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# Surface finish improvement during single point diamond turning based on in-situ balancing of the spindle with CNC controller

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**Abstract**

Ultra-precision single point diamond turning can realize the machining of complex surface and meet the requirements of high surface finish and high form accuracy. It plays an important role in the machining of precision infrared optics. To improve the surface finish of optical element，a new balancing technique for single point diamond turning machine is developed. Based on the theory model of microstructure, the influences of linear feed axis feed resolution and motorized spindle vibration on surface roughness are analyzed. In order to achieve the nanometre feed resolution, a motion control scheme is designed to optimize the positioning performance of the linear axis. The vibration of the spindle caused by imbalance is measured by the encoder signal of the linear scale. The position of the unbalanced mass is determined by the vibration signal and the zero impulse of the encoder which is integrated in the spindle. The balancing process of the spindle is carried out by adding the needed mass to the balance hole manually. This method do not require vibration sensors and additional measuring instruments, and can achieve the same balance quality as with a commercially purchased balance instrument. The experiment results shown that this method can improve the surface finish of diamond turning significantly.

diamond turning, surface finish, feed resolution, vibration, balancing

## 1. Introduction

Ultra-precision turning technology plays an important role in manufacturing technologies such as optical instruments, semiconductor processing and medical instruments. Surface finish is another important index to reflect the turning surface quality. Infrared optical elements require the turning surface roughness to be nanoscale. The surface finish of ultra-precision turning is related to the geometric parameters of the tool, the amount of cutter and the spindle speed, as well as the relative vibration between the tool and the workpiece.

The tool-workpiece vibration is one of the main factors affecting surface generation [1, 2]. Kim [3], Cheung [4] developed a model for simulating the surface morphology of ultra-precision diamond turning, and analyzed the relationship between vibration frequency and surface morphology. Zhang summarized the influence of tool-workpiece vibration on surface generation of workpiece [5].

The main factors of the tool-workpiece vibration include the vibration of the workpiece spindle system, the fluctuation of cutting force, workbench(feed table) vibration and the vibration of environment. The influence of the above factors on the machining surface quality is complex.

Workbench vibration determines the motion resolution of the linear feed axis. The smaller the motion resolution, the smaller the effective fine interpolation distance of the linear axis, so as to obtain better surface finish and shape accuracy.

When the balance effect of motorized spindle is poor, the relative vibration amplitude between the tool and the workpiece is large, resulting in serious cutter grain and excessive finish on the machined surface. Zhang conducted theoretical and experimental study on the dynamic characteristics of forced vibration caused by spindle imbalance in diamond turning and its influence on surface formation [6]. Melta proved that vibration modes of spindle are orthogonal to each other under certain conditions, which lays a theoretical foundation for the mode balancing method [7].

Federn and Parkinson have carried out in-depth theoretical research on the selection of correction plane and dynamic balance under special working conditions (such as initial bending of the spindle) [8, 9], and their research results can well solve the above problems. Zhang proposed a method for measuring and estimating the unbalanced vector of thin disc workpiece based on the single-side influence coefficient method, and fitted the fundamental frequency component from vibration monitoring signal using the least square method [10].

Harker and Tamura conducted in-depth studies on the influence coefficient method and successfully extended the influence coefficient method to the dynamic balance of flexible rotors [11, 12]. Liu proposed a low-speed holographic balancing method for flexible rotor dynamic balancing [13]. Xu comprehensively used initial phase holographic spectrum method and influence coefficient method to optimize rotor balance by using genetic algorithm [14].

The implementation of dynamic balancing method depends on vibration sensors and additional measuring instruments, which is expensive. Although the commonly used field dynamic balancing instrument can meet the test accuracy, its efficiency is low and can not meet the frequent dynamic balancing operation requirements. At present, based on the existing hardware conditions of machine tool, there is little researche on spindle dynamic balancing using machine data.

In this paper, based on the three-axis ultra-precision single point diamond lathe, a reasonable control scheme is adopted to improve the motion resolution of the linear feed axis and obtain the nano vibration of the workbench. A spindle dynamic balancing method based on real-time position data of NC machine tool is proposed. The relative vibration between tool and workpiece is reduced, and then the surface finish of ultra-precision turning is improved.

