euspen's 19th International Conference & Exhibition, Bilbao, ES, June 2019
www.euspen.eu

Development of an adaptive toolpath planning strategy for diamond face turning of freeform surfaces

Wenbin Zhong, Zhen Tong*, Wanqun Chen, Xiangqian Jiang

EPSRC Future Metrology Hub, Centre for Precision Technologies, University of Huddersfield, UK HD1 3DH

**z.tong@hud.ac.uk*

Abstract
Freeform surfaces are enormously demanded in advanced imaging and illumination applications. Sub-micrometre form accuracy is generally required to guarantee the designed functionality. However, there is a trade-off between the form accuracy and productivity when machining these surfaces, i.e. a sharp tool with finer toolpath segments can improve the form accuracy but at the cost of increased machining time. This paper proposes an adaptive toolpath planning strategy for freeform surfaces machining, which aims to achieve the highest productivity with the given tolerance. Instead of using the constant parameters to plan the toolpath, this strategy calculates the toolpath segment length by taking the tolerance and the curvature into account. Moreover, Fast Fourier Transform (FFT) is used to analyse the frequency components along the toolpath, and an optimized sampling frequency is selected to avoid losing small features on the surface. The toolpaths for diamond turning of a micro-lens array are generated by both conventional and adaptive toolpath planning methods. The results show that the adaptive toolpath can effectively reduce the number of points by one order of magnitude while improving the form accuracy by two-fold.

freeform surface; toolpath planning; form accuracy; productivity; diamond turning

1. Introduction

Freeform surfaces are playing increasingly important role in various areas, such as astronomy, automotive and semiconductor etc. due to the advantages of enhancing the optical system performance, simplifying system structure and realizing system integration [1]. Sub-micrometre form accuracy and nanometric surface topography are generally required to ensure the designed functionality of the freeform surface [2], which imposes considerable challenges to the manufacturing of these surfaces. Diamond machining has been recognised as the most effective method to fabricate these surfaces with mirror surface finish. The toolpath for diamond turning is usually designed in cylindrical coordinate [3], and it involves two sampling directions, i.e. radial (r) and azimuthal (θ), as shown in Figure 1(a). The deviation between the original surface and the toolpath segment is one of the main sources of form error. Conventional toolpath maintains constant sampling rates when approximating the freeform surface, which becomes problematic when there are high curvature features on the surface. Smaller toolpath spacing will increase the form accuracy but at the cost of increased machining time. Interpolate the toolpath at the post processor can increase the accuracy [4], but will result in a lot more toolpath segments as well.

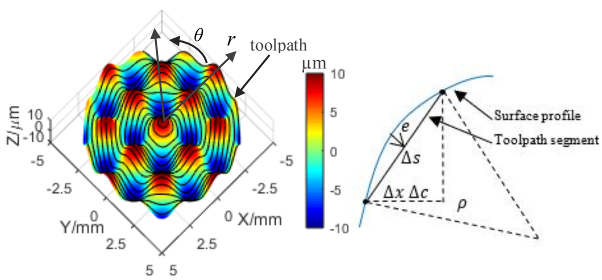
This paper develops an adaptive toolpath planning strategy which aims to achieve the highest productivity with a given tolerance. The detailed description of the strategy is given in Section 2. The effectiveness of the strategy is demonstrated in Section 3. Section 4 concludes the paper and points out the future work.

2. Adaptive toolpath planning strategy

The freeform surface is described as $z = f(r,\theta)\ r \in [0,R]\ \theta \in [0,2\pi]$ in cylindrical coordinate, where r is the radial distance, R is the radius of the workpiece, θ is the polar angle. To approximate the whole surface, the toolpath should sample along the radial and azimuthal directions simultaneously. The toolpath error increases with the length of the toolpath segment, as shown in Figure 1(b). For the given tolerance e, the maximum length of the toolpath segment Δs at the specific point on the surface is given by [5]

$$\Delta s = 2\sqrt{2\rho e - e^2} \quad (1)$$

Where ρ is the radius of curvature of the surface profile at the specific point. The increment of the feeding axis (e.g. Δx or Δc for X or C axis in the machine coordinate) can be calculated by projecting the segment to the axis. The maximum form error is $\sqrt{2}e$ if both sampling directions reach the tolerance at the same time.



(a) Toolpath for a micro-lens array (b) Error estimation
Figure 1. Toolpath for diamond turning.

2.1. Radial sampling

The maximum radial sampling length for the specific revolution is calculated first, and then the azimuthal sampling is carried out within this revolution. A series of surface profiles along the radial directions can be obtained with the discretization of the polar angle, as described in Equation 2.

$$z = f_r(r,\theta_i)\ \ i = 1,2,\cdots,N \quad (2)$$

Radius of curvatures corresponding to the selected surface profiles can be calculated. Then the maximum radial increment

Δr_i at different polar angle θ_i can be calculated with Equation 1. The maximum radial feed Δr_{max} for the whole revolution is given by

$$\Delta r_{max} = min\left\{\frac{2\pi}{\theta_i}\Delta r_i\right\} \quad (3)$$

Where $min\{\ \}$ denotes the minimum value in the bracket. The calculated value becomes more accurate when more surface profiles are selected.

2.2. Azimuthal sampling

The procedure of azimuthal sampling is illustrated in Figure 2. If current curvature is very small, the Equation 1 will give a large segment length, and some small features may be eliminated. According to the sampling theorem, the critical azimuthal sampling rate θ_{ct} can be calculated by performing FFT on the surface profile $z = f_\theta(r_0, \theta)$, where r_0 is the starting radius of the revolution. θ_{ct} corresponds to the maximum frequency component with an amplitude equal to the tolerance e.

