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In situ monitoring and controlling surface shape of the polishing pad in continuous polishing

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Abstract. High-power laser devices have stringent requirements for the surface accuracy of optical elements. Continuous polishing is an effective technique for polishing high-precision optical elements. To overcome the problem of poor real-time capability and low accuracy in traditional surface shape monitoring and controlling methods used in continuous polishing, an online monitoring device is developed to monitor the surface shape of the polishing pad. The experimental results of the online measurement are highly consistent with the offline results obtained using an interferometer. The correctness and feasibility of the online monitoring scheme are well validated. Based on the online monitoring device for the surface shape of the polishing pad, we propose a method of automatic control for the surface shape of the polishing pad. This method maintains the flatness of the polishing pad to 0.05λ (λ = 632.8 nm), peak to valley, as measured on a 100-mm monitoring element through computer control. [DOI: 10.1117/1.OE.57.7.074103]

Keywords: continuous polishing; surface shape of polishing pad; *in situ* monitor and control.

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1 Introduction

Large optical flats with high-precision surface shapes are widely used in high-power laser systems, such as ShenGuang, National Ignition Facility, and laser megajoule.[1–4] These optics not only require a surface figure with high precision but also need specific requirements for the wavefront distortion in the medium and high spatial frequencies. The conventional continuous polishing utilizes a large pitch lap, which usually covers the entire optic surface during the polishing process. This leads to unparalleled superiority in the restraint of medium and high spatial frequency errors relative to other polishing methods, due to the fluidity of the pitch lap. Therefore, to meet the requirements, continuous polishing is generally the last step of the manufacturing process chain.[5] The theoretical modeling analysis and experiments show that the continuous polishing system should be a deterministic system; there exists an equilibrium state that can keep the surface shape of the polishing pad unchanged under stable external conditions.[6] However, due to many uncertain factors in the continuous polishing process, a slight change in technical parameters has a significant impact on the results of the actual polishing process. This causes the traditional technique to have an uncertain processing time and an unstable processing quality, which relies heavily on the experience of the operators. Therefore, developing a technique for online monitoring and controlling the surface shape of the polishing pad based on accurate feedback control using a computer would lead to a process that is more deterministic, allowing optical glass fabrication to be performed in a more effective manner.

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At present, two main kinds of methods for monitoring the shape of the polishing pad in real time are available in the literature. The first kind of method determines the error in the radius of curvature of the surface of the polishing pad while the polishing machine is in operation. In this method, a monitoring element placed on the polishing surface is illuminated by a plano, monochromatic, and coherent light, which is substantially perpendicular to the polishing surface. The two reflected wavefronts from the upper and bottom surfaces are directed to a camera, and the interference fringes that are formed indicate the curvature of the bottom surface of the monitoring element.[7,8] The second kind of method obtains the relative heights of the pad to the reference surface at uniformly distributed locations using a high-precision displacement sensor. Based on the obtained data, the shape of the pad is calculated in terms of the matrices, whose elements represent the heights at the corresponding locations.[9]

In this study, based on the rule that any two parts that are in uniform contact at all locations and having angular orientations with respect to each other must be spherical and the inherent characteristic of continuous polishing, a novel method of online monitoring and controlling the surface shape of a polishing pad is proposed. The feasibility and accuracy of the method are demonstrated by comparison with experimental data of offline measurements obtained using an interferometer.

2 Experimental Principle and Device

2.1 *Principle of Online Monitoring*

The continuous polishing machine consists of a massive rotary table with an annular polishing pad. On one side is a large circular conditioning plate, which is substantially wider than the annulus. On the remaining portions of the

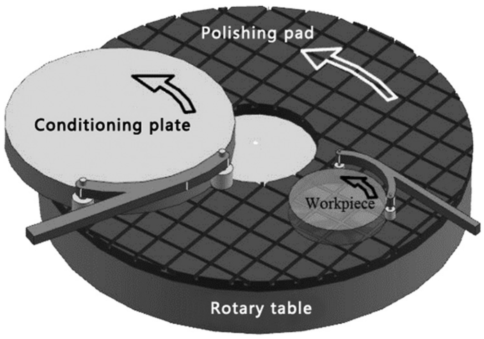

Fig. 1 Schematic of continuous polishing (one workpiece).

