Stability Prediction of CAD NC Cavity Milling Based on Clustering Algorithm

Xianyi Li[1] and Ashutosh Sharma[2]

[1]NingboTech University,Ningbo, Zhejiang 315100, China, xianyili7@163.com
[2]Southern Federal University, Russia, ashutosh@sfedu.ru

Corresponding author: Ashutosh Sharma, ashutosh@sfedu.ru

Abstract. In order to improve the machining efficiency and stability of complex surfaces, this paper proposes a method for predicting the machining stability of CAD NC cavity milling based on clustering algorithm. Firstly, the author classifies the cavity surface according to the machining characteristics of the surface. Then, according to the principle of k-means clustering analysis, the points on the cavity surface with similar processing characteristics and adjacent points are collected into a processing area, Furthermore, the cavity surface is divided into several surface patches with different machining characteristic. Finally, according to the characteristics of each surface patch, the tool path is planned to implement the slicing process, and the tool trace is controlled at the junction of the surface patch to achieve the purpose of improving efficiency and processing surface quality. Then, on the basis of using the semi-discrete algorithm to predict the constant milling stability of the tool-work piece meshing condition, this paper proposes a method to predict the machining stability of the cavity milling for the given machining path in combination with the change of the tool-work piece meshing information caused by the machining path in the NC cavity milling process. The experimental results show that the length of the track line is reduced by 16.7%, the processing time is reduced by 17%, and there is no chatter in the whole processing process. The milling surface is smooth without chatter, which is consistent with the predicted results. From the time domain and spectrum diagram, compared with the frequency component at the straight cutting path, the frequency component at the X-direction of the corner is 291.7Hz, the spindle rotation frequency is 291.7Hz, and the double frequency of the spindle rotation speed is 584.7Hz and the triple frequency is 876.5Hz, but there is no obvious flutter frequency excited in the spectrum diagram of the milling force. This method can significantly reduce the length of the machining path, improve the efficiency and quality of the machining, and successfully predict the milling stability in the cavity machining process during NC machining.

Keywords: Cavity milling; K-means clusters algorithm; Tool path; Flutter; Semi-discrete algorithm.
DOI: https://doi.org/10.14733/cadaps.2024.S6.41-52

1 INTRODUCTION

Mechanical equipment manufacturing industry is the foundation of the development of national economy and national defense industry, and high-speed and high-precision CNC equipment has become the most important part of modern mechanical manufacturing industry. However, in the process of high-speed and high-precision machining, cutting vibration, especially self-excited vibration (chatter), not only reduces the machining quality and cutting efficiency, but also causes serious fatigue damage to the machine tool and tool equipment. Therefore, the analysis and prediction of chatter is the key premise to ensure the smooth cutting process and improve the machining performance.

In order to evaluate and improve the ability of machine tool to resist chatter and select cutting conditions without chatter, it is necessary to judge the stability of machine tool cutting process. At present, the main method to determine whether the machine tool chatters is described by the stability lobes diagram (SLD) of the cutting process. The stable blade diagram represents the cutting stable region and chatter region as a function between the spindle speed and the critical axial cutting depth under the given radial cutting width. There is an obvious limit from stable cutting to chatter during machine tool cutting.

As long as the appropriate spindle speed and axial cutting depth are selected, the chatter-free and stable cutting process can be guaranteed. Regenerative chatter is the most common in machine tool cutting chatter. It is caused by the change of dynamic cutting thickness caused by the phase difference between two consecutive vibration patterns during the cutting process. When the dynamic cutting thickness reaches a certain value, chatter will occur. The existing methods for obtaining stable blade patterns for regenerative chatter in milling process mainly include analytical prediction method, time-domain numerical method, semi-discrete method and cutting experiment method. Among them, the analytical prediction method is by far the fastest and most widely used method to obtain the stable lobe diagram of milling process [1-2].

However, no matter which method is adopted to solve the stability lobe diagram of the machining process, it is necessary to obtain the frequency response function (FRF) of the tool tip of the machining system. Because the damping and stiffness of each joint on the machine tool cannot be known in advance, it is difficult to accurately predict the frequency response function of the machine tool spindle-tool-handle-tool system using analytical methods or finite element methods. So far, the most convenient and practical method to obtain the tool tip frequency response function is to conduct modal experiments. However, due to the huge amount of tool, tool handle and spindle combination, the change of any component parameter in the tool handle-tool structure will cause the change of the frequency response function of the tool tip, which requires a new round of modal experiment, which requires a lot of time and manpower input, and even requires the shutdown of the factory machine. Therefore, it is a good method to predict the frequency response function of the tool tip based on the least experimental data [3-4].