## 2. Influence of tool-workpiece vibration on surface accuracy

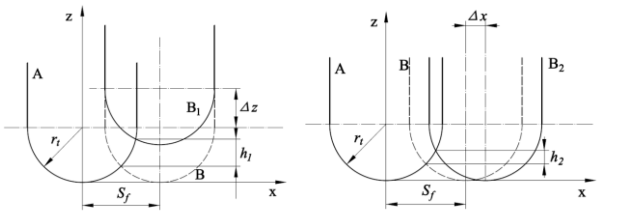
For the three-axis ultra-precision single point diamond lathe, the tool-workpiece vibration locate at X-axis direction and Z-axis direction. The relative vibration in the X direction is mainly caused by the imbalance of the spindle rotor, and the relative vibration in the Z direction is mainly caused by the static characteristics of the Z axis and the axial runout of spindle.

Due to the existence of tool-worpiece vibration in two directions, tool is offset to position B1 and B2 respectively (as shown in figure 1). The h1 and h2 are the contour error values in Z-axis direction and X-axis direction respectively. According to the geometric relationship, the contour error h1 and h2 are:

$$h_1 = r_t \sin\left\{\cos^{-1}\left(\frac{S_f}{2r_t}\right)\right\} - r_t \sin\left\{\cos^{-1}\left(\frac{\sqrt{{S_f}^2+\Delta z^2}}{2r_t}\right) - \sin^{-1}\left(\frac{\Delta z}{\sqrt{{S_f}^2+\Delta z^2}}\right)\right\} \tag{1}$$

$$h_2 = r_t \sin\left\{\cos^{-1}\left(\frac{S_f}{2r_t}\right)\right\} - r_t \sin\left\{\cos^{-1}\left(\frac{S_f+\Delta x}{2r_t}\right)\right\} \tag{2}$$

Where: $r_t$ -- arc radius of tool; $S_f$-- feed rate of tool along X axis per revolution; $\Delta x$-- amplitude of tool-workpiece vibration along X axis; $\Delta z$--amplitude of tool-workpiece vibration along Z axis .




(a) in the Z-axis direction (b) in the X-axis direction

**Figure 1.** Schematic diagram of the influence of tool-workpiece vibration on the surface profile

## 3. Linear axis motion resolution

### *3.1 Linear axis control scheme design*

Motion resolution is influenced by many factors, including the friction of transmission mechanism, displacement feedback resolution, vibration and noise of control system, so this index can reflect the performance of motion system.

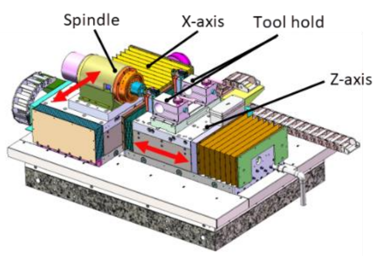



**Figure 2.** Mechanical layout of the single point diamond lathe LDT150

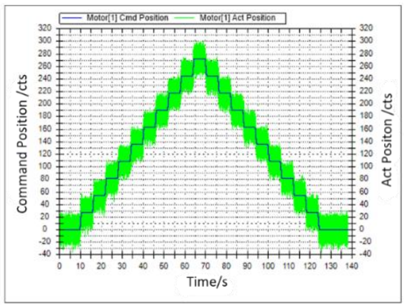
The structure of the independently developed three-axis single-point diamond lathe is shown in Figure 2. The motorized spindle is fixed on the X-axis slide, and the tool holder is fixed on the Z-axis slide. At the same time, the damping and isolation mechanism is installed under the bed to reduce the influence of external vibration on machining accuracy. The linear feed axis adopts hydrostatic guide rail, which forms a hydrostatic oil film between the relatively moving slide block and guide surface, and then uses the linear motor to drive the workbench for feed movement. The linear grating ruler with high resolution is selected as the feedback element of the linear feed axis. The signal period is 0.512µm. The feedback resolution of 0.0625nm is achieved by hardware frequency multiplication subdivision.