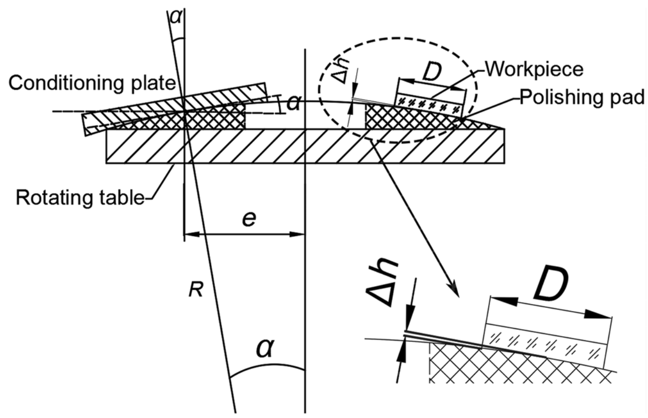

Fig. 2 Schematic diagram of the cross-section structure of the continuous polishing machine.

lap are two to three rings whose inside diameters match the annulus width. A phenolic septum within these rings holds the workpieces, as shown in Fig. 1.

The surface shape of the polishing pad can be adjusted by moving the conditioning plate radially outward or inward. If the conditioning plate is moved radially outward, the resulting increased overhang will cause an increase in the moment, leading to an increase in the linear pressure gradient. This pressure increase at the outer radii will cause the lap to become more convex. An inward movement will similarly result in a moment that tends to make the lap become concave.[10] When the center of the conditioning plate is located near the central region of the belt, the entire surface of the polishing pad will be removed approximately uniformly, and the surface shape of the polishing pad will be unchanged; this state of the system is the equilibrium state. When the workpiece is polished under the equilibrium state, the surface shape of the polishing pad is insensitive to the initial surface shape of the workpiece. If the polishing pad is damaged by the workpiece, it can be completely repaired by the conditioning plate so that the surface shape of the workpiece can stably converge into an ideal shape. This is the ideal working state of continuous polishing.[6,10] To achieve the equilibrium state, reliable online surface shape monitoring is absolutely necessary. Direct surface measurement during operation is not technically feasible due to the presence of slurry on the surface and the relative motion of the pad and workpiece. Therefore, the surface shape of the polishing pad should be monitored indirectly through the measurement of a process variable that is related to the surface shape of the polishing pad and can be measured directly. According to the inherent characteristic of the continuous polishing technology, any two parts in uniform contact at all locations and having angular orientations with respect to each other must be spherical, and the curvature may be positive, negative, or zero.[10,11] It can be considered that the three surfaces of the conditioning plate, polishing pad, and workpiece are spherical with the same radius of curvature.[12] Here, the workpiece is considered as a monitoring element, and the polishing system can be simplified to the model shown in Fig. 2.

The symbols are defined as follows:

D = diameter of workpiece,

e = distance from the center of the polishing pad to the center of the conditioning plate,

R = radius of curvature of the polishing pad,

Δh = peak to valley (PV) value of the bottom surface of workpiece, and

α = horizontal tilt angle of conditioning plate.

The positive and negative angles correspond to the convex and concave surface shapes of the polishing pad. Based on the geometric relations of mathematics, the relationship between Δh and α can be given as

$$\sin\alpha = \frac{e}{R} \quad \Delta h = R - \sqrt{R^2 - \left(\frac{D}{2}\right)^2}. \tag{1}$$

Considering that $\Delta h \ll R$ and $\sin\alpha \approx \alpha$, the equation can be expressed as

$$\Delta h = \frac{D^2 \sin\alpha}{8e} = \frac{D^2}{8e}\alpha. \tag{2}$$

It can be seen from Eq. (2) that if the horizontal tilt angle of the conditioning plate can be accurately measured online, the surface of the bottom surface of the monitoring element can be detected online; thus, the surface shape of the polishing pad can be detected indirectly.

The polishing pad deforms with the weight of the conditioning plate. Owing to the variables between the inside and outside of the polishing pad, the conditioning plate tilts, and the tilting angles vary with the position of the conditioning plate. Therefore, a quantitative analysis of the variables of the pad is necessary to figure out the effects of the angles caused by the deformation of the asphalt. ANSYS is an important tool for performing structural static analysis. With computer numerical calculation and image display, ANSYS can conduct numerical simulations on a system containing relevant physical phenomena, such as stress and deformation. The parameters used in the analysis are shown in Table 1.