2 LITERATURE REVIEW

The stability of machine tool machining refers to the ability of machine tool to resist chatter. In 1954, the concept of regenerative chatter was put forward, and the regenerative effect of cutting ripple is the main reason for chatter. In the middle of the 20th century, the mechanism of regenerative chatter was described as the relationship between the rotational speed of the chatter-free spindle and the critical axial cutting depth by the stability lobe diagram of the linear time-invariant orthogonal cutting system. In 1965, based on Nyquist stability criterion, the turning stability lobe diagram under orthogonal cutting conditions was also obtained. However, the cutting force and the direction of cutting thickness change with the rotation of the tool, which makes it difficult to directly apply the turning chatter theory derived from orthogonal cutting conditions to the prediction of milling chatter [5-7].

Although milling has many advantages [8], the existence of chatter in the milling process directly affects the surface quality of the work piece, the production efficiency of the machine tool, the life of the tool and the machine tool, and even directly threatens the life safety of the operator. In order to adapt to the development trend of high precision, high efficiency, multi-function and automation of CNC machine tools, the analysis and prediction of the stability of milling process to avoid the instability of milling process is the focus of many scholars. The analysis and simulation methods of milling process stability can be summarized into three categories: time domain method, frequency domain method and experimental method. Time domain method, as its name implies, is a method for simulating and analyzing the stability of cutting process in time domain. Different from the frequency domain simulation, the time domain simulation needs to determine the criteria of flutter occurrence, that is, the stability criteria. Frequency domain method is a method to simulate and analyze the stability of cutting process in frequency domain. In addition to the time domain method and the frequency domain method, the stability limit diagram can also be obtained by experiment [9-11].

In this paper, a new method based on k-means clustering algorithm is proposed to partition the mold cavity surface. This method has strong adaptability to surface and fast calculation speed. The specific process is as follows: First, the complex surface is discretized into points, and the bandwidth function of each point is obtained; then, k-means clustering algorithm is used to aggregate similar and adjacent points together with certain rules to form patches; after slicing, different trajectory planning methods are used for different slicing surfaces. The processing efficiency and quality are improved by the method of slicing processing. Then, on the basis of the semi-discrete method to predict the milling stability, combining it with the change of the tool-work engagement caused by the cavity milling path, a method to predict the stability of the cavity machining is proposed, and the effectiveness and practicability of the method is verified by the milling experiment.

3 RESEARCH METHODS

3.1 The Idea of k-means Clustering

Clustering algorithm is the core of clustering analysis. One characteristic of k-means clustering algorithm is to check whether the classification of each sample is correct in every single iteration. If it is not correct, it needs to be adjusted. After all the data are adjusted, modify the cluster center and enter the next iteration. If all data objects are correctly classified in an iterative algorithm, there will be no adjustment and no change in the cluster center, which marks the end of the clustering algorithm. Let the data set $X=\{x_i \mid x_i \in R^m, i=1,2,\dots,n\}$, k cluster centers are p_1,p_2,... ,p_k, respectively representing k clusters to be divided, and the distance between data is defined as formula (3.1)

$$d(x_i,x_j)=(x_i-x_j)^T(x_i-x_j) \tag{3.1}$$

The objective function is defined as equation (3.2)

$$J=\sum_{i=1}^{k}\sum_{j=1}^{n_i} d\left(x_j^{(i)},p_i\right) \tag{3.2}$$

Where, k represents the number of clusters; n_i represents the nth data object in the i-th class; $x_j^{(i)}$ represents the jth data object in class i; p_i represents the cluster center of class i.

3.2 Specific Process of Mold Cavity Surface Segmentation Based on k-means Clustering Algorithm

The clustering algorithm is divided according to the object similarity. In the process of machining, the curvature of the points on the surface and the radius of curvature of the tool path direction are important indicators that affect the cutting process and are also important parameters in trajectory planning. Therefore, taking the cutting direction angle θ as the similarity of the surface division criteria, that is, the clustering criteria of the mold cavity surface, is in line with the theory and practice [12, 13].

