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ORIGINAL ARTICLE

Investigation on the generation of the medium-frequency waviness error in flycutting based on 3D surface topography

Jianguo Miao [1,2] · Deping Yu [1] · Chenhui An [2] · Fengfei Ye [1] · Jin Yao [1]

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Abstract Undesirable medium-frequency waviness error along the cutting direction was often left on the machined surface of KDP crystals adopting ultraprecision single-point diamond flycutting (SPDF), reducing the optical performance of KDP crystals and restricting their capability in the inertial confinement fusion (ICF). In order to reduce such medium-frequency waviness error, an indirect method for investigating the generation of the error was proposed in this paper. The tool-tip vibration was indirectly extracted by combining the intermittent cutting trajectory of the flycutting process and the medium-frequency waviness error, which was extracted from the 3D surface topography using 2D wavelet transform method. The main frequency of the extracted tool-tip vibration was calculated and compared with the modals of the machine tool spindle system, which was obtained by FEM analysis and modal test. Finally, an improved spindle system was proposed based on the FEM analysis, and contrast tests between origin and improved machine tool were carried out. Results show that the tool-tip vibration can be effectively extracted by the proposed method, which deduces that the vibration that produced the medium-frequency waviness error is mainly generated by the sixth-order modal of the spindle system. In addition, the quality of the machined surface has been greatly improved with the improved spindle system.

Keywords Flycutting · Medium-frequency waviness error · 3D surface topography · Tool-tip vibration

✉ Deping Yu
williamydp@scu.edu.cn

1 School of Manufacturing Science and Engineering, Sichuan University, Chengdu 610065, China

2 Research Center of Laser Fusion, Mianyang 621900, China

1 Introduction

The potassium dihydrogen phosphate (KDP) crystals possess many special qualities such as high leaser-induced damage threshold (LIDT), fine light transmissivity, and achieving flat crystals with large size easily, which are specially fit for the requirement of inertial confinement fusion (ICF) [1, 2]. Thus, the KDP crystals are widely used in ICF, serving as frequency multiplication and pockels cells [3, 4]. However, the KDP crystals also possess some undesirable qualities, e.g., soft, brittle, thermally sensitive, and extremely easy to deliquesce, which make it difficult to be processed by traditional grinding and polishing method. At present, ultraprecision single-point diamond flycutting (SPDF) is the most useful manufacturing method to process KDP crystals to achieve optical quality surface [5, 6]. In flycutting, a diamond cutting tool which is fixed on a large flycutting head directly removes material from the workpiece and finally high-precision surface is achieved. However, undesirable periodical waviness errors with multi-frequency along the cutting direction are left on the machined surface. These waviness errors affect the optical performance of the KDP crystal and restrict the development of ICF.

In order to achieve better optical performance, many researchers have paid their attention to study these multi-frequency waviness errors on the machined surface that processed by SPDF. Li et al. [7–9] studied the influence of waviness error with small spatial frequency (<1 mm), which would affect the roughness of the machined surface, on the LIDT by combining the Fourier modal method and PSD method. They found that such waviness error was mainly caused by the axial vibration of the spindle. Chen et al. [10] investigated the influence of the waviness error with large spatial frequency (>33 mm), which mainly influences the root mean square gradient (GRMS) of the machined surface, based on the dynamics analysis of the machine tool. They found that the vibration of the tool-machine-workpiece system is the main cause of such waviness error. As for the waviness error with medium-frequency (spatial frequency less than 33 mm), it would cause the distortion of the refractive index of the laser and induce phase mismatch, which ultimately decreases the LIDT of the machined KDP crystals and may even cause the failure of the facility; hence, the medium-frequency waviness error must be restricted in ICF [11–13] while the error was rarely discussed before. Therefore, it is necessary to find the main source of the medium-frequency waviness error and propos a reasonable method to avoid the generation of the error, which can also be used to guide the design of the machine tool and greatly improve the optical performance of KDP crystals. Many researchers used simulation method to investigate the surface topography. Cao et al. [14] built an analysis and simulation model to predict the surface topography with cutting parameters. Zhou et al. [15] presented an integrated model and used power spectral density (PSD) to analyze the generated machined surface. Liang et at. [16] proposed an integrated dynamic-simulation model considering the intermittent cutting force and investigated the influence of tool-tip vibration on surface generation. The machined surface was successfully forecasted in the simulation result. Sun et al. [17, 18] studied the performance of an ultraprecision flycutting machine tool through an error budget methodology and proposed a cutting simulation considering the interaction between manufacturing process and machine tool. The waviness profile of the workpiece with large size was well predicted adapting the waviness simulation model with short time and high accuracy. However, the waviness profile and the tool vibration were studied and obtained by simulation, which needs further verification through experiments. Furthermore, the main source of the medium-frequency waviness error was not determined. And, no method was provided to reduce such waviness error and improve the quality of the machined surface. In addition, surface topography has become an important criterion to evaluate the quality of the machined surface in many researches [19, 20], but the method that based on machined surface to obtain the relative vibration is rarely proposed.