In order to meet the requirements of ultra-precision machining, the linear feed axis adopts the full closed-loop control mode. It is difficult for precision optical machining to accept the micro vibration introduced by PWM switching control. In order to reduce the noise of the control system, the linear amplifier is used to drive the linear motor to improve the motion control performance of the linear feed system. In this scheme, the calculation of position loop, speed loop and motor commutation is done by the upper controller, so that the calculation and propagation delay in the loop can be minimized. Thus, higher gain can be obtained by reducing delay, so as to obtain greater stiffness, bandwidth and acceleration capability.

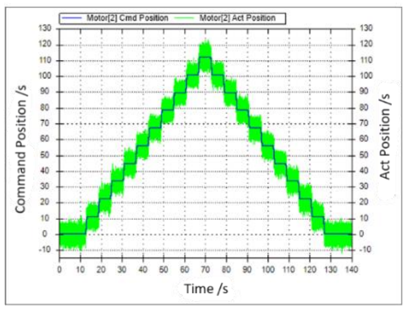
### *3.2 Detection of motion resolution*

The motion resolution of two linear axes is measured by step size motion test. During the test, the workbench first makes 10 step feeds in a certain step in the positive direction, and then makes the same 10 step feeds in the negative direction. After each feed, the workbench stays for 4 seconds.

See figure 3 forThe test data, in which the ordinate unit cts is pulse equivalent, 1cts is equal to 0.0625nm. It can be seen from figure 3(a): when the X-axis movement step is 1.7nm, the step effect is obvious, and the steady-state vibration amplitude of the workbench is about ±1.7nm, indicating that the X-axis motion resolution can reach 1.7nm. For Z-axis, as shown in figure 3(b), when the movement step is 0.7nm, the sampled signal can show a clear step effect. The steady-state vibration amplitude of the table is ±0.5nm, indicating that the motion resolution of Z-axis can reach 0.7nm.




(a) X-axis motion resolution (step size: 1.7nm)



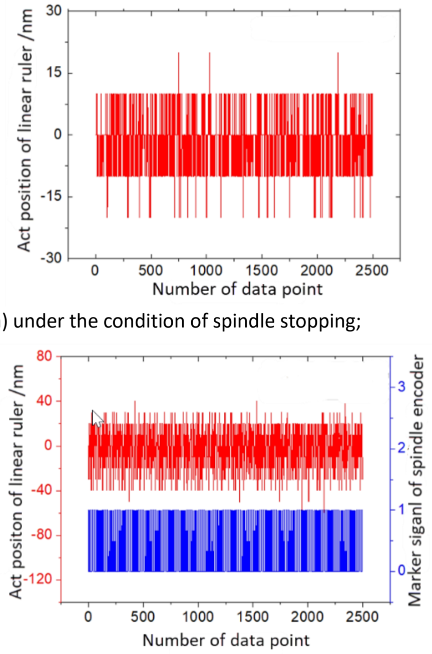

(b) Z-axis motion resolution (step size: 0.7nm)

**Figure 3.** Detection result of linear axis motion resolution

## 4. Spindle dynamic balance method based on real-time position feedback data of NC machine tool

### *4.1 Design of in-position spindle dynamic balance system*

Figure 4 shows the real-time position data curve collected by the X-axis grating ruler in the running and static state of spindle. Through the analysis of the two sets of data, it can be seen that when the spindle is running, there is obvious fluctuation in th position signal output by the grating ruler, and the fluctuatic amplitude increases from 10nm to 30nm.Therefore, the gratir ruler position signal can be filtered to obtain the fundament frequency vibration signal corresponding to the spindle spee so as to evaluate the dynamic balance of the spindle and adju the dynamic balance.




(a) under the condition of spindle stopping;



(b) under the condition of spindle running

**Figure 4.** Real-time position data curve of linear grating ruler

When the spindle is running, the periodic vibration generated by the imbalance is transmitted to linear axis, and the static position of linear axis changes due to the influence of spindle vibration. This change will be reflected in the real-time position data of linear axis as the micro fluctuation of static position. Vibration of the spindle is mainly distributed along the radial direction, therefore, the real-time position of the linear axis with a feed direction perpendicular to the spindle axis can be used to extract the unbalanced amplitude and phase angle of the spindle. The speed of the spindle and reference position of the correction masses can be calculated using the marker pulse (once per revolution) of the spindle measurement system.