3.2.1 Clustering criteria of mold cavity surface

For each point on the surface, according to its surface condition and the set residual height, the cutting bandwidth W is different in different cutting directions. In the parameter plane, set $P = S(u,v)$ as the parameter equation of the target surface, take the cutting point $P_0 = S(u_0,v_0)$ as the pole, and take the principal curvature direction corresponding to d as the polar axis to establish a polar coordinate system, as shown in Figure 1. In this coordinate system, establish the function of cutting bandwidth W and cutting direction angle θ (3):

$$W = 2\sqrt{2Rh}\sqrt{\frac{1}{1-R(k_1cos^2-\theta+k_2sin^2-\theta)}} \tag{3.3}$$

Where, R is the tool radius; h is the set residual height; k_1 and k_2 are two principal curvatures and $k_1 > k_2$; θ is the included angle between the cutting direction and the principal curvature direction corresponding to k_2. The image of this function in the polar coordinate system is shown in Figure 1. The direction with the largest polar diameter is the cutting direction with the largest cutting bandwidth.

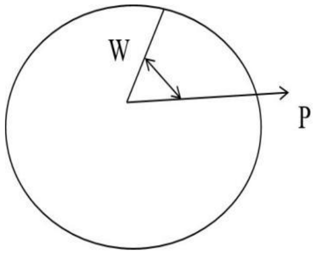

Figure 1: Relationship between cutting bandwidth and cutting direction angle.

According to formula (3.3), for a given cutting point and residual height, the cutting bandwidth is completely determined by the cutting direction. For any reference point on the surface, the cutting bandwidth map at that point can be obtained according to formula (3.3), so that the cutting bandwidth map of all points on the surface can be obtained, and the corresponding cutting direction of each point can be obtained under the condition that the maximum cutting bandwidth of each point is guaranteed.

The cutting direction of discrete points on the surface is the index of surface partition. According to the difference of the effective cutting direction angle θ of the surface, the discrete points on the surface are clustered according to the k-means clustering algorithm, and the mold cavity surface is segmented according to the clustering of the points [14].

3.2.2 Fragmentation based on k-means clustering

When k-means clustering is applied to the actual division of mold cavity surface, new problems arise. Because the mold cavity surface processing is to solve the problem of optimizing the processing direction, and the positive and negative directions of the cutting direction angle θ are the better cutting bandwidth directions, as shown in Figure 1, how to select θ becomes the key to solve the problem. Therefore, the clustering algorithm still needs to be improved when it is applied to the machining process of mold cavity surface [15].

Two key problems need to be solved when applying the traditional k-means clustering algorithm to surface segmentation: first, the data is the representation of the optimal cutting direction, because there are two optimal direction angles for each point, and the angle is periodic, and the difference is п, which is difficult to express with traditional vector or scalar; The second is the definition of the distance between data, which is derived from the first question. The "distance" in the two opposite directions should be defined as 0, so the traditional definition is not applicable. Therefore, it is necessary to redefine k-means clustering according to the cutting bandwidth function [16 -19].

Due to the complexity of mold cavity processing, if the divided processing areas are too many or too small to be processed as a surface piece after surface segmentation, the divided processing areas should be optimized and classified. Here, the optimization index of the surface is used as the index of surface optimization and merging [20].

3.2.3 Optimizable index of surface patches

K-means clustering divides the mold cavity surface into a series of small processing areas. If the total length of a divided small machining area along the optimal cutting direction of the surface is not significantly different from the total length of the machining path in the worst cutting direction of the surface, it means that the machining paths in each cutting direction of the area are equivalent, and the area has very small space for optimization. Therefore, we cannot consider the cutting direction of the region but consider how to optimize the region and the adjacent region to process the region more conveniently. In this paper, the optimization index of surface patches is proposed.

For any point $P_0 = S(u_0, v_0)$ on the surface, it can be seen from the function diagram of cutting bandwidth and cutting direction angle (see Figure 1) that when θ=90° and θ=0°, the cutting bandwidth along the local optimal cutting direction and the cutting bandwidth along the local worst cutting direction at this point can be calculated, which are referred to as the optimal bandwidth and the worst bandwidth, respectively, W^a and W^b, as shown in Formula (3.4) and (3.5).

$$W^a = 2\sqrt{2Rh}\sqrt{\frac{1}{1-k_2R}} \tag{3.4}$$

$$W^b = 2\sqrt{2Rh}\sqrt{\frac{1}{1-k_1R}} \tag{3.5}$$

Definition Assuming that the surface is discretized into n reference points, the optimal bandwidth and the worst bandwidth of the i point on the surface are W_i^a and W_i^b, respectively, and equation (3.6) is the surface's optimization index.

