MM Science Journal | www.mmscience.eu
ISSN 1803-1269 (Print) | ISSN 1805-0476 (Online)
Special Issue | HSM 2023
17th International Conference on High Speed Machining
October 25-28, 2023, Nanjing, China
DOI: 10.17973/MMSJ.2023_11_2023097

HSM2023-00001

BOOLEAN OPERATION-BASED FAST CALCULATION OF CUTTER-WORKPIECE ENGAGEMENT DURING PERIPHERAL MILLING

Xiaoqian Wang[1], Xing Zhang[1]*, Wei Zhang[1], Pengfei Zhang[1], Kunhong Chen[1]
[1]Xi’an Jiaotong University, School of Mechanical Engineering, Xi’an, China
*Corresponding author; e-mail: xingzhang@mail.xjtu.edu.cn

Abstract

The cutter-workpiece engagement (CWE) is an important basis for accurately predicting milling force and vibration of machining system, which can be dramatically affected by the complex tool path, variable part allowance and various tool profiles. The paper presents a fast calculation method of CWE during peripheral milling process based on the Boolean operation. A second-developed simulation environment embedded the kernel program with the aid of commercial CAM is established. In the computing model, the locally past-cut material entity of the workpiece is replaced by a set of neighboring tools, and the geometric entity of CWE is quickly obtained through the Boolean operation between the tool, workpiece blank, and past-cut entities. The instantaneous uncut chip thickness (IUCT) is further obtained after extracting the tooth start and end cutting angles. Thanks to the first-order computation time complexity, the method has a significant advantage of fast computing speed when compared to the traditional method with a globally updated workpiece. In the milling case of S-shaped workpiece, the results indicate that the method can effectively calculate the CWE status along the entire tool path, and achieve the fast prediction of milling force under a long-time machining condition.

Keywords:
CWE, Fast calculation, Peripheral milling, Boolean operation

1 INTRODUCTION

During the milling process, the CWE, including the IUCT and tooth start/end cutting angles, would directly determine the excitation characteristics of the transient milling force. However, it is difficult to obtain the geometric CWE quickly and accurately under complex machining conditions with the curved tool path, time-varying part allowance and various tool geometry.

In previous research, scholars have successively proposed the analytical method, discrete method, and solid method to characterize the CWE. Among them, the analytical method [Sun 2011, Wojciechowski 2014, Zhu 2016, Zhu 2017, Zhang 2018] calculates the IUCT through the simplified or numerical calculation by establishing the space trochoid motion of the cutting point, and the tooth start and end cutting angles are determined by the intersection points between the tooth trajectory surface and the up-to-date machined surface. As the workpiece material is continuously removed, the update calculation for the machined surface is very time-consuming, and the intersection points are difficult to obtain.

To avoid the above problem, some scholars have presented the discrete method, like Z-map technique [Wei 2013, Wang 2020, Qin 2023]. The basic idea of the method is to map the workpiece surface on a two-dimensional orthogonal plane and discretize it into several small square elements. These discrete elements are used to replace the continuous surface, and the height of the elements contacting with the tool is updated in milling. The primary problem of this method is that when the size of the workpiece is large (up to hundreds of millimeters to several meters), there is a high requirement for the computer to store the discrete data and fastly search and update, and there is also a problem of limited use for five-axis machining, especially under the closed-angle milling situation.

For realizing the milling simulation under complex conditions, scholars have also proposed the solid method [Lazoglu 2011, Tuysuz 2013, Altintas 2014, Aras 2014, Li 2018, Li 2021], including the solid geometry method CSG and boundary representation method B-Rep. This method mainly uses the point, line, surface and their topological relationships in computational graphics to construct the workpiece and simulate the cutting process through Boolean operation between tool and workpiece. The existing commercial CAM softwares mainly apply this kind of approach. However, the computing kernel of Boolean operation is not open to users, and almost all research can only be conducted based on the second-development. Besides, the downside of this method is that a huge number of small facets will be produced in the process of cutting off workpiece solid geometry. Then, the updated feature elements of workpiece geometry will increase rapidly, which will lead to the reduction of computation efficiency, and even the facet breakage, causing computing error and crash.

