Optimization of Cutting Power Based on Dynamic Cutting Force Model

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Abstract. The machine output power smoothing has an important significance to improve the efficiency and quality of machining. With the secondary development of cutting geometry simulation software, we have got the geometry cutting parameters, carried out a physical simulation of the whole cutting processing and optimized the cutting parameters in this paper. The results show that this method is efficient and practical and finally improve the stability of NC machining process.

1. Introduction

In an NC machining process, the cutting power reflects the magnitude and stability of the cutting forces directly and is closely related to cutting heat. It also affects the wear and breakage, as well as durability and other properties of the cutting tool. [1] Meanwhile, the stability of cutting power is also closely related to the cutting efficiency, the quality of processed surface and security of the machine. [2] Therefore, it is a hot issue of the cutting parameters optimization on how to reasonably choose the cutting parameters, ensure the cutting power smooth and avoid the abnormal phenomenon of flutter and tool damage owing to cutting power mutations in a cutting process. Research of cutting power calculation is divided into finite element analysis, empirical formula of cutting force and analytical method at this stage. [3] Although the finite element simulation can provide with more accurate cutting power data, it still has an inefficient calculation and cannot be combined with the optimization of cutting parameters. While the cutting force can be calculated and simulated efficiently using the empirical formula, the results can only reflect the average change of the cutting force but not its characteristics of changing cyclical with the change of cutting angle in the cutting process.[4] When the cutting power is calculated with the cutting force model obtained by the analytical method, it can actually reflect the change of cutting force with high efficiency of simulation. As a result of it, analytical model of cutting force is widely used in research on optimization of cutting parameters related to cutting force or cutting power. For example, Li Zhizhong et al proposed a method to predict the cutting power through discretization of the tool path to optimize cutting parameters [5]. Li Zhongqun et al. obtained cutting force and cutting power dynamically by construction of circular corner milling and T groove milling cutting force model and optimized the cutting parameters based on genetic algorithm [6]. Yang, etc. established a rose cutter cutting force model and surface error model to calculate the cutting force in order to get cutting power and optimize the cutting parameters. However, research on the optimization of cutting parameters based on the cutting power still remains some problems, as follows.1）The calculation of cutting force lack of the information interaction with the cutting geometry simulation. The calculation and optimization of complex cutting are still in low efficiency.

2）Present studies on the cutting parameters optimization usually treat the cutting power as a constraint condition rather than an optimization object. It is out of simplifying the optimization, yet ignores the importance of smoothing cutting power when machining.

3) At present, most of research results only provide the cutting parameters after optimization, how to adjust the cutting process based on these parameters and then optimize the NC code still require further study.

Firstly, combining the geometric information and the physical simulation for a machining, the method of getting cutting geometry information by secondary development of the cutting geometry simulation software -VERICUT is introduced. Then we try to find a method which can call the existing analytical model of cutting force in the VERICUT secondary development program in order to get the cutting power data of a complete cutting process efficiently and apply it in the research of cutting parameters optimization. At last, with the parser for NC code, we can optimize the NC code directly so as to achieve the goal of research which is smoothing the output power of the machining.

2. Acquisition of complete cutting geometry information

Cutting force is closely related to four elements of milling parameters: cutting speed, feed rate, back engagement (cutting depth), cutting width. Therefore, we must get complete geometric information accurately before the simulation of cutting force. VERICUT software is widely used in geometry simulation of NC machining (as shown in Fig.1) and has high simulation efficiency. Through the secondary development of this software, we can set a data collection point at regular intervals in the processing path and call the functions (as shown in Table 1) provided by VERICUT. Finally, we can get the cutting parameters of current data point.

Table 1 The function table of VERICUT secondary development program

double opapi_get_axial_depth(void);	Provide the data of cutting depth
double opapi_get_program_feed rate(void);	Provide the data of cutting feed rate
double opapi_get_spindle_speed(void);	Provide the data of spindle speed
void opapi_get_radial_width(void);	Provide the data of cutting width

The ultimate goal of this study is to optimize the G code in NC machining after obtaining the optimized cutting parameters. Therefore, the data points are expected not only to include information of cutting parameters for cutting power calculation, but also to record the information of current NC code, which includes the coordinates of current data point under workpiece coordinate and the G code corresponded with the sampling point. Therefore, we need to add in NC code analysis functions in the VERICUT secondary development program, combined with cutting tool location information provided by VERICUT secondary development function, so as to get the complete machining information of data points.