$$\eta = \frac{\sum_{i=1}^{n} W_i^a}{\sum_{i=1}^{n} W_i^b} \tag{3.6}$$

3.3 Cavity Milling Stability Prediction Algorithm

The milling SLD can be generated by the semi-discrete algorithm, but in the process of cavity milling, due to the existence of the non-linear machining path, the cutting angle and the cutting angle of the milling cutter teeth and the work piece will change with the machining path from mutual contact to separation, resulting in the inability to directly apply the SLD to select the final machining parameters. In consideration of this feature in cavity milling, the treatment method for judging the stability problem in the NC cavity milling process is shown in Figure 2. Without losing generality, the following will take the typical corner machining in CNC cavity milling as an example for subsequent analysis.

As shown in Figure 2, firstly, the SLD matrix is obtained from the meshing information, modal parameters and spindle speed of the tool-work piece along the machining path. In the process of milling, when the cutting thickness is constant, the critical axial cutting depth of milling will remain constant; When the cutting path is a curve or the cut-in and cut-out angles change due to the change of cutting thickness, for a given milling device, the critical axial cutting depth matrix that changes with the machining path at a certain spindle speed can be obtained.

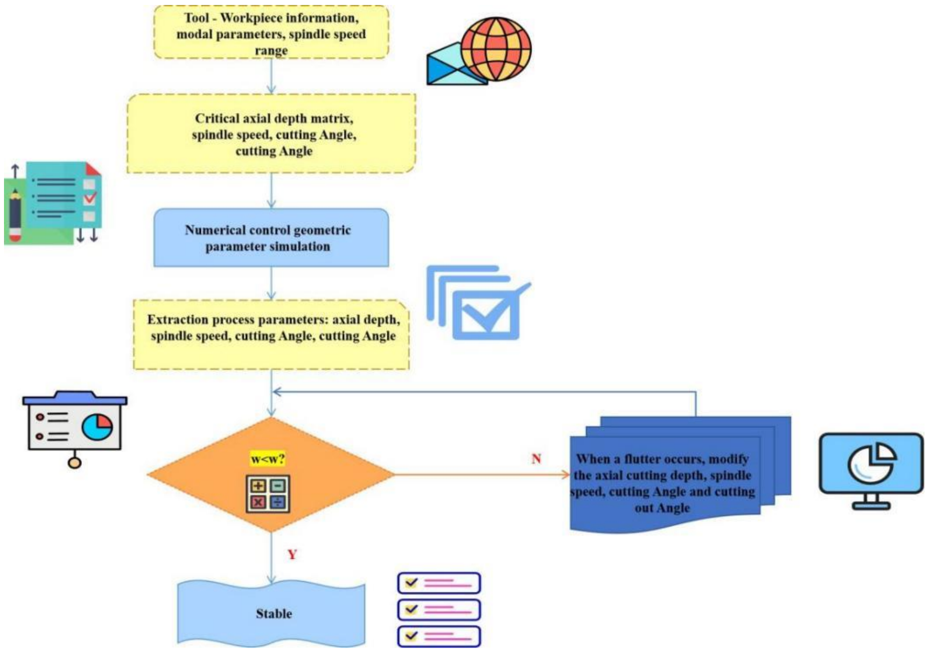

Figure 2: Stability prediction algorithm based on milling path.

Secondly, the contact condition between the tool and the work piece can be calculated according to the boundary information of the geometric model. The cut in angle, cut out angle and axial cut depth are simulated by CAM software.

Finally, the critical axial cutting depth along the path can be calculated by the milling chatter stability prediction algorithm, and then it is compared with the axial cutting depth selected in the machining process. If the selected axial shear depth is greater than the critical axial shear depth, flutter will occur; otherwise, the milling process is stable. When it is predicted that there will be chatter in the processing process, the processing parameters can be adjusted in advance, and then the processing parameters after the processing state changes can be recalculated. Compare the axial cutting depth and critical axial cutting depth again until the occurrence of chatter can be avoided by using new process parameters. In this way, it can avoid the repeated calculation of SLD caused by the change of meshing condition between tools and work piece caused by the change of tool path during the process planning of cavity milling.

