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ScienceDirect
Procedia CIRP 46 (2016) 230 – 233
www.elsevier.com/locate/procedia

7th HPC 2016 – CIRP Conference on High Performance Cutting

Epicycloidal versus trochoidal milling- Comparison of cutting force, tool tip vibration, and machining cycle time

M.Salehi[a,c]*, M.Blum[a], B.Fath[b], T.Akyol[b], R.Haas[a], J. Ovtcharova[c]

[a]*Institute of Materials and Processes, Karlsruhe University of Applied Science, Moltkestr.30, 76133, Karlsruhe,Germany*
[b]*Department of Mechanical and Mechatronik Enginnering, Karlsruhe University of Applied Science, Moltkestr.30, 76133, Karlsruhe,Germany*
[c]*Institute for Information Management in Engineering, Karlsruhe Institute of Technology, Kaiserstr. 12, 76131, Karlsruhe, Germany*

* Corresponding author. Tel.: +49-721-925-2087; fax +49-721-925-2024. *E-mail address:* mehdi.salehi@hs-karlsruhe.de

Abstract

Among several strategies for high performance cutting, trochoidal milling is an efficient one for roughing process and reduces the cycle times significantly. For maximization of the efficiency and reducing the machining cycle time in the trochoidal milling, a novel tool path strategy, so-called, epicycloidal milling is developed. In this paper, mathematical model of the epicycloidal milling is presented. For the two mentioned strategies, comparison between cutting forces, tool tip vibrations, and machining cycle times are performed by four levels of machining experiments. To calculate the tool tip vibration, modal parameters of machine tool are achieved by system identification and then dynamic models of the machine spindle has been developed. It is observed that epicycloidal milling can improve machining cycle time, while the measured forces and calculated vibrations increased slightly.

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Keywords: Machining cycle time; Cutting force; Machining vibration; Trochoidal tool path; Epicycliodal tool path

1. Introduction

The objective of high performance cutting is to increase the material removal rate and to lower cycle time, considering the machining process constrains such as machine tool dynamics, spindle power, machining qualities and the cutting tool failures [1]. In this context, some strategies have been used with some success, described as follows [2] and [3]:

- Optimizing of cutting parameters,
- Selection of optimum tool path,

Discussing the first above mentioned strategy, it is possible to increase machining parameters such as depth of cut, feed rate, and cutting speed, etc. to reach the goal. However, increase of the parameters is limited to some extends due to high cutting heat generation and the abrasive cutting materials as well as the constrains on tooling and the machine tool dynamics [4] and [5].

The second mentioned approach to enhance the roughing process performance is selection of optimum tool path. Among the new strategies, trochoidal milling is an efficient strategy for hard cutting [6]. trochoidal tool path strategy (in CAM softwares [2]) consists of circular motion and linear translation. Roughing by a trochoidal milling reduces the cycle time significantly. In comparison to the conventional slot milling, trochoidal slot milling reduces the number of axial passes, because the tool cuts using the entire cutting flute length [7].

Up to date, some researches have been performed in the field of modeling of trochoidal milling [2], [4], and [7] have already focused on analytical modeling of trochoidal tool path as well as prediction method for tool loads and wears. Here in this work, a novel tool path strategy, called epicycloidal milling is developed and its performance (cutting forces, tool tip vibration and cycle time) are compared with CAM software

Peer-review under responsibility of the International Scientific Committee of 7th HPC 2016 in the person of the Conference Chair Prof. Matthias Putz
doi:10.1016/j.procir.2016.04.001

generating trochoid path as well as real trochoid curvature. The experimental tests are performed on the 5 axes milling machine tool and the force values are measured by table dynamometer. The tool tip vibration is calculated, after achieving the machine modal parameters through system identification and inputting the measured forces values to the developed system dynamic model.

2. Mathematical modeling of epicycloidal tool path

Figure 1 depicts a geometric model of trochoidal tool path. Mathematical models of trochoidal curvature path has already been developed by M.Rauch et al. [2].