This paper proposes an indirect method for investigating the generation of the medium-frequency waviness error by analyzing the 3D surface topography of the machined surface, which directly reflects the relative position between tool-tip and workpiece. Firstly, the vibration of the tool-tip has been indirectly obtained by combining the intermittent cutting trajectory of the flycutting and the medium-frequency waviness error extracted from the 3D surface topography using 2D wavelet transform method. Then, the main source of the medium-frequency waviness error has been determined by comparing the main frequency of the obtained tool-tip vibration and the modal of the critical component within the flycutting machine tool. Finally, a method to reduce the medium-frequency waviness error has been proposed and verified through experiments.

2 Method for investigating the medium-frequency waviness error

The schematic diagram of the flycutting process is shown in Fig. 1. It can be seen that the spindle is axially installed on the aerostatic bearing, which can guarantee good rotating accuracy. A large flycutting head with a disk shape is fixed on the bottom of the spindle, while the diamond cutting tool is fixed on its edge. The workpiece is fixed on the linear feed slide through a vacuum chuck, which can achieve stable feeding. During the flycutting process, the workpiece which mounted on a vacuum suck, feeds towards the flycuting head and machined surface can be formed by each cutting step.

The flycutting process can obtain flat surface with high precision; however, undesirable periodical waviness with medium-frequency along the cutting direction was found to be left on the machined surface, which deteriorates the optical performance of the KDP crystal. In order to find the main source of this medium-frequency waviness error and improve the optical quality, an indirect method is proposed based on the 3D surface topography of the machined surface. It mainly contains three steps. The first step is to extract the medium-frequency waviness error from the 3D surface topography using the 2D wavelet transform method. The second step is to obtain the corresponding vibration of the tool-tip by combining the intermittent cutting trajectory of the flycutting and the medium-frequency waviness error extracted in the first step. The third step is to find the main source of the medium-frequency waviness error by comparing the main frequency of the tool-tip vibration and modal of the main components in the flycutting machine tool, which can be obtained by modal analysis using finite element method (FEM) and modal test. By doing so, the relevant components of the flycutting machine tool can be optimized to restrict the generation of the medium-frequency waviness error and the optical quality of the machined surface can be improved.

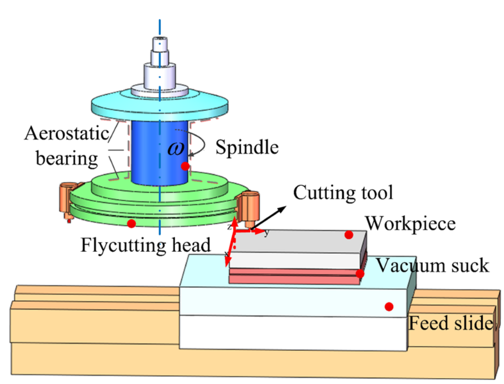


Fig. 1 Schematic diagram of the flycutting process

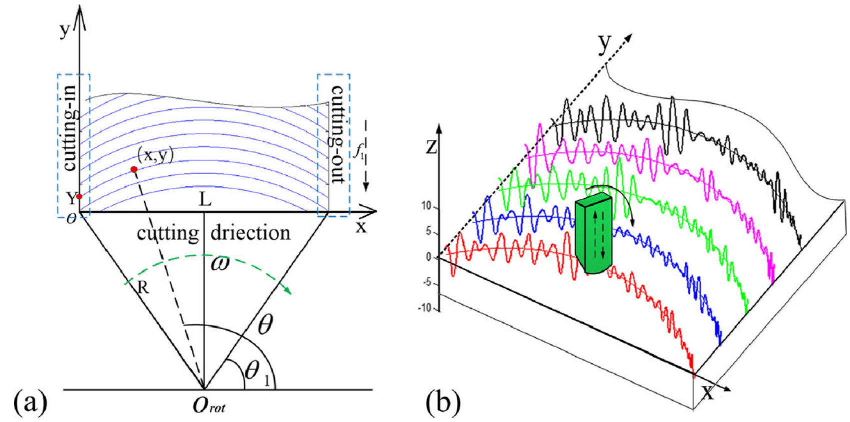


Fig. 2 Cutting trajectory in the flycutting process. **a** 2D cutting trajectory. **b** 3D cutting trajectory, i.e., tool-tip vibration