Since the force model used in the study still required detailed tool information, we parsed the tool file to get the tool diameter, tool teeth and the tool type of current machining. Finally, we use a strcuture to store information for each data point, as shown in Fig.2.

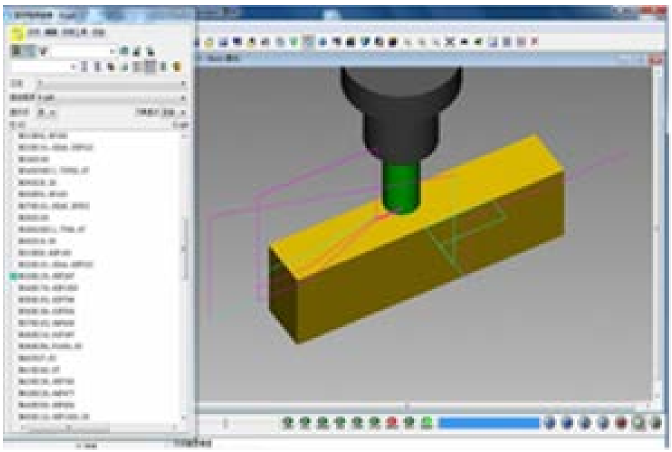

Fig.1 The simulation software VERICUT

```
struct NC_CODE_STRUCT {

    CString NC_code;
    // Used to store NC code of this datapoint.
    float cut_depth;// Used to store cutting depth
    float cut_width;// Used to store cutting width
    float cut_rotate_speed;
    // Used to store spindle speed
    float cut_feedspeed;
    // Used to store cutting depth
    XYZABC coordinates;
    // Used to store coordinates of the data point
    float cut_power;// Used to store cutting power
    float cut_area;// Used to store cutting area
    int toolteeth;
    // Used to store number of toolteeth
    float tooldiam;
    // Used to store the diameter of the cutter
    NC_CODE * pNC_CODE;
    int loc;

};
```

Fig.2 The structure of a data point

3. Creation and calculation of typical dynamic cutting force model

3.1 Overview of Classic dynamic milling force model based on cutting infinitesimal Overview

Milling process output power can be obtained from the product of the milling spindle speed and milling force, so the key to get the power is to establish the milling cutting force model [7].

According to the research by Y.Altintas et al. [8], existing milling force model with regard to the width and arc length of the cutting element divided the cutting part of tool into numerous cutting elements. The cutting force in three direction of each cutting element can be expressed as,

$$\begin{cases} dF_{t,j}(\theta,z)=[K_{tc}h_j(\phi_j(z))+K_{te}]dz \\ dF_{r,j}(\theta,z)=[K_{rc}h_j(\phi_j(z))+K_{re} \\ dF_{a,j}(\theta,z)=[K_{ac}h_j(\phi_j(z))+K_{ae}]dz \end{cases} \quad (1\text{-}1)$$

In the formula, h_j and dz is corresponding to the instantaneous undeformed cutting thickness and axial length of cutting element in the cutter tooth. In general, the milling force coefficients corresponding to different cutter tooth plate are equal. K_{te} , K_{re} , and K_{ae} are called as constant milling force coefficient. If same materials are used in different machining, force coefficients are treated as the same constants. By the mathematical model (1-1), we can see that the key to calculate the cutting force of each cutting element is obtaining the cutting thickness h.

3.2 The establishment of cutting thickness model based on cutting edge geometry

In the calculation of cutting thickness, the milling cutter track is simplified as a circle where f_z is the feed engagement of cutter, θ is the angular position of the tool nose. Research shows that the formula is the expression of instantaneous cutting thickness in the ideal machining state, which means the tool deformation and eccentricity being ignored and the feed being treated as a constant. This assumption can meet the requirements of cutting force calculation in most occasions. However, with the precision of cutting force calculation required to improve, it is necessary to propose a more accurate model of cutting thickness. In general cutting thickness is calculated through the tool track, so it is closely related with the cutting edge geometry. Different cutting thickness model should be established with cutting edge of different types. According to Liu Qiang, Li Zhongqun et al, cutting thickness model can be divided into three categories as follows,