The systematic geometric model and the contact element generated by meshing are shown in Fig. 3(a). The calculations after applying the loads and constraints are shown in Fig. 3(b). The calculated results indicate that the deformation at the outer and inner edges of the polishing pad is larger, decreasing from the outside and the inside of the pad to the center of the belt, and the deformation distribution is relatively uniform at the center of the belt. The reason is that the diameter of the conditioning plate is larger than the width of

Table 1 Characteristic parameters of the experiment device.

	Outside diameter (mm)	Inside diameter (mm)	Thickness (mm)	Young's modulus (MPa)	Poisson's ratio	Density (kg/m^3)
Polishing pad	690	220	20	20	0.4	1800
Conditioning plate	350		45	5500	0.25	3070

the polishing belt, the inner and outer protruding portions cause an increase in the moment, resulting in an increase in the pressure at the edges. The length is taken as 5 mm, and an analysis of the distributions of the variables on the surface of the polishing pad caused by the differences in the positions of the conditioning plate is conducted. The variables of the tilting angles of the conditioning plate are shown in Fig. 3(c).

The results show that the maximum tilting angle is $<1.7 \times 10^{-3}$ arc sec. According to Eq. (2), it can be concluded that, for a workpiece with a caliber of 100 mm, the error caused by the deformation of the asphalt is $<7.2 \times 10^{-5}\lambda$, and the error can be ignored.

A schematic diagram of the experimental device is shown in Fig. 4. A reflector with a diameter of 100 mm (PV $< 0.1\lambda$) and having a two-dimensional (2-D) adjustment frame was fixed at the center of the conditioning plate. A high-precision goniometer, connected with the light source through a light guide fiber, was fixed above the reflector using a mechanical support. When there is a slight change in the angle at the reflector, the reflected light also produces a difference angle, and the image spot on the photosensitive surface of the charge coupled device detector generates an offset. Thus, the real-time variation in the inclination angle of the reflector can be measured and recorded in real time by using the computer analysis software.

The goniometer used in the experiment was independently developed by our researchers. The picture and main performance parameters are shown in Fig. 5 and Table 2, respectively. When the conditioning plate is located near the center of the polishing annulus ($e = 0.2275$ m and the diameter of the monitor element $D = 100$ mm), the theoretical calculation shows that the accuracy of PV value Δh can be better than 0.1λ.

The goniometer can only measure the relative change in the angle instead of the absolute value of the angle. The angle measured by the goniometer does not truly reflect the surface shape of the polishing pad; therefore, the system needs to be