To meet the requirements of long-time machining, rapid computing and applicability under complex conditions, a fast calculation method based on Boolean operation is proposed in the paper. A kernel CWE algorithm is built up with the aid of the second-developed platform, which can avoid the problem of gradually updated workpiece geometry and loss of calculation efficiency. The validation results show that the method can be applied in complex milling conditions with fast calculation.

2 FAST CALCULATION OF CWE

As shown in Fig.1, a fast calculation procedure for the CWE during peripheral milling process is proposed in the study, which mainly includes the following three aspects.

2.1 Searching for the past-neighboring CLPs

After obtaining the G code file through the CNC programming carried out by CAM software, one can extract the position data of cutter location points (CLPs), and reconstructe the space continuous tool location in the machining coordinate system. As shown in step (1) of Fig. 1, for the current CLP P_k, the previous cut CLPs are set as the search target, one further searches the CLPs that participated in local position in the past and affected the current milling. The above past-neighboring CLPs are then formed as the set D. The searching distance between the previous CLPs and the current P_k should be less than or equal to the tool diameter D_0. The distance judgment for the search process in critical region is as follows.

$$D=\left\{\left|P_k-P_{1:1:k-1}\right|\le D_0\right\} \tag{1}$$

2.2 Fast Boolean operation for CWE

On the basis of the commercial CAD software, one builds up a second-developed simulation platform, and embeds the kernel program of the fast Boolean operation algorithm. With the aid of the past-neighboring CLPs, an entity set GE(D) of tools is established, which is used to represent the local past-cut material of workpiece at P_k.

As given in the following equation, the Boolean intersection between the tool and workpiece blank is carried out, and then it is subtracted from the set of past-neighboring tools to obtain the geometric entity of CWE. The specific Boolean calculation logic is shown as the step (2) in Fig. 1.

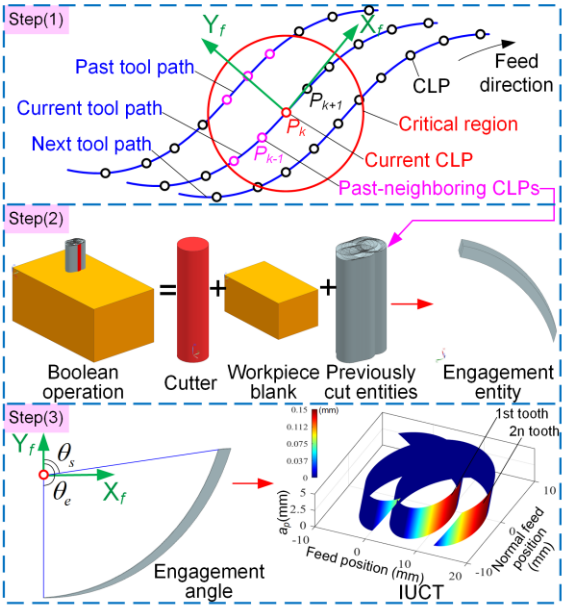


Fig.1: Fast calculation procedure for CWE during peripheral milling.

$$\mathrm{CWE}=\mathrm{C}\cap \mathrm{W}_b-\mathrm{GE}(D) \tag{2}$$

Where C is the geometric entity of the tool; W_b is the geometric entity of the workpiece blank.

2.3 Calculation of IUCT

As seen step (3) in Fig.1, after obtaining the entity of CWE at current time, the point coordinates corresponding to the entity boundary can be extracted on the cross-section perpending to the tool axis, and then the tooth start and end cutting angles are obtained, as well as the judgment function of the tooth cutting status.

$$W_{i,j}(t)=\begin{cases}1 & \theta_s\le\theta_{i,j}(t)\le\theta_e\\ 0 & \text{others}\end{cases} \tag{3}$$