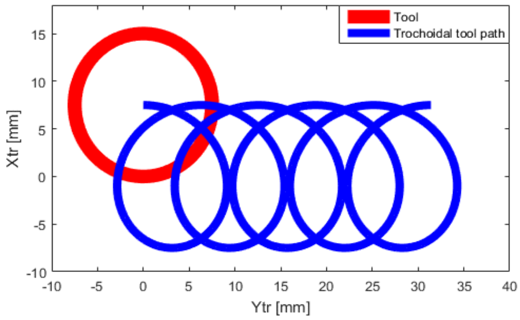

Figure 1. Model for trochoidal tool path

According to Figure 2, this work will focus on developing parametric equations of the novel tool path namely epicycloidal. According to the figure, the path which is developed for the center of the tool is divided into two arcs described as follows:

- Main arc is a trochoid curvature and determines the amount of step over (in green color),
- Side arcs that are trochoid curvatures (in blue color),

Defining the epicycliodal model for slot milling, the tool center positions in X and Y axes are:

$$X_{epi} = S_o \frac{\phi}{2\pi} + nB\sin\phi + nB\sin(m\phi) \quad (1)$$

$$Y_{epi} = nB\cos\phi + nB\cos(m\phi) \quad (2)$$

$$B = \frac{S_w - T_d}{2} \quad (3)$$

Where, X_{epi} and Y_{epi} are the positions of tool center in X and Y coordinate system, respectively. The S_o is step over, Φ is epicycloid path angle with the Y axis, S_w is slot width, and T_d is the tool diameter. n infers radial engagement ratio (rational number and smaller or equal to one) of side and main arcs. As an example, allocating $n=1/2$, the engagement ratio between the main and side arcs will be equal. m expresses the number of the side arcs.

As a result, using epicycloidal tool path (in comparison with trochoidal tool path), the step over value can be selected several times bigger. This makes the total curve length of epicycloidal tool path shorter than trochoidal path.

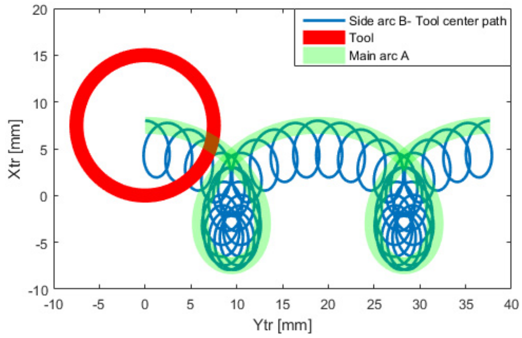

Figure 2.Model of epicycloidal tool path

3. Experimental system identification and machining tests, results and discussions

3.1. Experimental system identification process and modal parameters

In order to determine the modal parameters and developing the dynamic model for the spindle structure displacement, system identification is performed. In this scenario, an impulsive force was applied on the tool tip with an instrumented hammer. Then the accelerometers response (acceleration) is converted to the displacement (Figure 3).

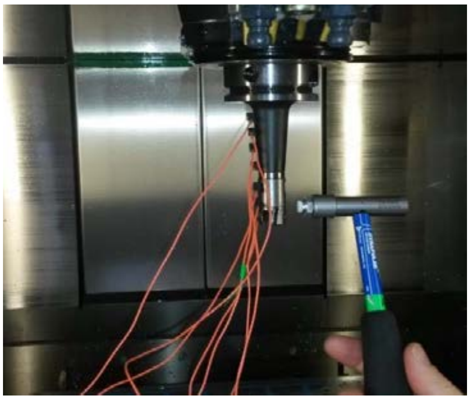

Figure 3. Experimental measurement of tool tip vibration by system identification

After experimental test, modal parameters are calculated by peak-picking technique [8]. In this case, the parameters are obtained from experimentally measured Frequency Response Function (FRF). Table 1 shows the identified modal parameters in Y axis.

Table 1. Identified modal parameters in Y axis

Modes	Freq. (Hz)	c_y (N-s/m)	k_y (N/m)	m_y (Kg)
1	2055	4.04e1	1.43e7	0,08568772

The modal parameters are used to create a simulated FRF. The compatibility of simulated FRF are validated by experimentally measured FRF. Figure 4 shows real and imaginary-measured and simulated- FRF of the tool tip displacement, applying short impact force to the tool tip in *Y* direction. Due to the selection of *Y* axis as a machining feed direction, the FRF, force, and vibration comparison will be represented only in this direction. According to the figure, they are approximated to be single degree of freedom system.