2.1 Wavelet method

The 3D surface topography of machined surface contains abundant position information of the flycutting process. It directly reflects the vibration between the tool-tip and the workpiece, which may be caused by different sources. To investigate the main source of the medium-frequency waviness error, the medium-frequency waviness error needs to be extracted from the 3D surface topography. It is achieved by the wavelet method.

Wavelet method has the advantage of fast computation with localization in both space and frequency domain. It can identify different feature of the signature and effectively extract both the detail information and the approximation information using flexible resolution, which is specially suitable for the multi-frequency analysis. For an arbitrary signal, its one-dimensional continuous wavelet transform can be defined by Eqs. (1) and (2):

$$\Psi_{a,b}(x) = \frac{1}{\sqrt{|a|}}\Psi\left(\frac{x-b}{a}\right) \tag{1}$$

$$W_{\Psi}(f)(a,b) = \langle f(x), \Psi_{a,b}(x)\rangle = \frac{1}{\sqrt{|a|}}\int_R f(x)\overline{\Psi}\left(\frac{x-b}{a}\right)dx \tag{2}$$

where a, b, and Ψ are the scale coefficient, the translation coefficient, and the mother wavelet, respectively. Usually, the dyadic discrete wavelet transform (DDWT) is used to analyze the original signal. It can be described by Eqs. (3) and (4):

$$\Psi_{j,k}(x) = 2^{-j/2}\Psi\left(2^{-j}x-k\right), \quad j,k\in Z \tag{3}$$

$$DW_{\Psi}(f)(j,k) = \frac{1}{\sqrt{2^j}}\int_Z f(x)\overline{\Psi_{j,k}}(x)dx \tag{4}$$

The 2D wavelet transform method uses the one-dimensional wavelet transform in row and column direction to decompose the raw signature of 3D surface topography [21]. It has been successfully used in surface topography analysis to obtain the different frequency information of 3D surface [22–24]. Thus, the 2D wavelet transform method is introduced to decompose the 3D surface topography of the machined surface in flycutting and extract the medium-frequency waviness error along the cutting direction.

2.2 Tool-tip vibration

In the flycutting process, the workpiece is fixed on a vacuum chuck which is supported by a hydrostatic slide with high stiffness. Thus, the vibration of the workpiece is slight and the 3D surface topography of the machined surface mainly reflects the vibration of the tool-tip.

As the diameter of the flycutting head is about 650 mm, which is larger than the length of the workpiece along the cutting direction (about 400 mm), the flycutting process is an intermittent cutting process and the cutting trajectory is an arc-shape as shown in Fig. 2a. In the flycutting process, the diamond cutting tool will cut the workpiece material from the cutting-in edge to the cutting-out edge per revolution of the spindle and leave the vibration information on the workpiece surface. However, the cross sectional information of the surface can only evaluate the quality of the machined surface. In order to obtain the vibration of the tool-tip, the cutting trajectory of the tool-tip need to be considered. By setting the cutting direction and the feed direction as the x axis

Table 1 Machining parameters of the workpieces

Parameters	No.			
	I	II	III	IV
Pressure of the aerostatic bearing (Mpa)	0.5	0.5	0.5	0.5
Rotation speed (rpm)	300	300	300	400
Feed speed (μm/s)	200	110	200	200
Cutting depth (μm)	10	5	5	15