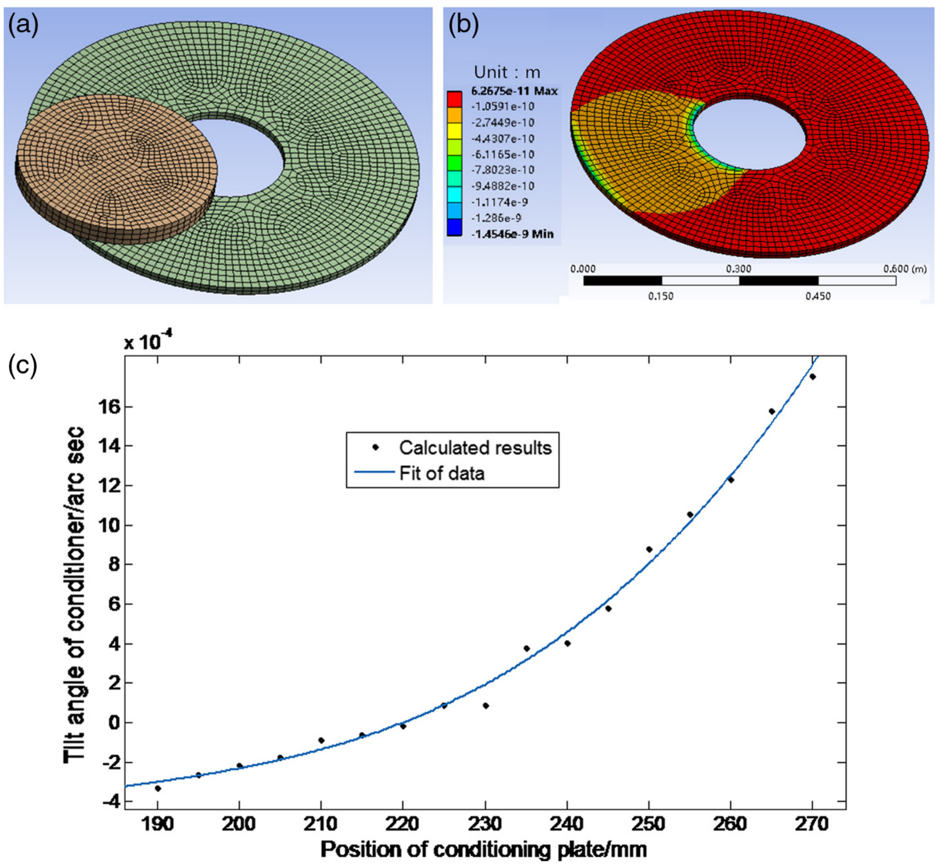

Fig. 3 Results analyzed using ANSYS software: (a) simplified model and meshing for continuous polishing, (b) deformation distribution of the surface of the polishing pad, and (c) relationship between the tilt angle of the conditioning plate and the eccentricity of the conditioning plate.

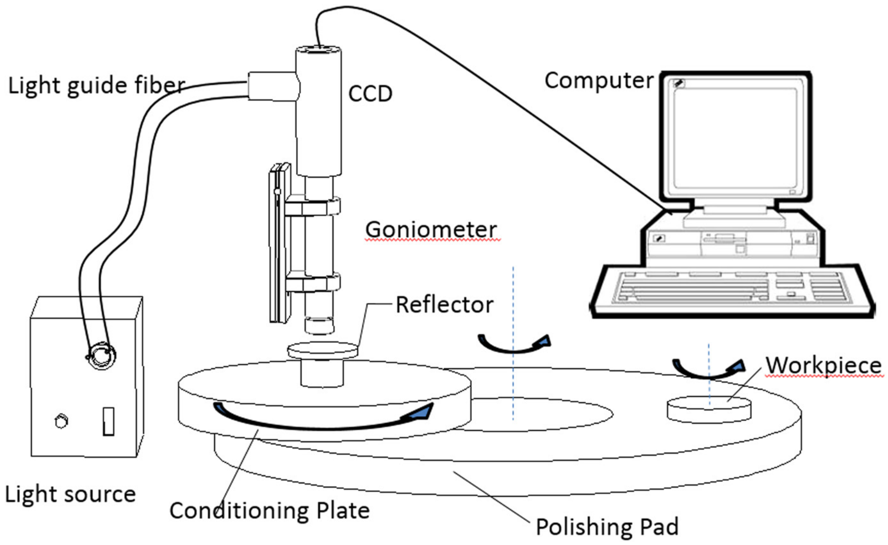

Fig. 4 Schematic diagram of the experimental device.

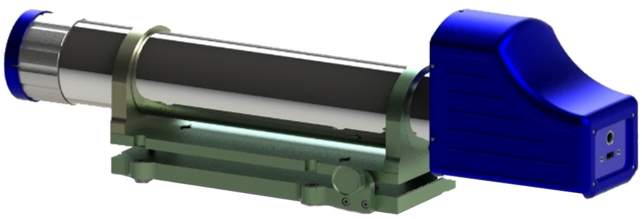

Fig. 5 Picture of the high precision goniometer.

Table 2 Performance parameters of high-precision goniometer.

Focus length	500 mm
Effective aperture	70 mm
Measuring range	0 to 950 arc sec
Resolution	0.01 arc sec

calibrated before use. In this study, the Zygo interferometer is used as a standard equipment to measure the actual surface shape of the monitoring element. The goniometer measures the corresponding angle value to obtain the calibration curve, which can be used as the basis of measurement. The angle measured by the goniometer can reflect the surface of the polishing pad accurately after calibration.