1) Cutting thickness model of flat head milling cutter

$$h(i,j,k)=\begin{cases} f_z\cos(\varphi(i,j,k)),\varphi(i,j,k)\in[\phi_{st},\phi_{ex}] \\ 0 \end{cases} \quad (1\text{-}2).$$

2) Cutting thickness model of ball-end cutter (As shown in Fig.3)

$$h(i,j,k)=f_z\bullet e_r=f_{zx}\sin\varphi_j\sin\kappa+f_{zy}\cos\varphi_j\sin\kappa+f_{zz}\cos\kappa \quad (1\text{-}3).$$

In the formula, f_z is the instantaneous feed, e_r is the normal vector of enveloping line of the cutter, φ is the cutting angle of the cutter tooth, κ is the axial inclination angle of this cutting element, which can be expressed as:

$\kappa(z)=\arccos\frac{R_0-z}{R_0}$, where z is the height of l segment element, R_0 is the cutter radius.

3) Cutting thickness of circular nose cutting edge

$$h=f_z\bullet\sin\varphi(i,z)\bullet\sin\kappa(z) \quad (1\text{-}4).$$

In the formula, f_z is the instantaneous feed, $\varphi(i,z)$ is the cutting contact angle, κ is the axial inclination angle.

3.3 The cutting force simulation based on the secondary development of VERICUT

The calculation model of the cutting force proposed is to obtain more accurate value of cutting power based on the VERICUT simulation. By the secondary development of VERICUT, we can add the cutting force simulation module in the program and then simulate the cutting force and power when we use VERICUT for geometric simulation of cutting process in order to get the data of cutting power for each sampling point.

The formula (1-1~1-4) shows that all cutting parameters of cutting force model and cutting thickness model can be obtained by VERCIUT except the cutting angle. Therefore a method to calculate the cutting contact angle is necessary. The milling force modeling method given by Altintas[14] pointed out that, the contact angle of cutter tooth j on the beam element l can be shown as

$$\theta_{l,j} = \varphi_1 - (j-1)\phi_p - \frac{z \times \tan\beta}{RAD} \qquad (1\text{-}5).$$

In the formula, φ_1 represents the contact angle of cutter tooth NO.1; ϕ_p represents the tooth-spacing angle of cutter; z represents the height of beam element l; β is the helical angle of cutter; RAD is the theoretical radius value of cutter. φ_1 can be calculated by cutting speed v, milling spindle speed n and cutting time t, that is,

$$\varphi_t = \phi_{st} + \Omega \bullet t \qquad （1\text{-}6）.$$

In the formula, Ω is the angular velocity, ϕ_{st} is the cutting angle, t is the practical machining time at current position.

We can get the cutting force of the effective cutting part of each cutter tooth by integrating the machining part of cutter tooth during simulation. The integral upper limit for the cutting force of each cutter tooth is calculated by the cutting depth, cutting width and tool diameter of current sampling point. By summing the cutting force of the effective cutting part, we can get the total cutting force of each cutter tooth for current sampling data point. The integral step is set as 0.05mm in order to simplify the calculation, as shown in the formula.

$$\begin{cases} F_t(\theta,z) = \sum_0^{N_j} \int_0^{Z_{\max}} [K_{tc} h_j(\phi_j(z)) + K_{te}] dz \\ F_r(\theta,z) = \sum_0^{N_j} \int_0^{Z_{\max}} [K_{rc} h_j(\phi_j(z)) + K_{re}] dz \\ F_a(\theta,z) = \sum_0^{N_j} \int_0^{Z_{\max}} [K_{ac} h_j(\phi_j(z)) + K_{ae}] dz \end{cases} \qquad （1\text{-}7）.$$