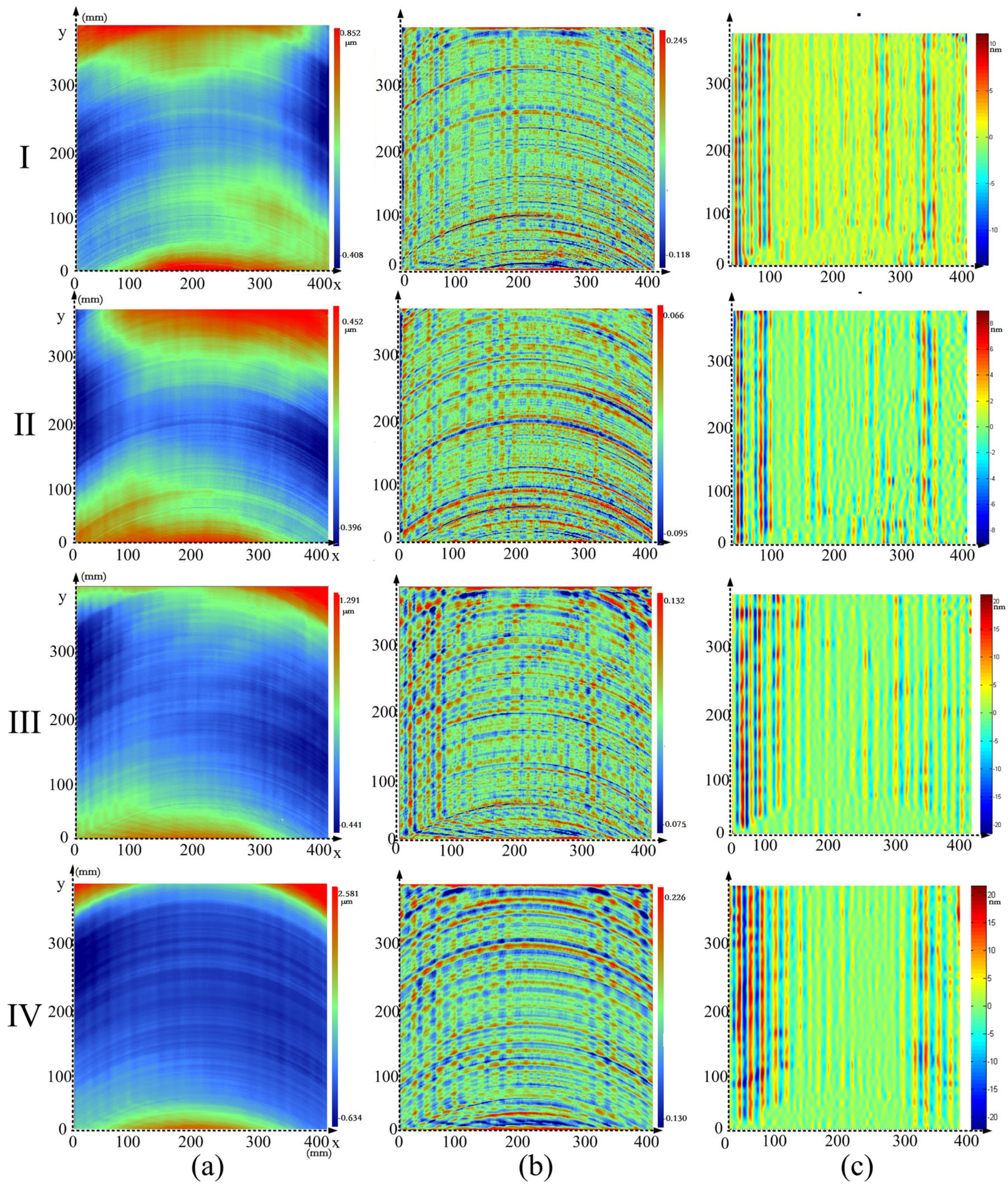


Fig. 3 The 3D topographies of the machined surfaces. **a** Measured surface topography. **b** Surface topography evaluated by PSD1. **c** Surface topography extracted by the wavelet method

and the *y* axis, respectively, the intermittent cutting trajectory of the tool-tip can be expressed by Eq. (5):

$$\begin{cases} x = R\cos\theta + \dfrac{L}{2} \\ y = R\sin\theta + ft + Y - \sqrt{R^2 - \dfrac{L^2}{4}} \end{cases} \quad (5)$$

where L, R, n, f, and Y are the length of workpiece along the cutting direction, the radius of the flycutting head, the speed of the spindle, the feed speed, and the value of the cutting-in location, respectively. And $t \in \left[0, \frac{\pi - 2\theta_1}{\omega}\right]$; $\theta = \pi - \theta_1 - \omega t$; $\omega = \frac{2\pi n}{60}$; and $\theta_1 = \arccos\left(\frac{L}{2R}\right)$. For an arbitrary intermittent cutting trajectory with a cutting-in location Y, the z value of the tool-tip at any point (x, y) can be obtained from the

Fig. 4 The vibration of the tool-tip at different machining parameters. **a** Vibration of the tool-tip. **b** Frequency of the vibration