The arc length l is used to replace the angle θ when calculating a meaningful curvature along the azimuthal surface profile, as both l and z have the unit in length, as described in Equation 4.

$$z = f_l(r_j, l) \quad (4)$$

Where $l = r_j\theta$, r_j is the radius of current sampling point. The maximum azimuthal increment $\Delta\theta_{max}$ can be calculated with Equation 1, while the actual azimuthal increment $\Delta\theta_j$ is selected as the smaller value of $\Delta\theta_{ct}$ and $\Delta\theta_{max}$. When the sampling reaches the end of the revolution, the next revolution sampling begins with the calculation of the maximum radial increment as discussed in Section 2.1. The next toolpath point can be calculated with the updated radius and polar angle, as shown in Equation 5.

$$\theta_{j+1} = \theta_j + \Delta\theta_j$$
$$r_{j+1} = r_j + \frac{\Delta\theta_j}{2\pi}\Delta r_{max} \quad (5)$$

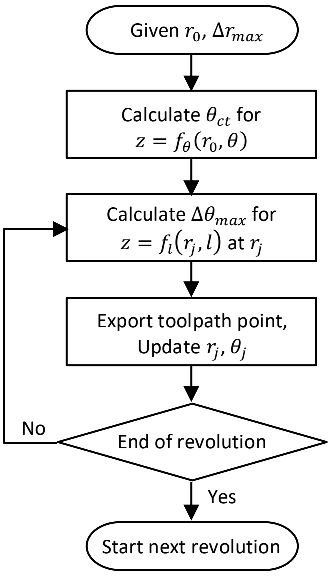


Figure 2. Azimuthal sampling flow chart.

3. Experiment

Both the conventional and adaptive toolpaths are generated for a typical micro-lens array surface, as shown in Figure 1(a), which can be represented by $z(x, y) = A_x\cos(2\pi f_x x) + A_y\cos(2\pi f_y y)$, where $A_x = A_y = 5\mu m$, $f_x = f_y = 0.4mm^{-1}$. The workpiece radius is 5 mm.

The radius sampling rate for the conventional toolpath is 10 μm/rev, and there are 256 points for each revolution. For the adaptive toolpath, a tolerance of 20 nm is used. Table 1 shows the comparison of the toolpaths. The results confirm that the adaptive toolpath can reduce the number of points by one order of magnitude while improving the form accuracy by two-fold.

Table 1. Toolpath comparison.

	Conventional	Adaptive
Total points	128,000	23,187
Max form error/nm	58	26

Owning to the merits of the dynamic adjustment of sampling rate, as shown in Figure 3, the adaptive toolpath uses much fewer points, which will increase the productivity significantly. It takes 122 and 500 revolutions for the adaptive and conventional toolpath to finish the sampling, respectively. Figure 4 shows the error map by subtracting the reconstructed surface with the original surface. The form error of the conventional toolpath increases with the radius, this is because the length of the toolpath segment increases dramatically. On the contrary, the form error of the adaptive toolpath is independent of radius.

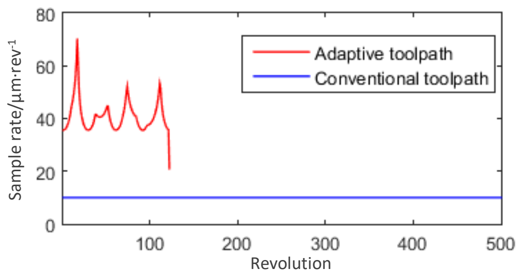
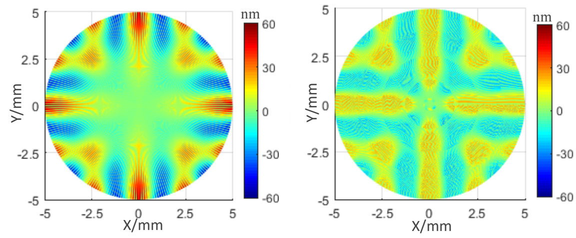


Figure 3. Sampling rate variation in radial direction.



(a) Conventional (b) Adaptive

Figure 4. Toolpath error map.

4. Conclusions and future work

The conventional toolpath plaining strategy is of low efficiency when high form accuracy is required. This proposed adaptive toolpath planning strategy can achieve much higher productivity while keeping higher form accuracy. The next step of the work is to enhance this algorithm for machined surface predication considering the residual tool mark between successive revolutions and tool radius compensation.

References

[1] F. Z. Fang, X. D. Zhang, A. Weckenmann, G. X. Zhang, and C. Evans, “Manufacturing and measurement of freeform optics,” *CIRP Ann. - Manuf. Technol.*, vol. 62, no. 2, pp. 823–846, 2013.

[2] X. J. Jiang and D. J. Whitehouse, “Technological shifts in surface metrology,” *CIRP Ann. - Manuf. Technol.*, vol. 61, no. 2, pp. 815–836, 2012.

[3] F. Z. Fang, X. D. Zhang, and X. T. Hu, “Cylindrical coordinate machining of optical freeform surfaces,” *Opt. Express*, vol. 16, no. 10, p. 7323, 2008.

[4] P. Vavruska, “Interpolation of Toolpath by a Postprocessor for Increased Accuracy in Multi-axis Machining,” *Procedia CIRP*, vol. 46, pp. 336–339, 2016.

[5] W. Zhong, X. Luo, W. Chang, F. Ding, and Y. Cai, “A real-time interpolator for parametric curves,” *Int. J. Mach. Tools Manuf.*, vol. 125, no. August 2017, pp. 133–145, 2018.