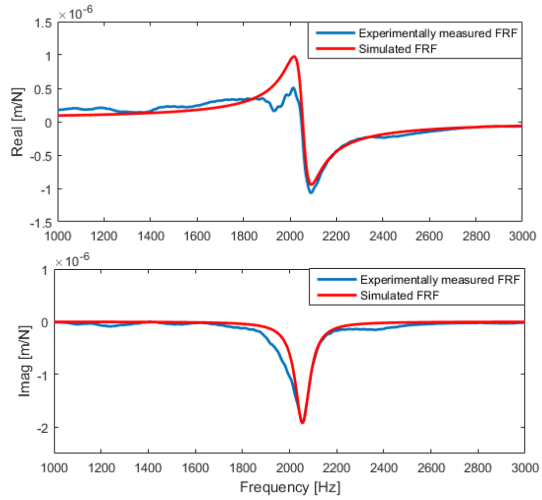

Figure 4. Comparison of measured and simulated, real and imaginary FRF

Considering single degree of freedom in *Y* axis the dynamic model for calculation of tool tip vibration is written as follow:

$$m_y\ddot{y} + c_y\dot{y} + k_y y = F_c \Rightarrow \ddot{y} = \frac{F_c - c_y\dot{y} - k_y y}{m_y} \quad (4)$$

Where $\ddot{y}$ is acceleration, m_y, c_y, and k_y are the modal mass, damping and stiffness in *y* axis, respectively (according to Table 1). Fc is cutting force which is going to be measured experimentally and fed to the model.

$$\dot{y} = \dot{y} + \ddot{y}.dt \Rightarrow y = y + \dot{y}.dt \quad (5)$$

Where $\dot{y}$ and y are velocity and displacement (vibration) determined by numerical integration in Simulink software.

3.2. Machining set up for experiments

In order to evaluate the performance and efficiency of epicycliodal tool path versus trochoidal one (both CAM and real trochoidal path), experimental tests were performed after the mathematical model descriptions. The goal of the experiments were investigation of the paths performances with regard to consuming cutting force, tool tip vibrations (machine tool dynamic behavior in response to the strategies) and the machining cycle times.

In this regards, the machine tool was Hermle Dynamic C40, five axis machine, the cutting tool was indexable endmill, the workpiece material was carbon steel RSt 37-2 (according to the DIN standard). For measuring the forces, Kistler dynamometer has been used in the test structure. The tool and cutting parameters for the epicycloidal and trochoidal milling are listed in Table 2.

Table 2 cutting parameters

No.	Cutting parameters	Epicycloidal milling and trochoidal milling
1	Cutting width	30 mm
2	Cutting depth	2 mm
3	Feed per tooth	0.1mm
4	Cutting speed	150 m/min
5	Tool diameter	20 mm
6	Number of teeth	3
7	Cutting length in Y axis	70 mm

Table 3 shows the four test strategies for the mentioned tool paths.

Table 3 Experimentes Strategy

No	Test strategies	Curve length	Main arc	Side arc	Step over
1	CAM trochoid	1081 mm			2 mm
2	Real trochoid	1037 mm			2 mm
3	Epicycliod1212	1111 mm	B/2	12*B/2	12 mm
4	Epicycliod1215	930 mm	2/3 B	15*1/3 B	12 mm

According to the Table 3, the curve lengths of the test strategies number 1, 2, and 3, were taken into account approximately equal (with 5-10% variation), in order to have integer values for the step overs. Furthermore, test strategy number 3 consists of 12 side arcs for every main arc. The main and side arcs has 50% of cutting width radial engagement. In addition, test strategy number 4 consists of 15 side arcs for each main arc. In addition, the cutting width engagement for main and side arcs are 66% and 33%, respectively.

3.3. Experimental results and discussion

Figure 5 depicts the comparison of cutting forces and vibration between CAM generation and real trochoidal milling with the mentioned cutting parameters. According to the figure, the amount of force (750 N) and tool tip vibration (55 micron) for the two strategies are equal, while the real trochoidal curvature is 50 mm shorter.

Figure 6 compares the cutting forces and tool tip vibration of real trochoidal milling and epicycloidal 1212 strategy. Regarding to the figure, the measured cutting forces and the calculated tool tip vibration values for the epicycloid are increased up to 10% (in steady state cutting) as compared to the real trochoidal tool path. However, the curve length for the epicycloidal 1212 is 26 mm shorter.

Figure 7 shows the comparison of cutting forces and tool tip vibration of epicycloidal 1212 and epicycloidal 1215 tool paths. According to the figure, the measured cutting forces and calculated tool tip vibration are approximately equal (epicycloid 1215 has up to 3% more force and vibration values). Nevertheless, the curve length of the epicycloid 1215 is 181 mm shorter than epicycloid 1212.