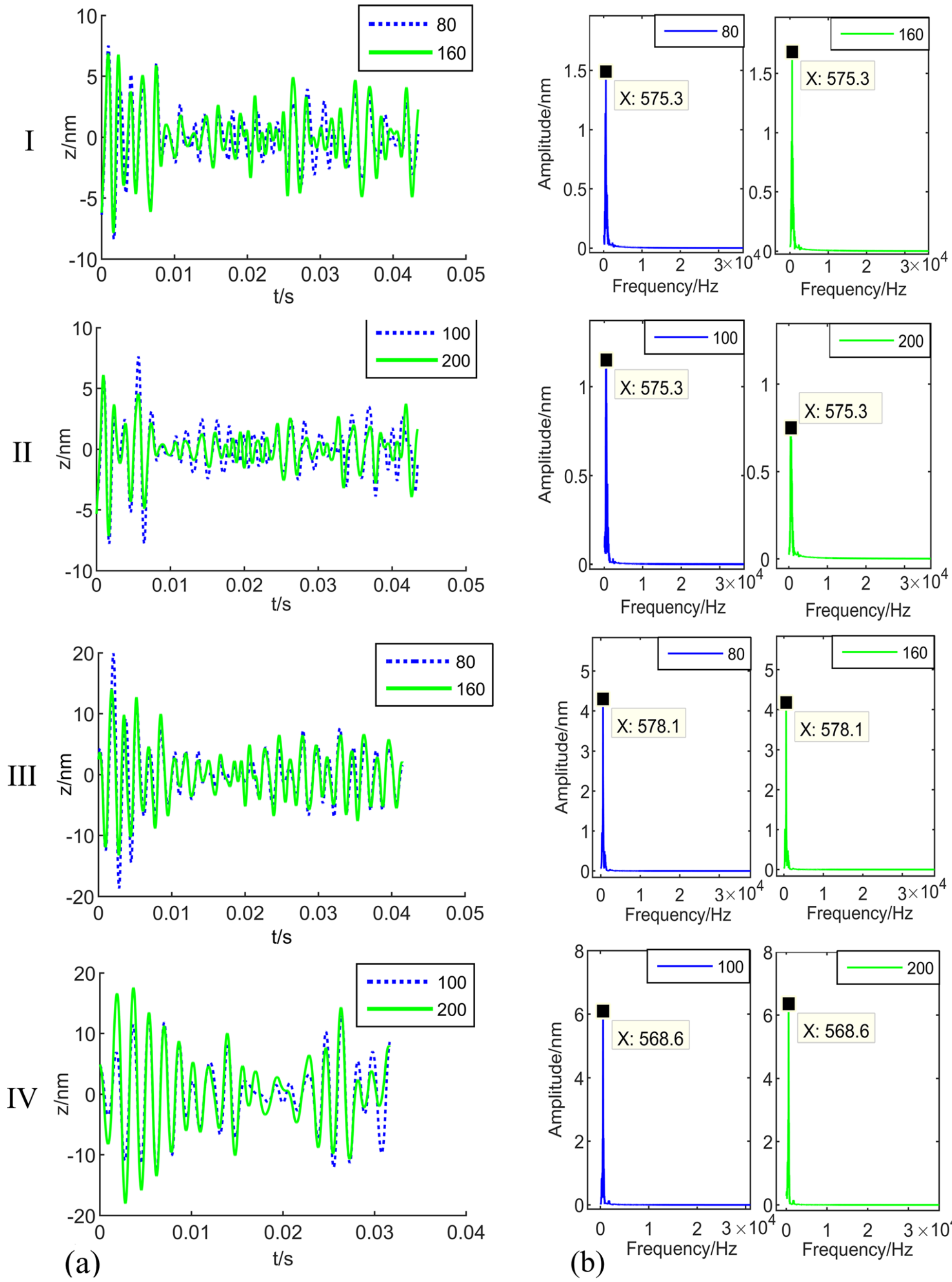
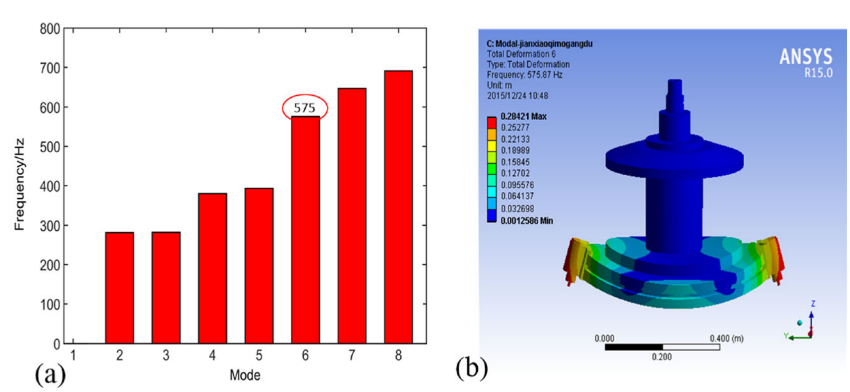


