Parallel tool servo turning of microstructured surfaces using complementary filters

Hao Wu, ZeLong Jia, MingJun Ren, XinQuan Zhang# and LiMin Zhu

State Key Laboratory of Mechanical System and Vibration, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, P. R. China
Corresponding Author / Email: zhangxinquan@sjtu.edu.cn, TEL: +86-15802107897

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Abstract*: Tool servo diamond turning is a promising technology for machining microstructured surfaces. Since the tool trajectory of complex microstructured surfaces contains a mix of low-frequency and high-frequency components, traditional slow slide servo technology faces challenges in processing quality and machining efficiency, because of the constrained control bandwidth of the large-mass slow slide. Although the current ultra-precision machine tool is equipped with a fast stage to compensate for the tool servo tracking error of the slow slide, the high-frequency spectral components in the trajectory can still cause nonlinear motion errors of the slow slide. Such motion errors are orthogonal to the motion direction of the slow slide and thus cannot be compensated for by the fast stage. To address these issues, this paper proposes the concept of a parallel tool servo (PTS) by integrating a tool decomposition method into the dual-stage machine tool to obtain the high-precision manufacturing of microstructured surfaces. Utilizing the complementary filters, this method decomposes the original tool trajectory into a low-frequency trajectory for the long-stroke slow slide and a high-frequency trajectory for the high-bandwidth fast stage. This tool path decomposition method fully utilizes the dynamic features of the slow slide and fast stage, thus enabling the cooperative operation of the dual-stage machine tool. Compared to the conventional geometry-based trajectory decomposition method, the proposed frequency-based PTS method significantly reduces the form errors of the machined composite microlens arrays, thereby demonstrating the effectiveness and superiority of the proposed PTS approach in producing microstructured surfaces.*

NOMENCLATURE

z_{low} = low-frequency tool path
z_{high} = high-frequency tool path
z_i = the tool path
h_{low} = impulse responses of the low-pass FIR filter
h_{high} = impulse responses of the high-pass FIR filter
z_{base} = base surface trajectory
z_{micro} = microstructure trajectory

1. Introduction

Unlike traditional geometrical optics, modern microstructured optics are composed of a large-depth base surface integrated with intricate microstructures [1]. Due to their multifunctional capabilities and compact design, microstructured optics are increasingly utilized in various fields, including automotive head-up displays, virtual reality, and augmented reality [2]. However, as the demand for higher machining precision and efficiency grows, current manufacturing technologies face significant challenges in fabricating these microstructured surfaces [3]. As a deterministic material removal technology, the tool servo diamond turning process has become the predominant method for manufacturing microstructured surfaces, achieving nanometer-scale surface finishes and submicron-level form accuracy [4].

With the slow slide servo (SSS) of ultra-precision machine tools, the conventional tool servo diamond turning process can position the cutting tool over a wide range. However, due to the large moving mass of the slow slide, the SSS exhibits low machining efficiency when producing microstructured surfaces [5]. Furthermore, while the fast tool servo (FTS) with a high-bandwidth actuator effectively tracks the high-speed trajectory, it struggles to manage the trajectory of a large-depth base surface due to the limited stroke of the fast stage. In summary, the current tool servo diamond turning process faces a trade-off between stroke length and control bandwidth of the single servo axis when machining microstructured surfaces [6].

Therefore, this paper proposes a novel diamond tool servo turning process called parallel tool servo (PTS) turning. This cooperative turning method combines a fast stage with an existing ultra-precision lathe to create a synergistic dual-stage feed drive system. Utilizing complementary filters, the original trajectory is separated into low-frequency and high-frequency trajectories. The slow slide follows the low-frequency trajectory, while the fast stage handles the remaining high-frequency trajectory. A simulation procedure is developed to identify the optimum cut-off frequency. A series of diamond turning experiments are conducted to validate the effectiveness of the proposed PTS method.

2. Parallel tool servo using complementary filters

2.1 Principle of the PTS

As previously discussed, traditional tool servo diamond turning processes assign the complicated trajectory along the depth-of-cut direction to only one servo axis, whether it be a slow slide or a fast stage. This method may lead to issues where the assigned trajectory is not accurately tracked by the single servo axis due to the inherent dilemma between stroke length and bandwidth [7].