In the actual machining process, the spindle vibration of ultra-precision single point diamond lathe is mainly caused by the workpiece reclamping and other reasons. The imbalance is mainly concentrated on the end face of the spindle, mainly manifested as radial vibration, which causes the tool-workpiece vibration along X-axis, and then affect the machining surface finish. Figure 2 shows that the x-axis drives the spindle to feed together, and its motion direction is perpendicular to the axis of the spindle. According to the above introduction, real-time position feedback signal of X-axis can be acquired to evaluate the dynamic balance of the spindle.

As shown in figure 5, the in-situ spindle dynamic balance system software of the NC machine tool is integrated into the NC system. Through the data acquisition interface provided by the NC system, the real-time feedback position of the relev linear axis and the marker pulse of the spindle are collec After analyzing the data, the proposed system outputs correction masses and mounting positions. The CNC contrc used in this study must be a system with openness, ther allowing the proposed balancing system to collect data.

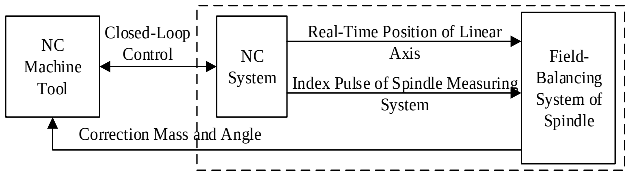



**Figure 5.** Schematic diagram of spindle dynamic balancing system of the machine tool

Figure 6 shows the software interface of the spindle dynamic balancing system, which includes signal acquisition system and software system. The signal acquisition system realizes the acquisition and storage of spindle encoder and linear grating ruler signals. The software system is designed based on LabView to realize real-time data acquisition, data analysis and processing, output theoretical counterweight parameters, realize real-time in-situ balance evaluation and dynamic balance operation of motorized spindle, and expand the intelligent function of NC system. This approach does not need additional sensors and has high integration.

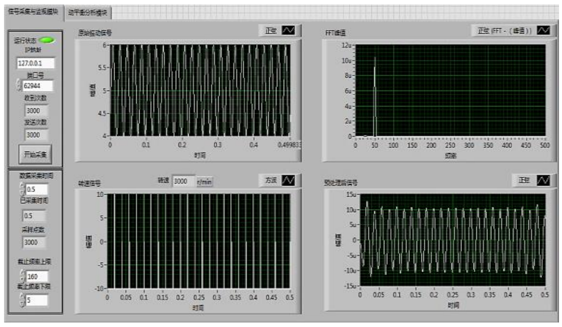


**Figure 6.** User interface for spindle dynamic balancing system

### *4.2 Extraction of spindle vibration amplitude and phase*

The sampling signal contains various noises due to the influence of the fluctuation of the air pressure of the air-floating spindle or the oil pressure of the hydrostatic spindle, and the vibration of the surrounding environment. The adaptive harmonic wavelet filtering method is used to filter the non-fundamental frequency components, so as to effectively reduce the interference of noise and improve the signal-to-noise ratio. Harmonic wavelet has the characteristics of zero phase shift and "box" spectrum. It decomposes and reconstructs the target signal in a specific frequency band, separates it from the original signal, and its data points and sampling frequency remain unchanged to achieve signal filtering and noise reduction.

The calculation of amplitude and phase of vibration signal determines the accuracy of the whole dynamic balance system. In this paper, the cross-correlation method is used to extract the amplitude and phase of spindle vibration. The reference signal and the measured signal are used for cross-correlation processing. There is no correlation between the system noise and the reference signal, and the measured signal and the reference signal are related in the same frequency. Therefore, the influence of noise can be eliminated through the cross-correlation method, and the amplitude and phase of the measured data with the same frequency as the reference signal can be accurately extracted. Figure 7 shows the conceptual diagram of the cross-correlation method [15].