Fig. 5 Modal analysis of the spindle system. **a** Modals. **b** Sixth-order modal shape



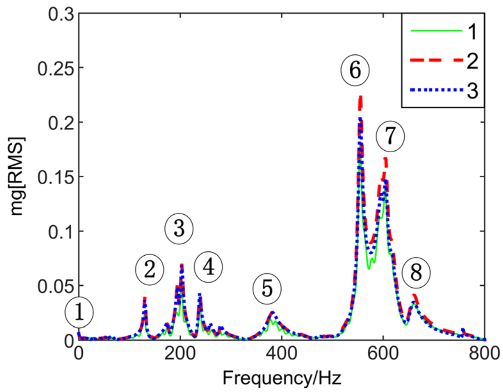


Fig. 6 The result of the modal test

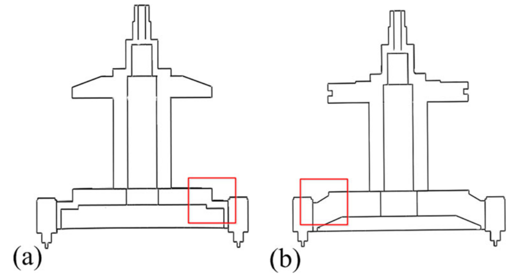


Fig. 7 The schematic structure of the spindle system. **a** The initial spindle system. **b** The improved spindle system

extracted medium-frequency waviness error information through interpolation. Each position (x, y) of the intermittent cutting trajectory corresponds to a relative cutting time t. Thus, the vibration of the tool-tip that generates the medium-frequency waviness error can be obtained shown in Fig. 2b.

With the indirectly extracted tool-tip vibration, the main source of the medium-frequency waviness error is to be determined by relating the main frequency of the tool-tip vibration with the modals of the structure of the flycutting machine tool. The modals of the structure of the flycutting machine tool were obtained by modal analysis using FEM and modal test. Finally, the relative structure can be optimized to restrain the generation of the medium-frequency waviness error and improve the optical quality.

3 Experiments and discussions

Experiments were carried out on an ultraprecision flycutting machine tool with a maximum cutting diameter of about 650 mm. In this paper, four pieces of flat KDP crystals workpieces (I, II, III, IV) were machined with different flycutting parameters as shown in Table 1. The initial 3D surface topographies of the machined workpieces were measured by a laser interferometer (INF600LP-WM), which has a maximum

Table 2 The result of the modal analysis and test

Mode	Analysis frequency (Hz)	Test frequency (Hz)
1	0.02	0
2	281.5	131.5
3	282.3	202.6
4	379.8	238.1
5	393.3	385.6
6	575.9	555.2
7	647.4	605.5
8	691	664

measurement diameter of 600 mm. The measured results are shown in Fig. 3a, in which the x axis is the cutting direction and the y axis is the feed direction. It can be seen that there exists a periodical waviness error along the cutting direction in the initial 3D surface topographies but not very clear.

A number of parameters have been used to evaluate the properties of the optical surface, such as peak-valley value (PV), root mean square (RMS), and power spectral density (PSD1 and PSD2). PSD analysis provides an accurate evaluation in many occasions [22, 25]. And here, PSD1 is specially selected as a criterion to evaluate the medium-frequency waviness error on machined flat surface in ICF, whose spatial frequency is between 2.5 and 33 mm [26]. Thus, PSD1 was applied to evaluate the medium-frequency waviness error from the measured 3D surface topographies, and the results are shown in Fig. 3b. It can be seen that the waviness existed along both the cutting direction and feed direction, which is clearer than the original measured results. However, only the waviness along the cutting direction is concerned.

A normal wavelet “bior 3.9” was adopted to decompose the measured 3D surface topographies and extract the medium-frequency waviness error along the cutting direction. The wavelet decomposition order is 5, and the extracted results are shown in Fig. 3c. It can be seen that the medium-frequency waviness errors of the machined surfaces of I, II, III, and IV have been effectively extracted by the wavelet method.

