calculation of the process model for impeller channel machining is very important. Due to the impeller channel surface and rough surface are rotary surfaces, assuming $\psi_1(u,v)$ and $\psi_2(u,v)$ are the corresponding morphing model parameters. Since the geometry of theoretical surface is similar to the rough surface, the scalar function corresponding to the normal vector on each surface is set to be $\psi_1(u,v)=\psi_2(u,v)$. The value of scalar function corresponding to the normal vector at each point of the channel surface and the rough surface is calculated according to Sec. 3. Since the channel surface and the rough surface are rotary surfaces, so it is only necessary to calculate the scalar function values on any one of the blade-shaped rotation curve. Fig. 6 is a comparison of the scalar function obtained by different adjustment factors in case of the corresponding points on any of the blade-shaped curve on the channel surface.

In the case of determining the morphing model parameters corresponding to the geometry to be machined, the process surface in the machining of impeller channel when $\boldsymbol{w}$ = 0.025

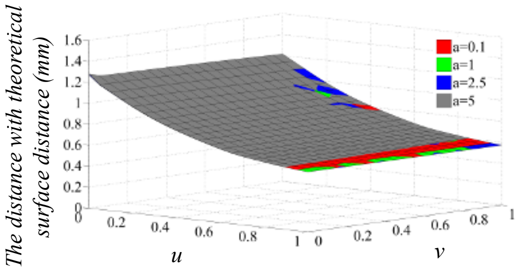
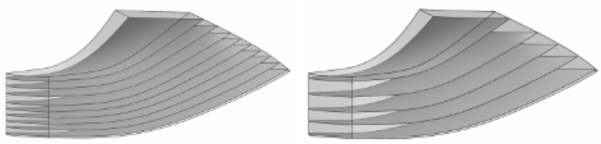
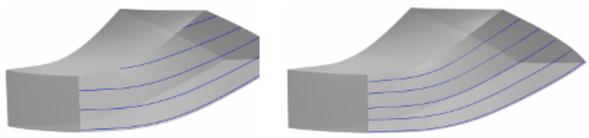


Fig. 7. A comparison of the distance between process surface generated by Hermite transfinite interpolation and theoretical surface under different adjustment factors when $w = 0.025$.



(a) (b)

Fig. 8. Process surface of the impeller channel roughing: (a) Intermediate process surfaces; (b) process surfaces.



(a) (b)

Fig. 9. Comparison of tool path: (a) Isometric surface offset; (b) hermite interpolation.

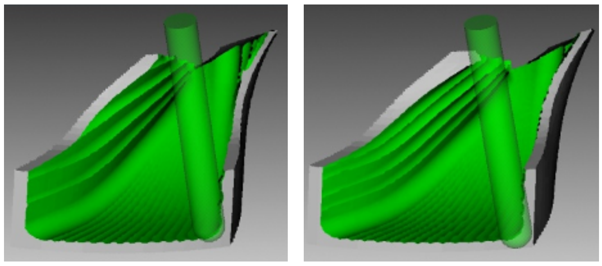
is calculated by using the hermite transfinite interpolation method. When the adjustment factor a is different, the distance between the process surface and the theoretical surface is smaller than that generated by the linear interpolation method, but the distance difference between the process surface and the theoretical surface is very small in the hermite transfinite interpolation method, as shown in Fig. 7.

Assuming $a = 1$, the intermediate process surfaces of impeller channel is calculated, as shown in Fig. 8(a). Fig. 8(b) shows the process surface of the impeller channel roughing when the adjustment factor a = 1, which is selected according to the cutting depth of the cutter in a series of intermediate process surfaces produced by the morphing technology.

In order to further illustrate the validity of the method proposed in this paper, a comparison with the commonly used isometric surface offset method is conducted. Fig. 9 shows the tool path comparison for the process model determined by the two methods in a section of the impeller channel. By the hermite interpolation, it can be seen that the process surface is composed of iso-parametric curves, so the tool path is determined at the same time of calculating the process surface, which will save the tool path calculation time. It can be seen from Fig. 9 that the tool path obtained by this method is from the inlet to the outlet of the impeller channel, always along the direction of the blade curve.