4 RESULT ANALYSIS

In order to verify the effectiveness of the algorithm for path planning of complex surface of mold cavity based on k-means clustering, an experimental study was carried out on seat cavity surface for three-axis machining in view of the experimental conditions. According to the clustering algorithm, the number of clusters k should be determined first. The usual approach is to take the case of k=1, k=2, k=3, and calculate the objective function J according to formula (3.2), and observe the numerical relationship between J and k. For a certain number k, if J changes little when k>k, then k is the best number of clusters. For a given surface, the number of clusters is 2, and the surface is divided into 4 separate regions. Too few clusters will lose the advantages of the partition, and too many clusters will complicate the trajectory planning. The tool cutting path of each partition after clustering is generated by the equal residual height method, with the edge as the initial trajectory, and the tool path direction in different regions is different.

4.1 Experimental Conditions

Experimental equipment: MAKINO FNC vertical machining center. Semi-finishing tool: Φ 10 Ball head knife (high speed steel). Work piece material: steel quenched and tempered (HRC35-37). Work piece machining surface size: 150 mm × 200 mm. The path is generated by the equal residual height method. See Table 1 for processing parameters.

Spindle speed/(r·min -1)	***Feed rate/(mm·min -1)***	***Tool diameter/mm***	***Residual allowance/mm***	***Processing accuracy/mm***
1500	400	10	0.05	0.01

Table 1: Semi-finishing parameters.

4.2 Experimental Results

From the surface quality after processing, it can be seen that the surface brightness of partitioned processing is better and the residual height is more uniform. In order to compare the processing efficiency before and after slicing, the generated trajectory is simulated, and the length of the trajectory and processing time are calculated. It can be seen from Table 2 that the length of the track line after slicing is reduced by 16.7% and the processing time is reduced by 17%.

Processing method	***Total length of track line/mm***	***Processing time/s***
Slice processing	30 139. 5	3 755
Traditional processing	36 167. 5	4 515

Table 2: Comparison between slicing and traditional processing methods.

4.3 Cavity Milling Chatter Prediction Test

Since the stability problem of the semi-discrete algorithm when it is used for straight cutting has been verified, the stability at the corner of the cavity milling will be predicted, and then verified by the experiment.

Whether chatter occurs in the milling process is often judged by observing whether there are vibration lines on the surface of the work piece, or by investigating the amplitude spectrum components of the cutting force after Fourier transform. It has been proved that due to the complexity of the milling process, accurate results cannot be obtained by judging the occurrence of chatter through the spectrum component of milling force. The research on milling chatter also shows that the performance of chatter frequency when chatter occurs is not obvious. Therefore, the flutter test at the corner is mainly determined by the vibration pattern, and the cutting force and its spectrum during the test are used [21].

According to the test parameters, the flutter stability diagram during processing is obtained (Figure 3). According to Figure 3, we choose the spindle speed of 14000r/min and 17500r/min, and other processing parameters are the same. When the milling cutter enters the corner, the radial cutting depth of the cutter will increase, resulting in a decrease in the axial critical stable cutting depth. When the milling cutter enters the corner, the radial cutting depth will increase, resulting in the gradual decrease of the cutting angle of the cutter.

According to the relationship between the milling path and the change of the cut in and cut out angles with the path as shown in Figure 4, the results predicted by the stability algorithm are as follows: When the spindle speed is 14000r/min, when the milling cutter passes the corner, the cut in angle decreases first and then increases. When the cutting angle is less than 1.78rad and the critical axial cutting depth is less than 3mm (Figure 5), the milling process will produce chatter. As the machining proceeds, when the cutting angle gradually increases from the minimum value and exceeds 1.78 rad, the critical axial cutting depth will be greater than 3 mm, and the chatter will gradually disappear. Therefore, when the spindle speed is 14000r/min, the cutting process is stable at the straight cutting path, and there will be chatter when machining at the corner. When the spindle speed is 17500r/min, it can be seen from Figure 5 that the critical axial cutting depth is always greater than 3mm no matter how the cutting angle changes. Therefore, the whole machining process is stable.

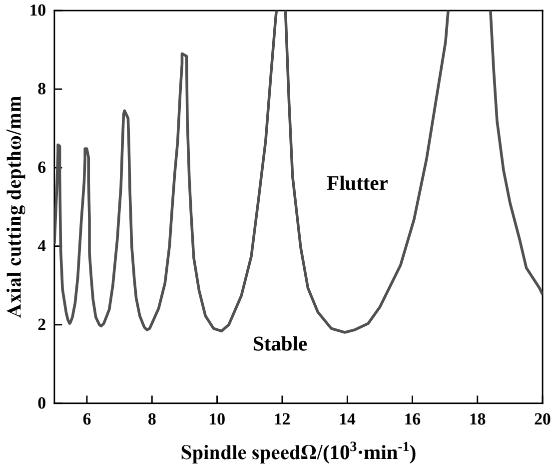

Figure 3: Diagram of milling stable blade.