2.2 *Adjustment Rules of Surface Shape and Method of Automatic Control*

The automatic control of the surface shape of the polishing pad includes the adjustment of the surface shape and the long-term maintenance of the ideal surface shape. The adjustment of the surface shape in continuous polishing is achieved by moving the conditioning plate. The surface figure of the pad is determined by the material removal distribution; the material removal in continuous polishing has been historically described by the widely used Preston equation [13]

$$H = C \int_{T_n}^{T_{n+1}} PV\mathrm{d}t = C \int_{T_n}^{T_{n+1}} P\mathrm{d}S, \tag{3}$$

where H is the change in thickness value of the polishing pad at a given point in a cycle, C is a proportionality constant, P is the pressure over the contact area, V is the relative velocity, t is the conditioning time, S is the relative sliding distance on the polishing pad, and $T_n \sim T_{n+1}$ is the cycle, respectively. The relative sliding distance can be calculated by using geometric relations. The Winkler's hypothesis can be used to determine the contact pressure, owing to the small thickness and the grooves in the surface of the lap, it can be written as follows:[14]

$$P = k \cdot Z, \tag{4}$$

where P is the contact pressure, Z is the deformation in the thickness of the lap, and k is the elastic coefficient, which can be expressed as the ratio of the Young modulus to the thickness of the lap.

Taking into account the force balance and torque balance of the conditioning plate and the workpiece, the distribution of contact pressure can be calculated according to Eq. (4); then, the material removal in the polishing lap surface can then be established. To simplify the calculation, the contact pressure is assumed to be remain constant in a cycle, and the surface shape is modified at the end of the cycle. The contact pressure is then updated according to Eq. (4). The amount of the material removed in each cycle is calculated by repeating the Eqs. (3) and (4).

Figure 6 shows the simulation results (using computer) based on the above model. The horizontal axis represents the distance between the center of the conditioning plate and the polishing lap, whereas the vertical axis represents the change speed of the surface shape of the polishing pad (with a change to a concave surface when the axis is positive and a change to convex surface when it is negative). According to the calculation results, the basic rules of the surface adjustment of the disk surface are obtained as follows. (1) If the conditioning plate is not moved, the surface PVs of the polishing lap will change at a constant speed.

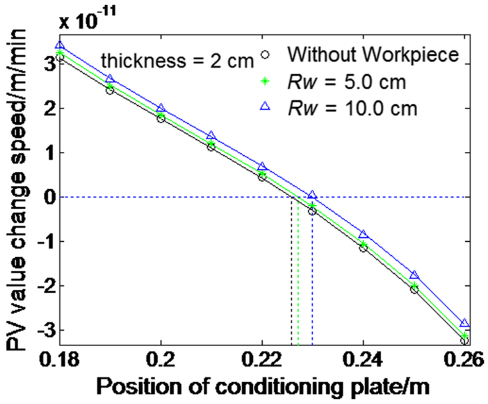

Fig. 6 Relationship between the change speed of the pad surface PV value and the eccentricity of the conditioning plate.

(2) An equilibrium state exists in the system, indicating that the surface shape could remain unchanged, and the surface shape could be flat or spherical with a small curvature.[15] In the equilibrium state, the position corresponding to the conditioning plate is called the equilibrium position of the system, that is, the surface change speed of the polishing pad in the figure is zero. However, it is worth noting that the equilibrium position of the system is different under different working conditions, as can be seen in Fig. 6 (*Rw* in the figure denotes the radius of workpiece). (3) The characteristic curve has the same shape under different conditions; however, a certain shift occurs in the direction of the vertical axis. Therefore, only the relationship between the change rate of polishing and the eccentricity in a working condition needs to be measured experimentally and saved into the computer. When the working condition changes, the surface change rate of the polishing pad can be measured using the online monitoring system under the new working condition. The new characteristic curve under the new working condition can be deduced and the new equilibrium position of the system under the new conditions can also be established.