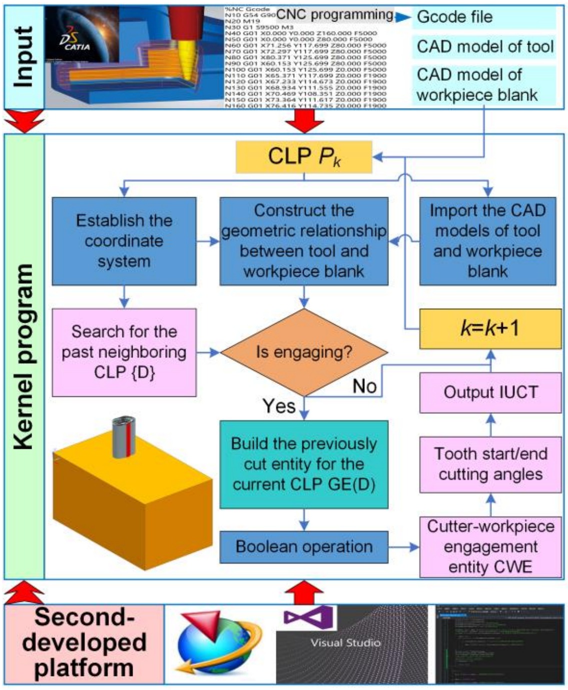
Where t is the machining time, i is the tooth number, j is the number of axial cutting unit.

During the peripheral milling, the IUCT in slot milling can be expressed as a sine function $f_t\sin\theta(t)$. Under the condition of non-full cutting width, the IUCT of CWE can be reconstructed after obtaining the start and end cutting angles, as shown in the following formula.

$$h_{i,j}(t)=f_t\sin\theta_{i,j}(t)W_{i,j}(t) \tag{4}$$

3 KERNEL PROGRAM DEVELOPMENT OF THE FAST BOOLEAN OPERATION

As shown in Fig. 2, based on the commercial CAD software NX10.0, a second-developed platform is built up by using the combination of NXOpen and Visual Studio C++, in which the kernel program development of the fast Boolean operation is embedded. By importing the CAD model of the tool and workpiece blank, as well as the CLP file, the relative pose between cutter and workpiece can be reconstructed at the current CLP by employing the UFUN and NXOpen API function libraries. Using the Parasolid PK kernel function, one can quickly establish the collection of past-neighboring tool entities to represent the



```
%NC Gcode
N10 G54 G90
N20 M19
N30 G1 S9500 M3
N40 G01 X0.000 Y0.000 Z160.000 F5000
N50 G01 X0.000 Y0.000 Z80.000 F5000
N60 G01 X71.256 Y117.699 Z80.000 F5000
N70 G01 X72.297 Y117.699 Z80.000 F5000
N80 G01 X80.371 Y125.699 Z80.000 F5000
N90 G01 X60.153 Y125.699 Z80.000 F5000
N100 G01 X60.153 Y125.699 Z0.000 F5000
N110 G01 X65.371 Y117.699 Z0.000 F1900
N120 G01 X67.233 Y114.673 Z0.000 F1900
N130 G01 X68.934 Y111.555 Z0.000 F1900
N140 G01 X70.469 Y108.351 Z0.000 F1900
N150 G01 X73.364 Y111.617 Z0.000 F1900
N160 G01 X76.416 Y114.735 Z0.000 F1900
```

Fig.2: The second-developed platform for fast calculation of CWE.

local past-cut material of the workpiece, further carry out the Boolean operations between tool, workpiece blank, and local past-cut entities. Finally, the geometric entity of CWE can be obtained.

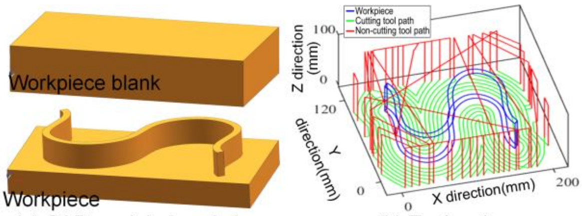
The method reconstructs the previous cut material entity of the workpiece by searching for the past-neighboring tools, without pursuing a global update of the workpiece geometric entity step by step. The method can ensure a relatively constant computation time for each step, and avoid the number of geometric surface features of the workpiece increasing sharply, in which the single-step computing time would rise rapidly, even the error and crash occur. In addition, the developed kernel program also has the computing ability for five-axis milling condition, and the algorithm verification work will be conducted in the future.