Unlike traditional tool servo diamond turning processes that rely on a single servo axis, the proposed PTS method integrates the long-stroke slow slide with the high-bandwidth fast stage to create a dual-stage feed drive system. In this approach, the trajectory is decomposed into two separate paths using complementary filters and then assigned to the respective parallel servo axes. The low-frequency component of the trajectory is allocated to the slow slide, while the left component is managed by the fast stage. This feed drive system enables high-speed, high-precision positioning of the diamond tool across a wide range, fully accommodating the kinematic and dynamic characteristics of the servo axes. Fig. 1 presents a schematic diagram of the proposed complementary filter-based tool trajectory decomposition method for the parallel tool servo turning process.

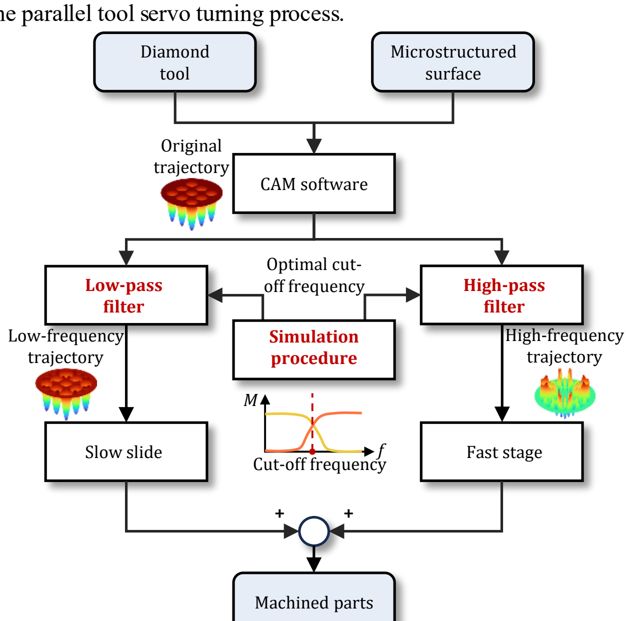

Fig. 1 Principle of the proposed complementary filter-based trajectory decomposition method for the PTS.

Fig. 2 illustrates the configuration of the manufacturing system for the PTS. This system has three translational axes and one rotary axis, including a long-stroke Z-axis (slow slide) and a fast-response W-axis (fast stage). Specifically, the workpiece moves along the radial X-axis and rotates via the tangential C-axis, while the tool oscillates along the depth-of-cut direction, facilitated by the parallel Z-axis and W-axis. Unlike traditional fast tool servo systems that use an independently controlled auxiliary axis, all axes in the PTS system are coordinated under C-axis position feedback control. Detailed dynamic modeling of this system is provided in the authors' previous work [6].

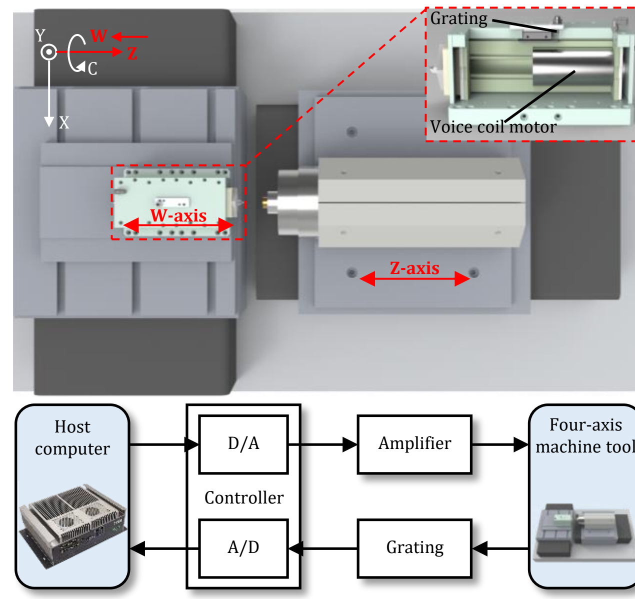

Fig. 2 Parallel tool servo system configuration.

2.2 Tool path generation and decomposition algorithm

In the proposed PTS method, the tool path generation algorithm closely resembles that of the three-axis diamond tool servo turning method. Specifically, this paper adopts a constant angle sampling and steady X tool radius compensation algorithm to generate the tool trajectory (θ_i, ρ_i, z_i). This approach ensures that the reciprocating motion occurs exclusively along the depth-of-cut direction, as detailed in [6]. For this paper, a composite lens array has been designed as the target component, with its structural parameters listed in Table 1.