A computer is used to control the surface of the polishing pad according to the program flowchart (shown in Fig. 7), which is based on the above rules. Here, $\alpha(t)$ denotes the horizontal inclination angle of the conditioning plate, β denotes the allowable error, e denotes the eccentricity of the conditioning plate, e_1 and e_2 represent the innermost and outermost positions of the conditioning plate on the radially adjustable range of the polishing pad, and e_{eq} represents the equilibrium position of the system, respectively. When the system operating parameters of the system are set correctly, the horizontal inclination of the calibration plate is detected in real time. If $|\alpha(t)|$ is greater than the allowable error β, and the angle changes evenly over time, it means that the surface of the polishing pad, conditioning plate, and the workpiece has been matched with each other. However, the surface figure does not meet the requirement of processing accuracy yet; therefore, we need to calculate the rate of change of the inclination angle and the change rate of the surface shape under such conditions. The equilibrium position e_{eq} of the system can be obtained according to the basic characteristics of the polishing system. When the angle is equal to zero, it indicates that the surface shape of the polishing pad has attained a good value; the conditioning plate

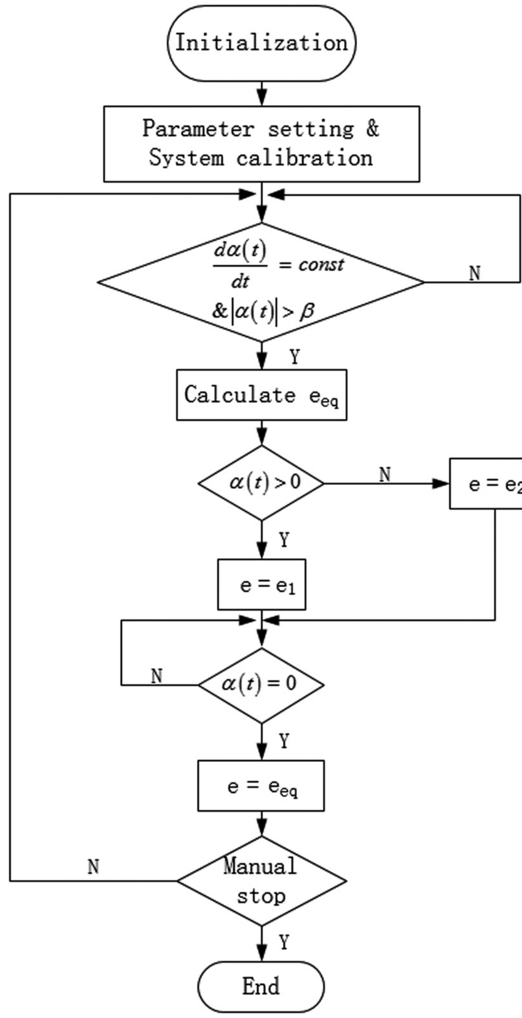

Fig. 7 Flow chart of the automatic control program for surface shape.

should be pushed to equilibrium position of the system to keep the ideal shape for a long time. Otherwise, the conditioning plate would be pushed to the outermost or innermost side in the radial direction area of the adjustable range by the automatic actuator, depending on whether the surface shape is concave or convex.

3 Experimental Results

In the experiments, the material of the pad consists mainly of the Xi'an #66 polishing pitch produced in China with some additives, such as beeswax and plastic powder; its thickness is 18 mm, and a square mesh is used in the lap. The squares have edges of 3.0 cm separated by grooves 3 mm in width and 2 mm in depth. Two monitoring components are placed on the disk. A 1% concentration, water-based CeO_2 polishing slurry is added every 5 min, 30 mL a time. The conditioning disk is made of "Jinan Green" stone, sourced from Shandong, China. This is a kind of granite with high stability and low coefficient of thermal expansion. The temperature is maintained at 25°C, and the relative humidity in the polishing workshop is 60%. The size of the continuous polishing machine used in the experiment is shown in Table 1, and two different workpiece parts are arranged as the monitoring elements. The diameters of workpieces are 100 and 45 mm, and

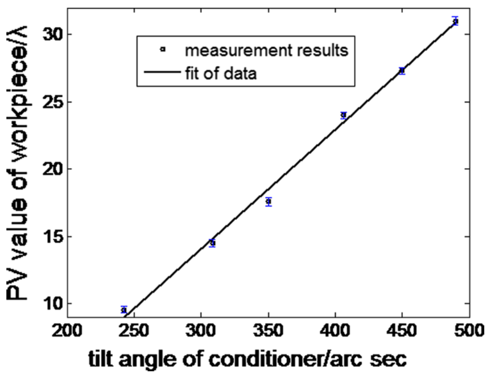

Fig. 8 Relationship between the PV value of the workpiece and the measured inclination.

the thicknesses are 20 and 15 mm, respectively. The material of workpieces is fused silica glass.