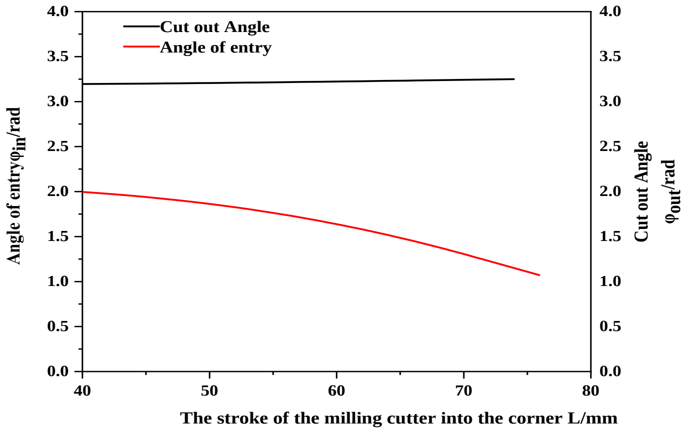

Figure 4: The change of the cutting angle and the cutting angle with the stroke of the milling cutter entering the corner.

The above two sets of process parameters are used for milling test. From the vibration pattern at the corner, it can be seen that chatter occurs after the milling cutter enters the corner. The main difference between the chatter part and the straight cutting part is that the cutting force spectrum in the X-direction of the corner part is 933.8Hz, which is 4 times of the spindle rotation frequency.

Compared with linear tool walking, the amplitude of spindle rotation frequency 233.2Hz is also significantly increased. The milling force in X direction is not large during machining. The main shaft passing frequency and its harmonic frequency are quite different from the natural frequencies in the X and Y directions of the main shaft system. Therefore, when the milling cutter passes the corner, in addition to the obvious increase in the amplitude of the main shaft rotation frequency, the second harmonic of the cutter tooth passing frequency 466.7 Hz is obvious [22].

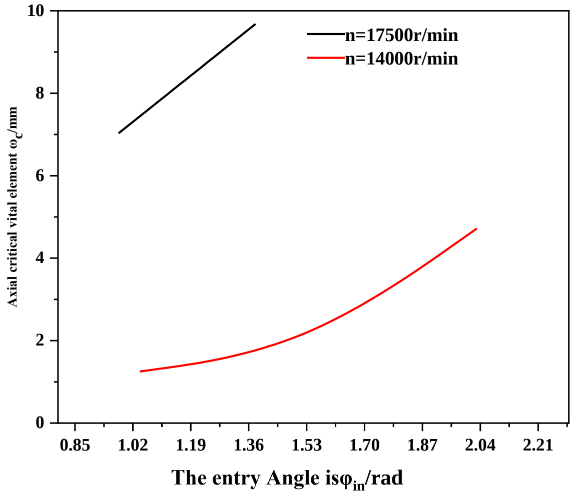

Figure 5: Relationship between axial critical cutting depth and cut in and cut out angles.

According to the prediction results of the algorithm, there is no chatter in the whole machining process. The milling surface is smooth without chatter, which is consistent with the predicted results. From the time domain and spectrum diagram, compared with the frequency component at the straight cutting path, the frequency component at the X-direction of the corner is 291.7Hz, the spindle rotation frequency is 291.7Hz, and the double frequency of the spindle rotation speed is 584.7Hz and the triple frequency is 876.5Hz, but there is no obvious flutter frequency excited in the spectrum diagram of the milling force.

5 CONCLUSION

1) Based on the k-means clustering method, we can successfully realize the slicing of complex mold cavity surface by introducing the optimization index, which enhances the robustness of this algorithm and provides a theoretical basis for mold cavity slicing.
2) In the process of slicing complex surfaces, we can effectively divide the regions with similar cutting states based on the cutting bandwidth of the surface as the basis of clustering. Therefore, in the subsequent processing, the cutting state changes less, the cutting force is more stable, and the tool life and surface quality are improved.
3) After the k-means clustering method is used for slicing, for each region, we can more conveniently plan the path according to the optimal cutting direction, effectively reduce the length of the processing path and processing time and improve the processing efficiency and quality.
4) The author discretized the stable lobe figure obtained by the semi-discrete algorithm, and obtained the axial critical cutting depth array that varies with the cut-in angle and cut-out angle at a certain speed. We extract the machining parameters from the NC code according to the machining geometry model and compare the axial cutting depth with the critical cutting depth at a certain speed. If the axial cutting depth extracted from the NC machining code is greater than the critical axial cutting depth, chatter will occur; On the contrary, the validity of this algorithm has been verified by experiments in cavity milling. In more complex machining

paths, this method can also predict the chatter that may occur during the machining process during the process planning, and then avoid the chatter by modifying the machining parameters.