Table 1 Detailed structural parameters of the microstructured surfaces.

Parameters	Values
Radius of the base surface	3 mm
Depth of the base surface	10 μm
Radius of the sub lens (microstructured surface)	0.5 mm
Depth of the sub lens	10 μm
Spacing between the sub lenses	1.1 mm

Regarding the traditional method of tool path decomposition according to the geometrical features of the microstructured surfaces, the initial tool trajectory can be expressed as follows:

$$z_i = z_{\mathrm{base}} + z_{\mathrm{micro}} \tag{1}$$

Using complementary filters, the initial trajectory can be split into two halves based on its spectral features. These resulting trajectories are represented as the convolutions of the initial tool paths with the impulse responses of the complementary filters [8], as follows:

$$\begin{cases} z_{\mathrm{low}} = z_i * h_{\mathrm{low}} \\ z_{\mathrm{high}} = z_i * h_{\mathrm{high}} \end{cases} \tag{2}$$

To enhance the tracking accuracy of the dual-stage lathe, optimizing the filter parameters is essential, which would be described in Sect. 2.3.

2.3 Complementary filter parameter optimization

Subsequently, the cut-off frequency of the complementary filters should be determined, as illustrated in Fig. 3(a). The optimization procedure is designed to find out the optimum cut-off frequency value, where the peak-to-valley (PV) value of the servo axis tracking errors is minimal, with the associated variations depicted in Fig. 3(b). The results indicate that the optimum frequency for the selected trajectory is 32.4 Hz. Using the determined optimal cut-off frequency, Fig. 4(a) illustrates the decomposed tool path. For comparison, Fig. 4(b) displays the segmented tool path obtained through the geometry-based method. It is evident that, in the traditional approach, the slow slide deals with the trajectory with longer strokes and more energy.

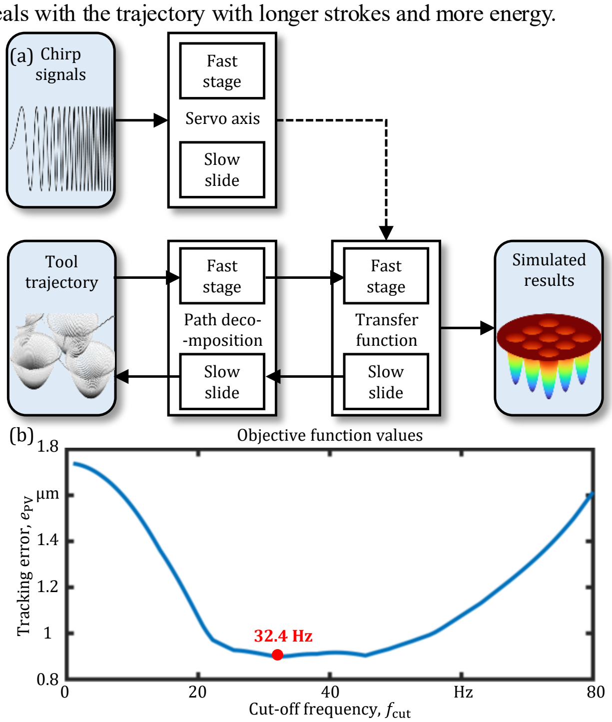

Fig. 3 Complementary filter parameter optimization procedure: (a) simulation procedure, and (b) objective function value variation.

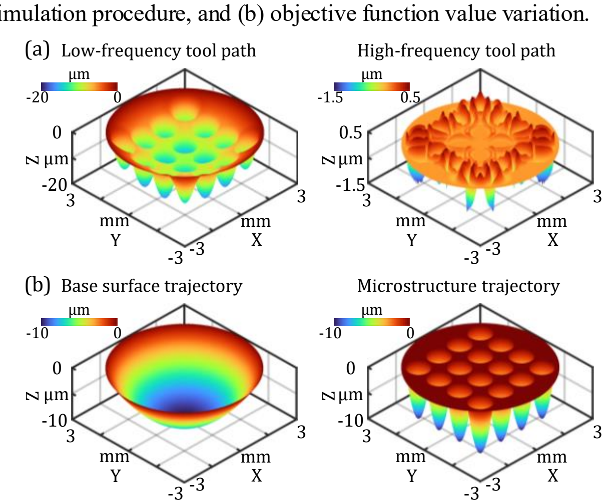

Fig. 4 Tool path decomposition for microstructured surfaces: (a) the proposed frequency-based PTS method, and (b) the geometry-based method.