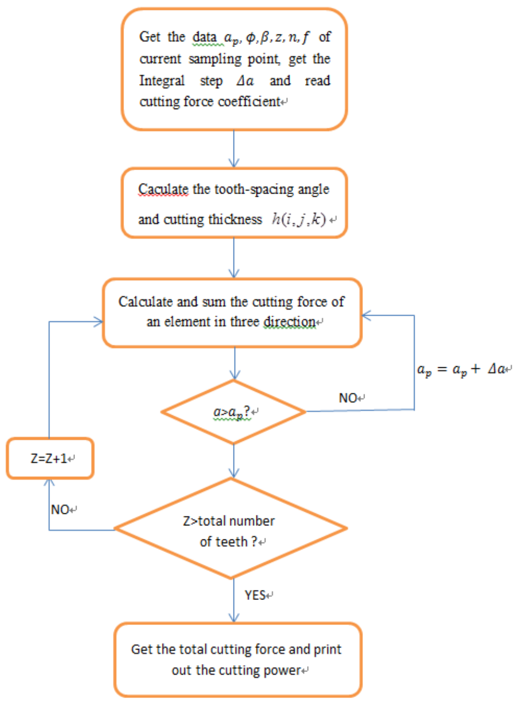

Fig. 4 Flow chart of cutting force calculation

As shown in Figure 4, caculating the cutting force of each sampling point, we can get the cutting power data of the NC code corresponding to a complete machining process, as well as the power curve of this cutting process. At this point, an optimization for smoothing cutting power is completed.

4. Optimization of cutting parameters for power smoothing

4.1 Segmentation of cutting power curve

In a typical cutting process of aircraft structure, the cutting distance is about 1000m. There will be about 100 thousand data points according to the optimization method proposed in this paper. If the cutting parameters are optimized point by point, it will reduce the overall efficiency of the optimization program and cause the NC code fragmented. At the same time, the pointwise optimization can no doubt improve the accuracy in the actual machining, it still bring about an excessive number of G-Code lines, too large manufacturing routing files and frequently changing feed speed which is difficult to control in the real machining environment and so on.

Under the premise of meeting optimization requirements, sacrificing some optimization accuracy, data points are segmented and each segmented data point is treated as the minimum unit of the cutting parameters optimization. That is, the optimization object is the average power of each data segment. The main method is as follows.

In the segmental algorithm of tool path based on clustering, the collection of the cutting power data for the sampling point is set as Q, the current clustering is T_i, new data point is q_i and the number of sampling points in current clustering is N_i. The algorithm of division center is $t_{i,0} = \frac{\sum_{j=1}^{N_i} t_{i,j}}{N_i}$.

The algorithm of division radius R is $R_i = \left\{ \frac{\sum_{j=1}^{N_i} (t_{i,j} - t_{i,0})^2}{N_i} \right\}^{\frac{1}{2}}$.

q_i is handled based on d_i , the distance between new data point and the division center. If d is less than R_i, the data point will be added into current clustering. Otherwise it will stop the current sequence and generate a new clustering. We treat the last point as the dividing point and output the processing information of it. Setting a minimum threshold sequence length C in this algorithm can not only prevent the effect of a local extreme point, but also avoid a low computational efficiency caused by few data points in one sub sequence. The flow chart of the data processing is as Fig 5.

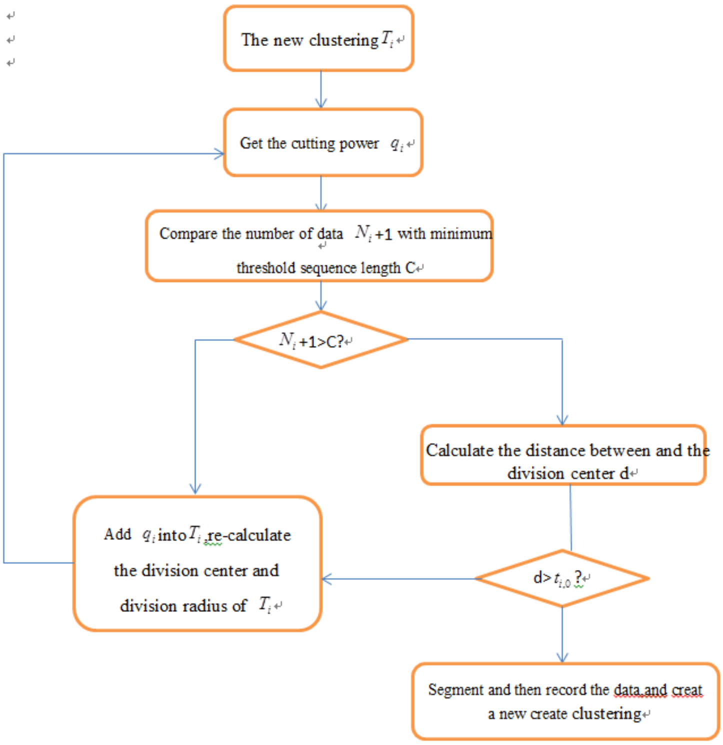

Fig. 5 The data point segmentation algorithm based on clustering

The average power of each segment of the data points is denoted by $\overline{q_i}$, which is the direct object of the optimization during the power smoothing. Each data point in one segment has the same feed rate and cutting depth before and after the optimization. So we can generate a new NC code on the subsection point and turn the optimization of cutting parameters to NC code.