6 ACKNOWLEDGEMENT

1) The Ministry of Education's Project of Cooperative Education of Production and Learning: Cultivation of Laser New Technology Innovation Talents for New Engineering (No.202101133002).
2) Zhejiang Educational Science Planning Project: Exploration and Practice of Teaching Reform in the Engineering Training Center for Training Innovative Talents for New Engineering Subjects, Project(No. 2021SCG189).
3) Higher Education Research Project of Zhejiang Institute of Higher Education: Construction of Engineering Training General Course and Practical Course System of Ideological and Political Education, Project (No.KT2022029).
4) The "Fourteenth Five Year Plan" Teaching Reform Project of Ordinary Undergraduate Universities in Zhejiang Province (No. jg20220681).
5) The Ministry of Education's Project of Cooperative Education of Production and Learning: Training for Teachers of Engineering Training Course Ideological and Political (No.221003941101409).
6) The Ministry of Education's Project of Cooperative Education of Production and Learning: Training for Teachers of Laser Processing (No.221004082121309).
7) Course Ideological and Political Demonstration Course Construction Project of NingboTech University:Engineering Training(No. 7).
8) The First-class Course Construction Project of NingboTech University:Engineering Training (No.NITJG-202066).

Xianyi Li, https://orcid.org/0009-0009-5244-1610
Ashutosh Sharma, https://orcid.org/0000-0002-4990-5252

REFERENCES

[1] Xing, Q.; Gao, X.; Zhang, Q.: Effects of processing parameters on electrode loss of micro-EDM milling with spiral electrode, The International Journal of Advanced Manufacturing Technology, 121(5-6), 2022, 4011-4021. https://doi.org/10.1007/s00170-022-09598-y
[2] Ma, K.; Wang, G.; Yang, K.; Hu, M.; Li, J.: Tool wear monitoring for cavity milling based on vibration singularity analysis and stacked LSTM, The International Journal of Advanced Manufacturing Technology, 120(5-6), 2022, 4023-4039. https://doi.org/10.1007/s00170-022-08861-6
[3] Zhao, G.; Cheng, K.; Wang, W.; Liu, Y.; Dan, Z.: A milling cutting tool selection method for machining features considering energy consumption in the STEP-NC framework, The International Journal of Advanced Manufacturing Technology, 120(5-6), 2022, 3963-3981. https://doi.org/10.1007/s00170-022-08964-0
[4] Lu, F.; Zhou, G.; Zhang, C.; Liu, Y.; Chang, F.; Xiao, Z.: Energy-efficient multi-pass cutting parameters optimisation for aviation parts in flank milling with deep reinforcement learning, Robotics and Computer-Integrated Manufacturing, 81, 2023, 102488. https://doi.org/10.1016/j.rcim.2022.102488
[5] Xie, J.; Zhao, P.; Hu, P.; Yin, Y.; Zhou, H.; Chen, J.; Yang, J.: Multi-objective feed rate optimization of three-axis rough milling based on artificial neural network, The International Journal of Advanced Manufacturing Technology, 114, 2021, 1323-1339. https://doi.org/10.1007/s00170-021-06902-0