4 VERIFICATION

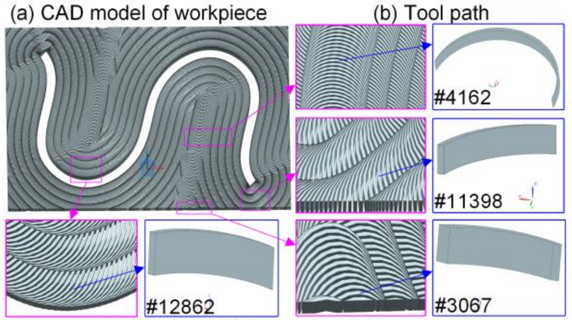
In order to verify the proposed fast Boolean operation algorithm, a case study of S-shaped workpiece in peripheral roughing milling has been carried out. Fig. 3(a) shows the CAD models of the workpiece blank and S-shaped workpiece. Fig. 3(b) illustrates the tool path through CNC programming, including the cutting and non-cutting segments. The total number of CLPs is 13866. A two-teeth flat-end cutter with a diameter of 16mm, and a helical angle of 35° is applied in the milling process. The spindle speed is 9500rpm. The feed speed in cutting and non-cutting process are 1900mm/min and 5000mm/min, respectively. The nominal cutting depth and width in the down milling are 2mm and 5mm, respectively. The total tool path length is about 11626mm. The machining time is about 256.8s.

The proposed fast Boolean operation algorithm is used to calculate the CWE throughout the total roughing process. Fig. 3(c) stands for the geometric entities of CWEs at each CLP along the entire tool path. Among them, one can see the partial enlarged view of the geometric CWE in the step of 3067, 4162, 11398 and 12862, which indicates that the algorithm can accurately calculate the CWE under variable milling conditions.

Fig. 4(a) displays the number of past-neighboring CLPs under each tool position, and Fig. 4(b) shows the single-step computing time for the geometric entity of CWE. It can be seen that the single-step time along the entire tool path is closely related to the number of past-neighboring CLPs, and there is no significant trend of increasing with the step number. This computing performance benefits from that the computation time complexity of the algorithm is first-order with the number of CLPs.

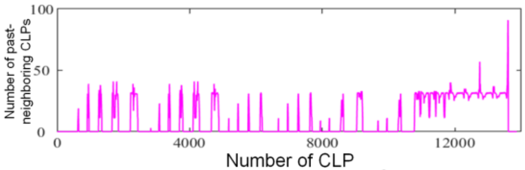


(a) CAD model of workpiece (b) Tool path

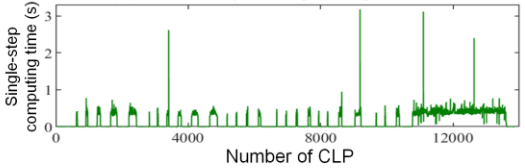


(c) Calculated CWEs along total tool path

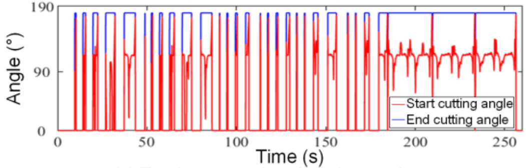
Fig. 3: The calculated CWEs in S-shaped workpiece milling.



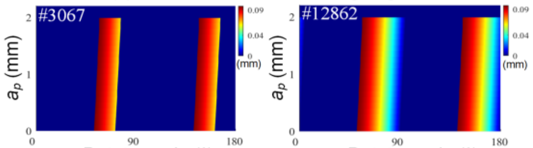
(a) Number of past-neighboring CLPs



(b) Single-step computing time(s)



(c) Tooth start and end cutting angles



(d) IUCT

Fig. 4: Calculated results along the total tool path.

Along the total tool path, the computing time for CWE is about 2001.2s. The average single-step computing time is 0.144s. The average single-step time under in-cutting situation is 0.416s. The maximum single-step time is 3.173s. Besides, the single-step times for a very small number of CLPs will exceed 2s, which is mainly due to the existence of the approximate tangency among multiple entities in Boolean operations, resulting in a contradiction between the patch feature distance and the Boolean tolerance. In summary, the calculation results deduce that the method proposed in this paper has a good fast computing performance and can provide an important foundation for rapid prediction of milling forces.