Then, the tool-tip vibration that causes the medium-frequency waviness error in four different machining parameters was obtained by adopting the foregoing method. As shown in Fig. 4a, the tool-tip vibration with different cutting-in locations Y are very close to each other, and the tool-tip vibration at the locations near the cutting-in zone is much larger than the other locations. It can be inferred that the tool-tip vibration which causes the medium-frequency waviness error is well obtained and it is caused by the same source.

Figure 4b shows the frequency of the tool-tip vibration at the four sets of machining parameters. It can be seen that the dominant frequencies of the tool-tip vibration at different machining parameters are very close to each other, which are 575.3, 575.3, 578.1, and 568.6 Hz, respectively. That means that dominant frequency of extracted tool-tip vibration is not

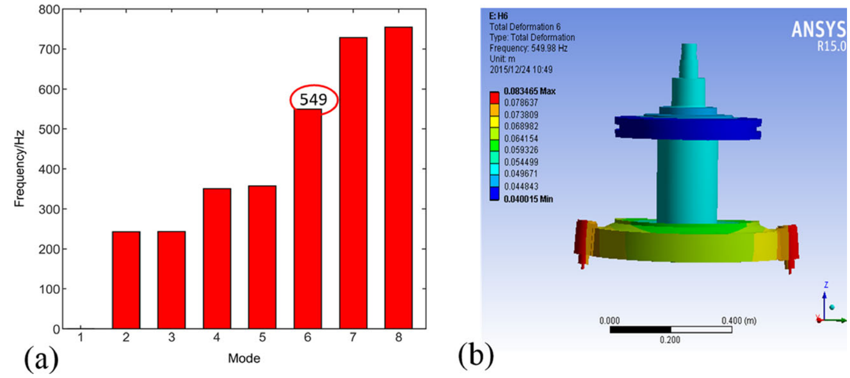


Fig. 8 Modal analysis of the improved spindle system. **a** Modal analysis. **b** Sixth-order modal shape

affected by the spindle speed, the feed speed, and the cutting depth. In the flycutting process, the diamond cutting tool intermittently cuts the workpiece and introduces an intermittent cutting force, which can impact the tool-tip and cause the vibration of the machine tool structure. And then, the vibration will be reflected in the tool-tip and finally influence the profile of the machined surface.

Above all, it can be inferred that the medium-frequency waviness error is mainly generated by the vibration caused by the intermittent cutting force and it is mainly determined by the structure of the flycutting machine tool.

To verify it, modal analysis of the structure of the flycutting machine tool was carried out using both the FEM and modal test method. It is well known that the spindle system plays an important role in the flycutting machine tool and the cutting tool is directly fixed on its edge. Thus, the spindle system was analyzed and tested first. In the FEM analysis of the spindle system, elastic supports were selected to constrain the spindle system, and the axial and radical stiffness were set to 3574.4 and 1670.6 N/μm, respectively. The analysis result is shown in Fig. 5a. It can be seen that the frequency of sixth-order mode is about 575 Hz, which is close to the main frequency of the tool-tip vibration obtained above. In addition, the sixth-order modal of the spindle system is a flexural modal shape and it directly reflects the displacement of the tool-tip along *z* direction, i.e., tool-tip vibration.

Furthermore, modal test was carried out to obtain the dynamic characteristics of the spindle system. An acceleration sensor (ULT2030VB) was chosen to measure the response of the spindle system in the impact test. The test result is shown in Fig. 6. It can be seen that the test result is well repeated in the frequency region of 0–800 Hz, and the amplitude of the sixth-order is larger than other modals. The results of the modal test and the FEM analysis are shown in Table 2. It can be seen that the test result is well consistent with the FEM analysis result. Therefore, it can be inferred that the sixth-order mode of the spindle system plays an important role in the generation of the medium-frequency waviness error.