3. Experimental setup

To validate the effectiveness of the proposed method, composite lens arrays are machined on a self-developed ultra-precision lathe. As depicted in Fig. 5, the high-bandwidth W-axis is driven by a voice coil motor (AKRIBIS, AVM50), and the long-stroke Z-axis is driven by a linear motor (AKRIBIS, AUM3). The brass workpiece is secured to the C-axis using a vacuum chunk, and the round diamond tool, featuring a 0° rake angle, a 0.5 mm tool radius, and a 15° relief angle, is mounted on the W-axis using a specialized jig. To quantitatively assess surface accuracy, the fabricated workpieces are measured using a white light interferometer (ZYGO, Nexview^{TM} NX2). The operational parameters of the machine tool are listed in Table 2.

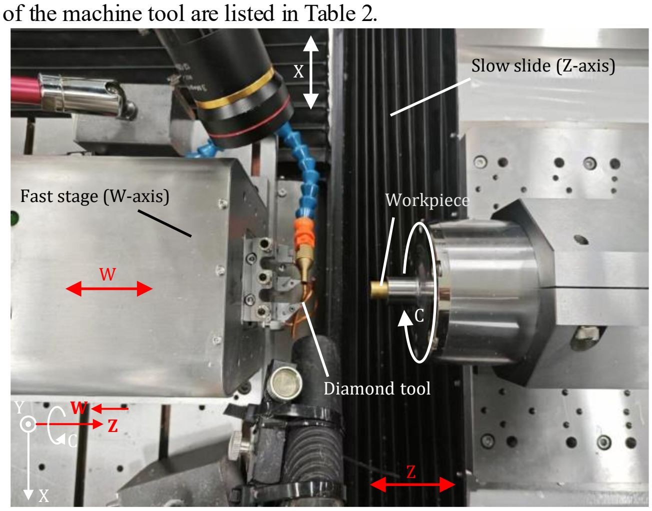

Fig. 5 Experimental setup.

Table 2 Detailed operation parameters of the machine tool.

Parameters	Values
Sampling frequency of the lathe controller	1 kHz
Spindle rotary speed	83 RPM
Feed per revolution	5 µm/rev

4. Results and discussions

The measurement results of the machined microstructured surfaces obtained by an interferometer are shown in Fig. 6. These form errors are determined by extracting the best-fit target surface from the experimentally obtained surface data. It can be observed that the proposed PTS approach significantly enhances the form accuracy of microstructured surfaces compared to the traditional method. The form error of the selected surface generated with the PTS method is 0.98 µm, approximately half of that obtained with the traditional geometry-based method. These results indicate that the proposed PTS method enhances form accuracy through cooperative operation.

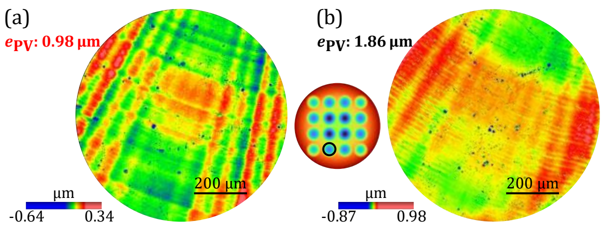

Fig. 6 Measurement results of the machined microstructured surfaces obtained by the white light interferometer: (a) the proposed frequency-based PTS method, and (b) the geometry-based method.

5. Conclusion

This paper proposes a novel complementary filter-based tool trajectory decomposition method for the parallel tool servo turning process, aimed at achieving efficient and precise fabrication of microstructured surfaces. The optimum cut-off frequency for the complementary filters is identified through the proposed simulation procedure. Then, the initial tool path is divided into two paths: the low-frequency path is allocated to the slow slide, and the high-frequency path is allocated to the fast stage. The integrated system and the proposed method are validated through cutting experiments, where composite lens arrays are fabricated using a self-developed dual-stage machine tool. Experimental results reveal that compared to the traditional geometry-based tool path decomposition method, the form errors of the machined parts are significantly reduced, demonstrating the effectiveness and practicality of the proposed method for machining microstructured surfaces with excellent form accuracy.

ACKNOWLEDGEMENT

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