Fig. 4(c) further extracts the tooth start and end cutting angles based on the geometric entities. It can be easily found that although the nominal cutting width is constant in the CNC programming, its actual values would fluctuate sharply along the curved tool path. This also demonstrates that it is necessary to calculate the instantaneous CWE for predicting milling force. Fig. 4(d) highlights the IUCTs for the step of 3067 and 12862. Its instantaneous changes indicate that the extraction algorithm of CWE status is correct.

In order to verify the validity of the Boolean operation algorithm, a series of experiments are further conducted on the DMG DMU50 high-speed machine tool. Fig. 5(a) shows the actual milling experimental process. The workpiece material used in the test is aluminum alloy 7050. The cutting force coefficients are: k_{ts}=849.5 N/mm^2, k_{rs}=388.3N/mm^2, k_{tp}=22.1N/mm, k_{rp}=9.5N/mm. As described in Figs. 5(b) and (c), the dynamic milling forces are collected and stored by using a dynamometer (Kistler 9265B, sensitivity 200N/V) with a sampling frequency of 5.0kHz during the machining process.

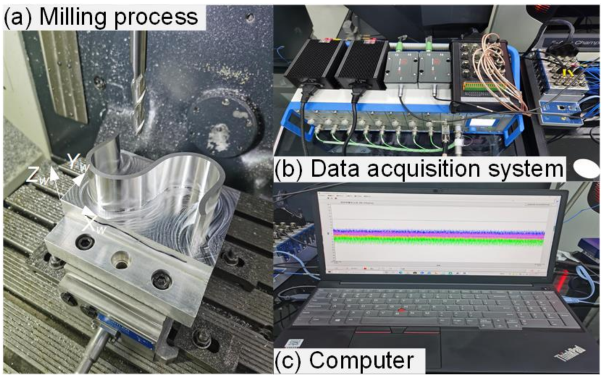


Fig. 5: Experimental setup.

Fig. 6 shows the comparison results of predicted and measured milling force in the Y_w direction. Among them, Fig. 6(a) draws out the milling force for the total tool path. One can conclude that the predicted value can well reflect whether the tool is in-cutting or not. Fig. 6(b) brings insight into the local milling force data from 220s to 250s, indicating that the predicted value can accurately reveal the variation trend of its amplitude. Here, the main reason for the larger amplitude of the measured value is the presence of forced-vibration during the machining process, which would cause some interference from the inertia force into the workpiece system.

Fig. 6(c) further shows the transient change of milling force under a small number of spindle rotation cycles. One can still realize that the predicted value can correctly represent the instantaneous force waveform formed in the cutting stage. The fluctuation phenomenon of measured force in the non-cutting stage also implies the occurrence of significant vibration interference during the milling process. Ignoring these disturbances, the calculation method for CWE proposed in the paper can provide a fast and effective basis for predicting the milling forces.

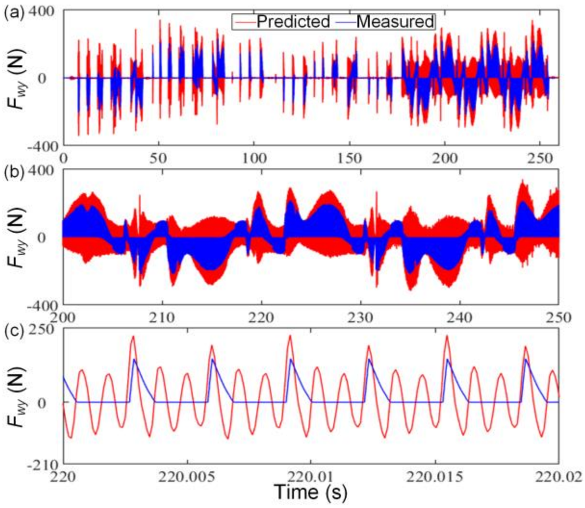


Fig. 6: Comparison of predicted and measured milling forces.

5 CONCLUSION

The paper proposes a fast calculation method for instantaneous CWE based on the Boolean operation. With the aid of commercial CAM software, a kernel program for CWE simulation is developed, and a second-developed platform has been established. In the calculation model, the main contribution is to reconstruct the locally previous cut material entity of the workpiece by the set of cutter in past-neighboring CLPs, and quickly obtain the CWE through Boolean operations among the tool, workpiece blank, and the previous cut entity. Compared to the traditional method with a globally updated workpiece model, the approach has a first-order computation time complexity with the number of CLPs and a relatively constant single-step computing time. In the milling case of the S-shaped workpiece, the average single-step computing time during in-cutting is about 0.416s. The experimental verification results show that the method can effectively calculate the transient CWE and IUCT during peripheral milling, and achieve the fast prediction of milling forces under long machining time and complex tool path situation. In the future, the method will be further expanded into five-axis milling conditions.