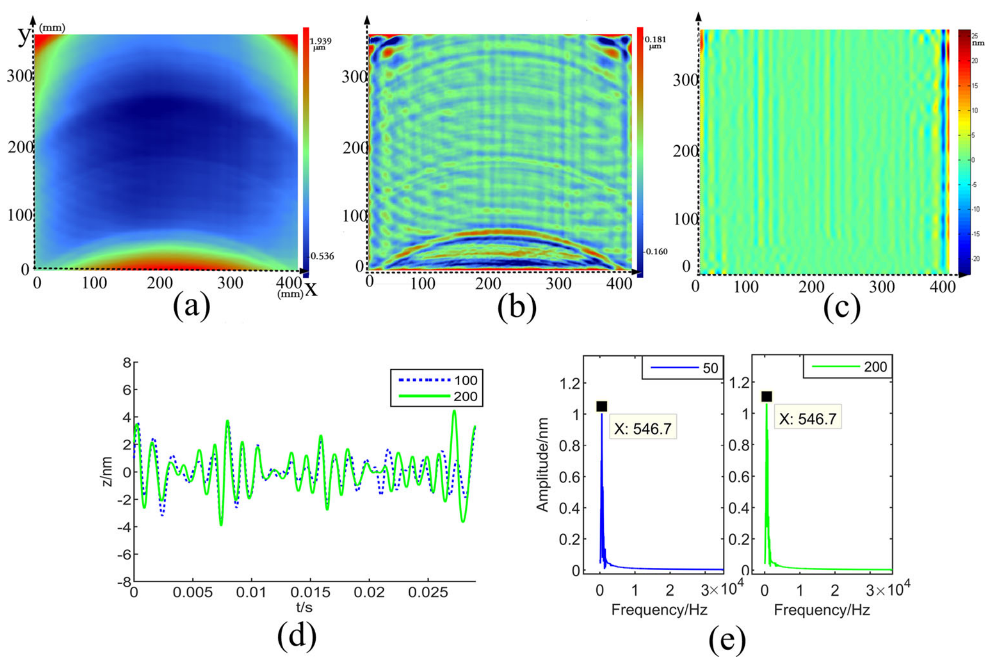


Fig. 9 Results obtained using the improved spindle system. **a** Measured surface topography. **b** Surface topography evaluated by PSD1. **c** Surface topography extracted by the wavelet method. **d** Extracted tool-tip vibration. **e** Frequency of the tool-tip vibration

Therefore, the medium-frequency waviness can be restricted by changing the structure of the spindle system. In order to improve the optical quality of the workpiece, the spindle system structure needs to be optimized to restrict the generation of the medium-frequency waviness error. In this paper, an improved spindle system as shown in Fig. 7b is proposed. The initial flycutting head with step structure as shown in Fig. 7a was replaced by a cone structure flycutting head, and the thickness of the flycutting head was increased. FEM analysis of the improved spindle system was carried out to evaluate its performance. The analysis result is shown in Fig. 8a. It can be seen that the frequency of the sixth-order mode decreases from 575.87 to 549.98 Hz. In addition, from the sixth-order modal shape as shown in Fig. 8b, it can be seen that the influence on the cutting tool decreases due to the reinforced structure of the flycutting head, which helps to restrict the generation of the medium-frequency waviness error.

To demonstrate that, an experiment was carried out on a flycutting machine tool with the improved spindle system. A flat workpiece was machined with the following machining parameters: feed speed of 200 μm/s, rotation speed of 400 rpm, and cutting depth of 10 μm. The measured and analysis results are shown in Fig. 9. It can be seen that the amplitude of the medium-frequency waviness error is decreased. And the main frequency of the waviness error along the cutting direction decreases to 546.7 Hz, which is well consistent with the result of the FEM analysis.

4 Conclusion

An indirect method for investigating the generation of the medium-frequency waviness error by analyzing the 3D surface topography of the machined surface has been presented in this study. The method has been validated by performing machining tests on the different flycutting machine tools with different machining parameters. The following conclusions can be drawn from the study:

- The proposed method that combines the intermittent cutting trajectory of the flycutting and the medium-frequency waviness error extracted from the 3D surface topography using 2D wavelet transform method is effective in indirectly extracting the tool-tip vibration, which provides a good way for investigating the dynamic behavior of the machine tool.
- The change of rotation speed, feed speed, and cutting depth has a little influence on the frequency of the medium-frequency waviness error and thus the relative tool-tip vibration. By comparing the modal analysis results of two different machine tools using FEM method, which was verified by the modal tests, it was found that the medium-frequency waviness error was caused by the tool-tip vibration generated by the sixth-order modal of the spindle system with the frequency of 546.7 Hz.
- Changing the flycutting head of the spindle system from step structure to a cone structure, the effect of its six-order modal is reduced both in terms of amplitude and frequency and thus the medium-frequency waviness error can be reduced which show great coincident with the experiment.

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