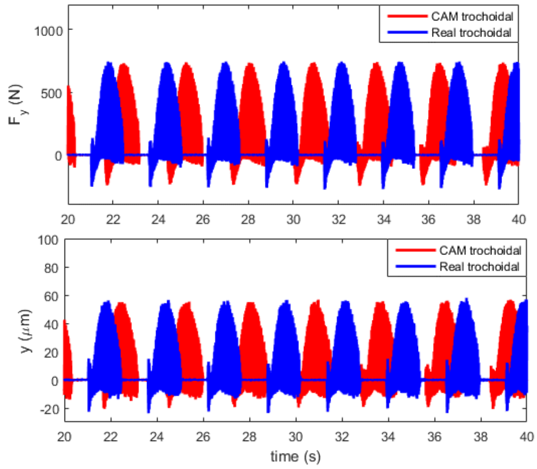

Figure 5. Comparison of CAM generating and real trochoidal milling cutting forces and tool tip vibration in feed direction

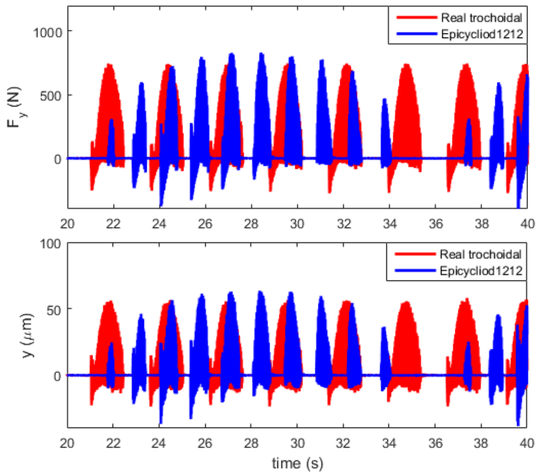

Figure 6. Comparison of cutting forces and tool tip vibration of real trochoidal milling and epicycloidal 1212 strategy in feed direction

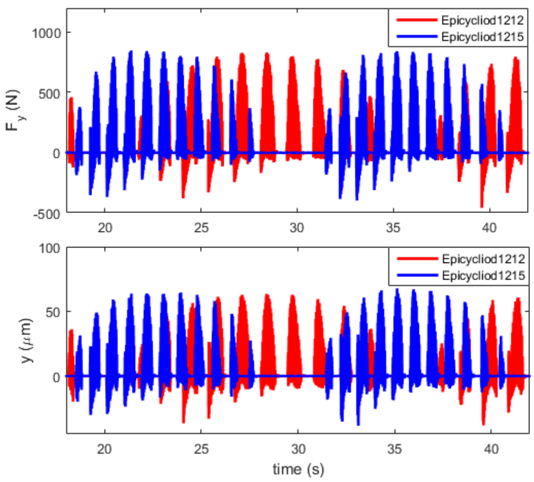

Figure 7. Comparison of cutting forces and tool tip vibration of epicycloidal 1212 and epicycloidal 1215 tool paths in feed direction

Machining cycle time can be calculated as:

$$T_c = \frac{C_l}{f_n \times n} \tag{6}$$

Where T_c is the machining cycle time in minute, C_l is the machining curve length in mm, f_n is feed per revolution in mm/revolution and n is the spindle speed in rpm. In this scenario, machining cycle time is calculated 1.55 and 1.29 minute for epicyclode 1212 and epicyclode 1215, respectively. Therefore, the later has nearly 20 % shorter machining cycle time as compared to the former one.

4. Conclusion

Here in this paper, a novel tool path strategy, namely epicycloidal path has been developed from troichoidal milling. The path consists of two trochoidal arcs, namely main and side arcs. In order to investigate the performance of the epicycliodal versus trochoidal milling, the cutting force, tool tip vibration and machining cycle time criterion have been studied by performing four levels of experimental milling tests. At the end the below points are concluded:

- The force and vibration values increase approximately up to 10 % starting from real trochoidal and ending epicycloidal 1215 strategy,
- Machining cycle time is reduced up to nearly 20 %, using the epicycloidal 1215 tool path comparing to the other strategies,
- The 20% cycle time reduction are achieved at the expense of 10% cutting force and vibration increase. This can be investigated further in the future research, since, the increase may cause more tool wear.

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