6 ACKNOWLEDGMENTS

This work was financially supported the Major Science and Technology Project of Shaanxi Province (No. 2019zdzx01-01-02), the National Natural Science Foundation of China (No. 51905410), and the China Postdoctoral Science Foundation (No. BX20180253, 219945).

7 REFERENCES

[Sun 2011] Sun, Y. W., and Guo, Q. Numerical simulation and prediction of cutting forces in five-axis milling processes with cutter run-out. International Journal of Machine Tools and Manufacture, 2011, Vol.51, No.10-11, pp 806-815.

[Wojciechowski 2014] Wojciechowski, S. The estimation of cutting forces and specific force coefficients during finishing ball end milling of inclined surfaces. International Journal of Machine Tools and Manufacture, 2014, Vol.89, pp 110-123.

[Zhu 2016] Zhu, Z. R., Yan, R., Peng, F. Y., et al. Parametric chip thickness model based cutting forces estimation considering cutter runout of five-axis general end milling. International Journal of Machine Tools and Manufacture, 2016, Vol.101, pp 35-51.

[Zhu 2017] Zhu, K. P., and Zhang. Y. Modeling of the instantaneous milling force per tooth with tool run-out effect in high speed ball-end milling. International Journal of Machine Tools and Manufacture, 2017, Vol.118-119, pp 37-48.

[Zhang 2018] Zhang, X., Zhang, W., Zhang, J., et al. General modeling and calibration method for cutting force prediction with flat-end cutter. Journal of Manufacturing Science and Engineering, 2018, Vol.140(2), pp 021007.

[Wei 2013] Wei, Z. C., Wang, M. J., Cai, Y. J., et al. Prediction of cutting force in ball-end milling of sculptured surface using improved Z-map. The International Journal of Advanced Manufacturing Technology, 2013, Vol.68, pp 1167-1177.

[Wang 2020] Wang, J. R., Luo, M., and Xu. K. Generation of tool-life-prolonging and chatter-free efficient toolpath for five-axis milling of freeform surfaces. Journal of Manufacturing Science and Engineering, 2020, Vol.141(3), pp 031001.

[Qin 2023] Qin, S. Q., Hao, Y. P., Zhu, L. D., et al. CWE identification and cutting force prediction in ball-end milling process. International Journal of Mechanical Sciences, 2023, Vol.239, pp 0020-7403.

[Lazoglu 2011] Lazoglu, I., Boz, Y., and Erdim, H. Five-axis milling mechanics for complex free form surfaces. CIRP Journal of Manufacturing Science and Technology, 2011, Vol.60(1), pp 117-120.

[Tuysuz 2013] Tuysuz, O., Altintas, Y., and Feng H. Y. Prediction of cutting forces in three and five-axis ball-end milling with tool indentation effect. International Journal of Machine Tools and Manufacture, 2013, Vol.66, pp 66-81.

[Altintas 2014] Altintas, Y., Kersting, P., Biermann, D., et al. Virtual process systems for part machining operations. CIRP Annals, 2014, Vol.63(2), pp 585-605.

[Aras 2014] Aras, E., and Albedah. A. Extracting cutter/workpiece engagements in five-axis milling using solid modeler. The International Journal of Advanced Manufacturing Technology, 2014, Vol.73(9-12), pp 1351-1362.

[Li 2018] Li, Z. L., and Zhu, L. M. An accurate method for determining cutter-workpiece engagements in five-axis milling with a general tool considering cutter runout. Journal of Manufacturing Science and Engineering, 2018, Vol.140(2), pp 021001.

[Li 2021] Li, G., Liu, Y., Zhao, D., et al. A general method for instantaneous undeformed chip thickness calculation in five-axis milling based on Boolean operations. The International Journal of Advanced Manufacturing Technology, 2021, Vol.116, pp 2325-2334.