Table 1. Comparison of simulation time.

Items	The morphing technology method	The isometric surface offset method
Tool description	Ball-end cutter with diameter of 10 mm	Ball-end cutter with diameter of 10 mm
Feed speed	250 mmpm	250 mmpm
Machining time	1:27:10	1:04:31



(a) (b)

Fig. 10. Comparison of cutting surface in simulation: (a) Isometric surface offset; (b) hermite interpolation.

Fig. 10 shows the channel machining simulation of two methods under the VERICUT software. It can be seen from the figure that the use of isometric surface offset method leaves more obvious residue on the machined surface in the case of cutting the same number of process models, and the cutting traces is not consistent with the direction of blade-shaped line, so the semi-finishing is used to eliminate the cutting traces, which will increase the titanium alloy impeller roughing time.

On this basis, the comparison of simulation processing time is conducted between the two methods under the same feed speed and cutter parameters. If the feed rate is set to be 250 mmpm, and using a ball-end cutter with a diameter of 10 mm, the comparison result can be seen in Tabe 1. The machining time used by the presented method (1:27:10) is slightly slower than the isometric surface offset method (1:04:31), but the isometric surface offset method requires an additional semi-finishing process to eliminate the larger residue which remained on the blade surface, so the entire roughing time spent by the isometric surface offset method will be longer than the presented method in this paper.

Furthermore, the comparison of the actual machining for an impeller channel using the two above method were carried out on a WABECOH five axis vertical machine tool with double turntable. When the cutting parameter is set the same as the cutting parameter of simulation machining, the machining results is shown in Fig. 11.

From the comparative experiment, it can be seen that the total time (89 minutes, 12 seconds) for roughing one channel using the morphing technology method is longer than the total machining time of the isometric surface offset method (70 minutes and 22 seconds), but the surface quality of the morphing technology method is obviously better than that of the iso-

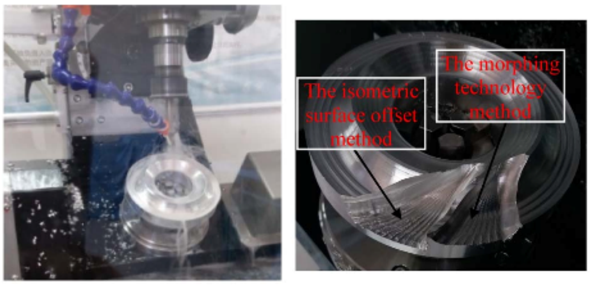


Fig. 11. Actual machining of impeller channel.

metric surface offset method, therefore, in order to obtain the same surface quality, the isometric surface offset method may require a semi-finishing to improve the surface quality and may take more machining time. Besides, the cutting process of the morphing technology method is more stable and there is no severe vibration, which indicates that the cutting force is continuously changed during the cutting process without sudden change, it is beneficial to improve the tool life.

5. Conclusions

(1) Compared with the linear interpolation method, the process constraints can be introduced into the hermite transfinite interpolation method based on the morphing technology, which can control the geometrical shape of the process surface, and the obtained process surface is closer to the theoretical surface.

(2) Compared with the traditional isometric surface offset method, the hermite transfinite interpolation method proposed in this paper makes the workpiece surface after machining without obvious ladder-like residue, avoid the semi-finishing stage, and shorten the total machining time of the complex parts.

(3) Since each process surface is selected according to the cutting depth of the tool, the cutting allowance on the process model in machining is continuously changed, and the size of cutting allowance is closely related to the cutting depth of the tool, so the cutting force during the cutting process does not change abruptly, to some extent, tool life can be increased.