4.2 Optimization of cutting parameters based on dichotomy algorithm

Although the segmentation of cutting power can effectively reduce the number of data points and improve the efficiency in the optimization of cutting power smoothing for a complete section of NC code, we could not directly get the formula for the optimized feed rate value due to the relationship between the milling force model and the integral operation. In this study, we use the dichotomy algorithm to optimize the cutting parameters through multiple iterations for the goal of smoothing the cutting power in machining.

The formula (1-5) shows that cutting parameters that can be optimized for cutting power smoothing include cutting feed rate, cutting speed and cutting depth. However, the mutation of the spindle speed should be avoided in the actual machining, so the adjustable cutting parameters in fact are the cutting feed speed and cutting depth. As the regulation of cutting depth would cause more or less change of the cutting path, which asks for the feeding NC code recompiled and the interference check. It will undoubtedly reduce the optimization efficiency and the machinability of the optimized NC code. As a result, cutting feed rate is the first choice for optimization and cutting depth serves as second one. That is, when the feed rate achieves its minimum while the optimized cutting power still have a big fluctuation, we will adjust the cutting depth and carry out a layered optimization for the NC program. The conditions of this optimization are as follows:

The maximum allowable fluctuation range between the target cutting power P_target for the average power of each segmented data points $\overline{q_i}$ is set as K. Feed speed should be in the range set by users, that is $f_{\min} \le f \le f_{\max}$.

The optimization process of each data segment is as follows and the initial N=2: layers N is stetted 2 in cutting depth stratification.

Step 1: if $\left|\dfrac{\overline{q_i} - P\_target}{P\_target}\right|$ is more than K, turn to Step2, otherwise turn to step7.

Step 2： if $\overline{q_i} > P\_target$, turn to step3, if not turn to step6.

Step3: if $f > f_{\min}$， set the optimized feed rate $f = \dfrac{f + f_{\min}}{2}$,turn to Step6,else set $f = f_{\min}$ and turn to Step4.

Step4: set $a_p = a_p$/N; N=N+1, turn to Step6

Step5： if $f < f_{\max}$， set the optimized feed rate $f = \dfrac{f + f_{\max}}{2}$,turn to Step6， else set $f = f_{\max}$

Step6： put f， a_p into the cutting fore model, recalculate the cutting power of each data point in this segment and calculate the average power according to $\overline{q_i} = \dfrac{\sum_{i=0}^{N} q_i}{N}$ ， and then turn to Step1.

Step7： Print out the optimized feed rate f and cutting depth a_p of this segment.

By the combination of the optimization results and NC program compiling software, we can generate a new NC code on the subsection point.. By adjusting the new generated NC codes after all the optimization is compelled and ensuring the consistency of the tool path before and after optimization, we can get the optimized NC code.

5. Application case

During the optimization of cutting parameters based on the cutting force model, we can collect a complete map of the cutting power for the whole cutting process. We use three axes NC milling machine for example. The control system is fan15m, maximum feed rate is 2500r / min, NC machining code line number is 825, spindle speed is 5000r / min, the material of the workpiece is carbon structural steel and tool material is hard alloy steel. The cutting power map is shown in Fig 6. From the power map we can observe considerable fluctuations of cutting power and the NC codes need to be optimized for smoothing the cutting power. By selecting the target power and limiting the cutting feed speed range, we can obtain the optimized power curve as the green line shown in Fig.7. Finally we can see that the optimized cutting power achieved overall smoothness, which is the ultimate goal of optimization.