[6] Siddhpura, M.; Paurobally, R.: A review of chatter vibration research in turning, International Journal of Machine tools and manufacture, 61, 2012, 27-47. https://doi.org/10.1016/j.ijmachtools.2012.05.007
[7] Yang, S.; Yin, T.; Wang, F.: Research on finite element simulation and parameters optimization of milling 7050-T7451 aluminum alloy thin-walled parts, Recent Patents on Engineering, 16(1), 2022, 82-93. https://doi.org/10.2174/1872212114999200902153633
[8] Vavruska, P.; Bartos, F.; Stejskal, M.; Pesice, M.; Zeman, P.; Heinrich, P.: Increasing tool life and machining performance by dynamic spindle speed control along toolpaths for milling complex shape parts, Journal of Manufacturing Processes, 99, 2023, 283-297. https://doi.org/10.1016/j.jmapro.2023.04.058
[9] Xiaohui, J.; Shan, G.; Yong, Z.; Shirong, H.; Lei, L.: Prediction modeling of surface roughness in milling of carbon fiber reinforced polymers (CFRP), The International Journal of Advanced Manufacturing Technology, 113, 2021, 389-405. https://doi.org/10.1007/s00170-021-06609-2
[10] Wu, G.; Li, G.; Pan, W.; Raja, I.; Wang, X.; Ding, S.: A state-of-art review on chatter and geometric errors in thin-wall machining processes, Journal of Manufacturing Processes, 68, 2021, 454-480. https://doi.org/10.1016/j.jmapro.2021.05.055
[11] Zhang, Y.; Li, H.; Qin, X.; Liu, J.; Hou, Z.: Analysis of vibration response and machining quality of hybrid robot based UD-CFRP trimming, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 235(6-7), 2021, 974-986. https://doi.org/10.1177/0954405420986093
[12] Singh, M.; Jain, V.-K.; Ramkumar, J.: 3-D fabrication using electrical discharge-milling: an overview, Materials and Manufacturing Processes, 37(11), 2022, 1215-1245. https://doi.org/10.1080/10426914.2022.2072888
[13] Duan, Z.; Li, C.; Ding, W.; Zhang, Y.; Yang, M.; Gao, T.; Ali, H.-M.: Milling force model for aviation aluminum alloy: academic insight and perspective analysis, Chinese journal of mechanical engineering, 34(1), 2021, 1-35. https://doi.org/10.1186/s10033-021-00536-9
[14] Kahya, M.; Ozbayoglu, M.; Unver, H.-O.: Precision and energy-efficient ball-end milling of Ti6Al4V turbine blades using particle swarm optimization, International Journal of Computer Integrated Manufacturing, 34(2), 2021, 110-133. https://doi.org/10.1080/0951192X.2020.1858504
[15] Li, W.; Li, B.; He, S.; Mao, X.; Qiu, C.; Qiu, Y.; Tan, X.: A novel milling parameter optimization method based on improved deep reinforcement learning considering machining cost, Journal of Manufacturing Processes, 84, 2022, 1362-1375. https://doi.org/10.1016/j.jmapro.2022.11.015
[16] Liu, B.; Liu, C.; Zhou, Y.; Wang, D.; Dun, Y.: An unsupervised chatter detection method based on AE and merging GMM and K-means, Mechanical Systems and Signal Processing, 186, 2023, 109861. https://doi.org/10.1016/j.ymssp.2022.109861
[17] Du, Z.; Ge, G.; Xiao, Y.; Feng, X.; Yang, J.: Modeling and compensation of comprehensive errors for thin-walled parts machining based on on-machine measurement, The International Journal of Advanced Manufacturing Technology, 115, 2021, 3645-3656. https://doi.org/10.1007/s00170-021-07397-5
[18] Liu, Q.; Xu, J.; Yu, H.: Experimental study on the reduction of process-induced deformation when milling a low stiffness structure made of Ti6Al4V titanium alloy, The International Journal of Advanced Manufacturing Technology, 116, 2021, 1975-1987. https://doi.org/10.1007/s00170-021-07586-2
[19] Malhotra, J.; Jha, S.: Fuzzy c-means clustering based colour image segmentation for tool wear monitoring in micro-milling, Precision Engineering, 72, 2021, 690-705. https://doi.org/10.1016/j.precisioneng.2021.07.013
[20] Herraz, M.; Redonnet, J.-M.; Sbihi, M.; Mongeau, M.: Toolpath planning optimization for end milling of free-form surfaces using a clustering algorithm, Procedia CIRP, 99, 2021, 139-144. https://doi.org/10.1016/j.procir.2021.03.021

[21] Liao, Z.-Y.; Wang, Q.-H.; Xie, H.-L.; Li, J.-R.; Zhou, X.-F.; Pan, T.-H.: Optimization of robot posture and workpiece setup in robotic milling with stiffness threshold, IEEE/ASME Transactions on Mechatronics, 27(1), 2021, 582-593. https://doi.org/10.1109/TMECH.2021.3068599
[22] Zhao, M.; Yue, C.; Liu, X.: Research on milling chatter identification of thin-walled parts based on incremental learning and multi-signal fusion, The International Journal of Advanced Manufacturing Technology, 125(9-10), 2023, 3925-3941. https://doi.org/10.1007/s00170-023-10944-x