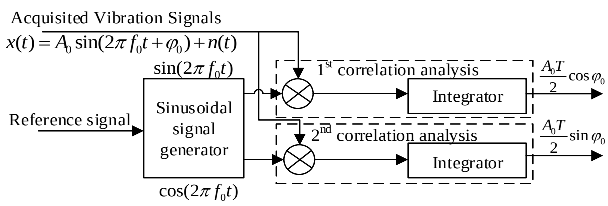


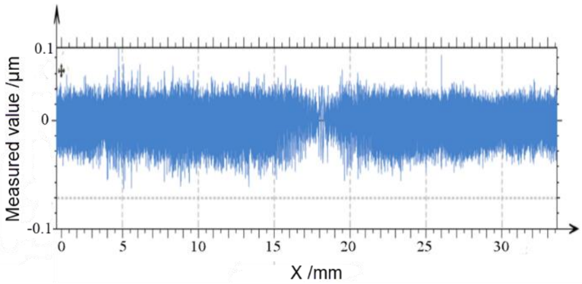

**Figure 7.** Schematic illustration of cross-correlation analysis method

The cross-correlation method has fast calculation speed and can suppress the DC component and noise in the vibration signal. After accurately extracting the vibration amplitude and phase of the spindle, the mass size and installation position of the spindle counterweight block can be obtained according to the single-side influence coefficient method, and the counterweight block can be added.

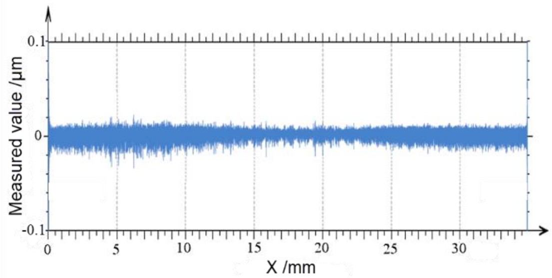
## 5. Experimental research

In this paper, the single variable testing principle is adopted, and the machining test is carried out on the self-developed ultra-precision single point diamond lathe LDT150. The workpiece surface radius is 154mm, the aperture is 34.8mm convex sphere, the workpiece material is germanium. In rough turning, the processing parameters are as follows: spindle speed *n* =2400rpm, cutting depth *ap* =50μm, feed speed *F* =8mm/min; When finishing turning, processing parameters are selected as follows: spindle speed *n* =2400rpm, cutting depth *ap* =5μm, feed speed *F* =4mm/min. The tool radius is 0.981mm, the front tool Angle is -25°, and oil mist cooling is adopted.

Without dynamic balancing adjustment of the spindle, the time-domain vibration amplitude of the spindle is about 360nm, and there are obvious corrugation machining defects on the turning surface of the workpiece, forming clear color lines of light interference. The surface roughness measured by profilometer is 20.2nm, as shown in figure 8(a). After the spindle dynamic balance, the spindle time-domain vibration amplitude is 30 nm, the fundamental frequency amplitude is 8.2 nm, the processing surface has good mirror effect. The surface roughness is 3.97 nm (see figure 8(b)), which meets the nanoscale surface roughness requirement of infrared optical element. Experiments verify the effectiveness of the in-situ spindle dynamic balance method based on real-time position data of NC machine tools.




(a) without field dynamic balancing correction




(b) after field dynamic balancing correction

**Figure 8.** Roughness of the machined surface and

## 6. Conclusion

In order to reduce the vibration of the table, the linear amplification drive control scheme is selected to achieve ultra-precision positioning accuracy and eliminate the micro vibration introduced by PWM switch control. Finally, the motion resolution of X and Z axes is nanometer level, and the steady-state vibration of the table is small. Based on the existing hardware conditions of ultra-precision lathe, an in-situ dynamic balancing method based on real-time position feedback signal is proposed. The real-time online balancing evaluation and dynamic balancing operation of motorized spindle are completed simultaneously without increasing the hardware cost, and the intelligent function of NC system is extended. The machined surface finish is effectively reduced from 20.2nm to 3.97nm through trial machining test, which verified the feasibility of spindle dynamic balancing method based on real-time position feedback signal of NC machine tool.

The above methods can effectively reduce the tool-workpiece vibration, improve the surface finish of ultra-precision turning, and solve the problem of low cost and high efficiency of the current dynamic balance method, which has certain engineering application value.

## Acknowledgements

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