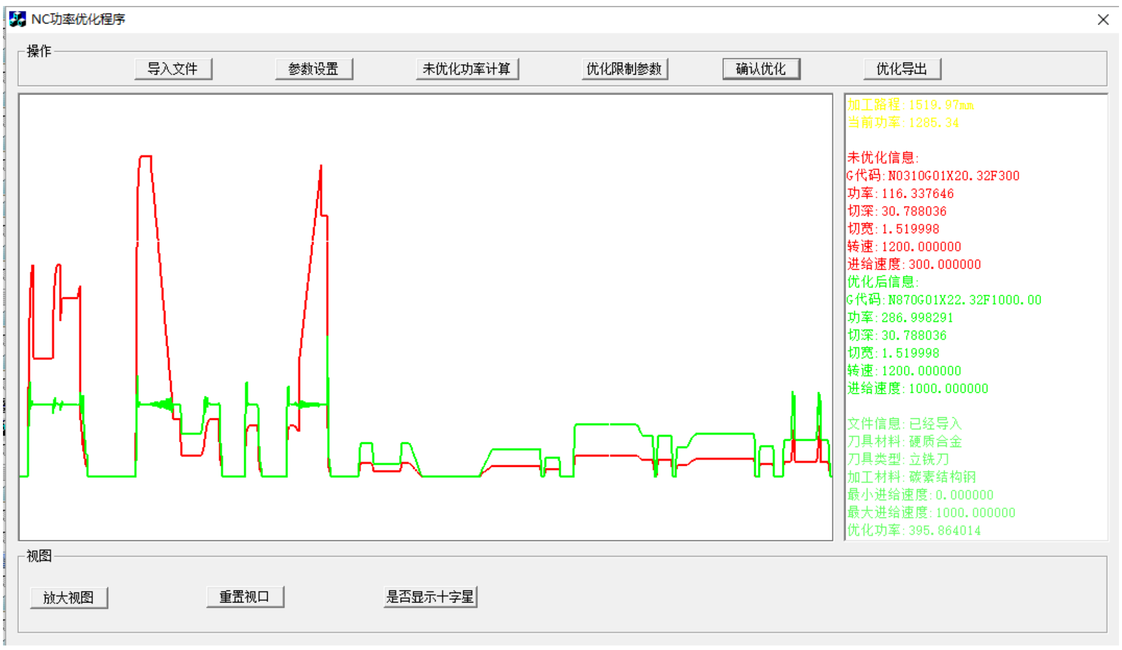

Fig.6 Power curve after optimized（Red line is before optimization）

N0050G01Y38.1F380.	N50G01Y25.07F330.00
• • • • • •	• • • • • •
N0120Z19.05	N230Z19.05
N0130G01X50.8F380.	N240G01X11.70F330.00 N250X16.71F49 N260X21.72F28 N270X50.80F26

Fig.7 The optimized NC codes (Left is before optimization)

6. Summary

By using the classic dynamic cutting force model and optimizing the cutting parameters iteratively based on the dichotomy, we can optimize the spindle output power to make it smooth. In this paper, we carried out a simulation of cutting power for the milling of carbon structural steel and optimized the cutting parameters and NC codes based on the results of simulation. Results show that this method can significantly improve the stability of the cutting power during the machining and can broaden the application of the cutting force and power simulation in the research of cutting parameters optimization. The study results have high practical value in engineering application. The Cutting Force Simplified Model of NC Code Optimization Platform developed by us has been applied to the production of a factory in AVIC.

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References

[1]. Liu Changqing.. The off-line optimization technology of NC milling process[D], 2007， Harbin Institute of Technology.

[2]. S. Smith, J. Tlusty, Current Trends in High Speed Machining. ASME Journal of Manufacturing Science and Engineering, 1997,(119):664一666.

[3]. Hirao.M, Terashima. A. Behavior of cutting heat in high speed cutting. Journal of the Japan Society for precision engineering,1998, (64).

[4]. M.Kovacic, J.Balic, M.Brezocnik. Evolutionary approach for cutting forces prediction in milling. Journal of Materials Processing Technology 155-156(2004)1647-1652.

[5]. Yang M., Park H. The prediction of cutting force in ball-end milling [J]. International Journal of Machine Tools and Manufacture, 1991, 31(1): 45 -54.

[6]. Zhongqun Li. Complex Cutting Condition of Dynamic Model ,f , simulation and optimization of high speed milling in comlex cutting condition[D]. Beihang University,2004,Beijing. 35-38.

[7]. Altintas Y., Budak E. Analytical Predication of Stability Lobes in Milling [C]. Annals of the CIRP, 1995, 44(1): 357-362。

[8]. Qiang Liu, Zhongqun Li. Simulation and Optimization of CNC Milling Process[M]. 2011，Aviation Industry Press；36-45.