Acknowledgments

This work was sponsored by China Postdoctoral Science Foundation (2018M633537), Basic research plan of natural science in shaanxi province (2018JQ5086), Natural Science Foundation of China (51605378), Shaanxi provincial department of education special fund (2018JK0510), Industrial Science and Technology Project of Shaanxi Science and Technology Department (2016GY-019) and National Key Research and Development Program (2017YCF0804310).

References

[1] J. P. Duncan and S. G. Mair, *Sculptured surfaces in engineering and medicine,* Cambridge: Cambridge University Press (1983).

[2] R. T. Farouki, The approximation of non-degenerate offset surfaces, *Computer Aided Geometric Design*, 3 (1) (1986) 15-43.

[3] L. X. Cao, H. Gong and J. Liu, Research on contact problem of surfaces and contact characteristics of offset surfaces, *Journal of Dalian University of Technology*, 47 (1) (2007) 39.

[4] L. A. Piegl and W. Tiller, Computing offsets of NURBS curves and surfaces, *Computer-Aided Design*, 31 (2) (1999) 147-156.

[5] T. Saito and T. Takahashi, NC machining with G-buffer method, *ACM SIGGRAPH Computer Graphics*, 25 (4) (1991) 207-216.

[6] B. K. Choi, D. H. Kim and R. B. Jerard, C-space approach to tool-path generation for die and mould machining, *Computer-Aided Design*, 29 (9) (1997) 657-669.

[7] B. K. Choi and R. B. Jerard, *Sculptured surface machining: Theory and applications*, Springer Science & Business Media (2012).

[8] S. Chen, G. R. Yan, Y. Q. Chen and X. X. Zhu, The intelligent machining based on stock-remaining model, *Computer Aided Engineering*, 9 (3) (2000) 25-32.

[9] D. Douglas and J. Gallier, Topological evolution of surfaces, *Graphics Interface*, 96 (1996) 194-203.

[10] F. Lazarus and A. Verroust, Three-dimensional metamorphosis: A survey, *The Visual Computer*, 14 (8) (1998) 373-389.

[11] P. P. Lefebvre and B. Lauwers, 3D morphing for generating intermediate roughing levels in multi-axis machining, *Computer-Aided Design and Applications*, 2 (1-4) (2005) 115-123.

[12] S. R. Han, *New unified machining process planning using morphing technology*, University of California, Los Angeles (2011).

[13] S. R. Han and D. C. Yang, *Volume interior parameterization for automated unified machining process of freeform surfaces*, Frontiers in Computer Education, Springer, Berlin, Heidelberg (2012) 577-584.

[14] B. Huang, *A unified approach for integrated computer-aided design and manufacturing*, University of California, Los Angeles (2013).

[15] T. Lin, J. W. Lee and E. L. Bohez, A new accurate curvature matching and optimal tool based five-axis machining algorithm, *Journal of Mechanical Science and Technology*, 23 (10) (2009) 2624.

[16] A. Can and A. Ünüvar, A novel iso-scallop tool-path generation for efficient five-axis machining of free-form surfaces, *The International Journal of Advanced Manufacturing Technology*, 51 (9-12) (2010) 1083-1098.

[17] A. Can and A. Ünüvar, Five-axis tool path generation for 3D curves created by projection on B-spline surfaces, *The International Journal of Advanced Manufacturing Technology*, 49 (9-12) (2010) 1047-1057.

[18] J. N. Lee, Tool path generation method for multi-axis ma-

chining of helical milling cutter with specific cross-section profile, *Journal of Mechanical Science and Technology*, 21 (10) (2007) 1644-1650.

[19] H. Jeon, J. Lee and J. Yang, A touch-probe path generation method through similarity analysis between the feature vectors in new and old models, *Journal of Mechanical Science and Technology*, 30 (10) (2016) 4705-4716.

Han Feiyan received her Ph.D. Mechanical Enginering in 2016. She is a Senior Lecturer in Xi'an University of Science and Technology. She has published many papers in different journals in the field of NC manufacturing.