To improve the measurement accuracy of the system and to reduce the influence of the system installation error on the measurement accuracy, the system needs to be calibrated before the experiment. The inclination measured in this experiment refers to the inclination of the conditioning plate relative to the horizontal plane. However, it is difficult to determine the position of absolute horizontal plane; therefore, any plane is set as the reference plane in the experiment, and the angle between the plane and the horizontal plane is α_0. Therefore, Eq. (2) should be corrected to Eq. (5)

$$\Delta h = \frac{D^2}{8e}(\alpha_\mathrm{m} + \alpha_0), \tag{5}$$

where α_m is the tilt angle of the conditioning plate relative to the reference plane measured by the goniometer. The relationship between the PV value of the workpiece and the measured inclination is shown in Fig. 8. The linear fit equation is $\Delta h = 0.08871(\alpha - 141.8104)$,
i.e., $\alpha_0 = -141.8104$ arc sec.

The conditioning plate, polishing pad, and monitoring element are set to rotate at the same speed (the absolute speed is 3 ± 0.05 r/min), the sampling period is set to 1 s, and the inclination of the conditioning plate is measured continuously. The machine will be shutdown and the surface of the polishing pad will be scratched manually at 9:00 am every day. At the same time, the Zygo interferometer is used to measure the actual surface shape of the monitoring elements. The measurement results for 10 consecutive days are shown in Table 3.

Figure 9(a) shows the results measured online with the goniometer. A large amount of the high-frequency interfering signal is mixed in the raw signal of online monitoring, such as the interference caused by the vibration of the machine, the periodic interference signal due to the spindle is not strictly perpendicular to the table. The partially enlarged signal is shown in Fig. 9(b). In the actual processing, the change rate of the surface shape of the polishing pad and the workpiece is very slow; therefore, the frequency of the useful signal is much smaller than that of the interfering signal. To recover the slowly changing angle signal, then raw signal is processed with an fast Fourier transform (FFT) to obtain the frequency spectrum, which is shown in Fig. 9(c). The cutoff frequency is taken as 5×10^{-4} Hz. The recovered signal filtered after the low pass filter is shown in Fig. 9(d); the series of spike signals are caused by the timing shutdown for scratching the polishing pad every day.

The surface shape of the polishing pad can be calculated theoretically according to the signal of the tilt angle of the conditioning plate with respect to time, combined with the actual operation of the experiment parameters shown in Table 3 and Eq. (5). Figure 10 shows the relationship between the theoretical value and the actual measurement value obtained using the Zygo interferometer; the negative values in the figure indicate that the surface shape of polishing pad is concave spherical.

It can be seen from Fig. 10 that for the monitoring element with $D = 100$ mm, there is some deviation between the theoretical curve and the actual measured value for the first three days because the monitoring element and the polishing pad were not matched completely. Three days later, the monitoring element and the pad became matched with each other. The online test curve is in good agreement with the offline test curve. Form the figure, it can be seen that for the monitoring element with $D = 45$ mm, the surface shape of the workpiece had only changed slightly in the first three days. The reason for this is that the contact area between the workpiece and the polishing pad was very small due to the smaller curvature of the convex sphere of the workpiece and the bigger curvature of the concave sphere of polishing pad. In addition, considering the effect of fluid mechanics on the slurry between the workpiece and the polishing pad, the mass of the element is very small, and the monitoring element is almost floating on the top of the polishing pad; therefore, the material removal rate is quite low. Starting from the third day, the surface shapes of the element and the polishing pad began to match each other due to the decrease in the curvature of the polishing pad. From Fig. 10, we can see that there was a noticeable change in the surface shape of the workpiece. The online measured and calculated curves are clearly in good agreement with the offline measurement from the fifth day. Thus, the feasibility and correctness of the online monitoring program have been validated.

Table 3 Measured results for 10 days.

Day	1	2	3	4	5	6	7	8	9	10
e (mm)	185	175	175	175	175	175	175	175	200	200
PV (D = 100 mm)(λ)	4.171	5.976	7.124	11.934	14.515	17.575	24.000	31.030	35.061	38.053
PV (D = 45 mm)(λ)	3.192	3.040	3.180	3.006	3.315	3.489	4.608	5.896	6.803	7.106

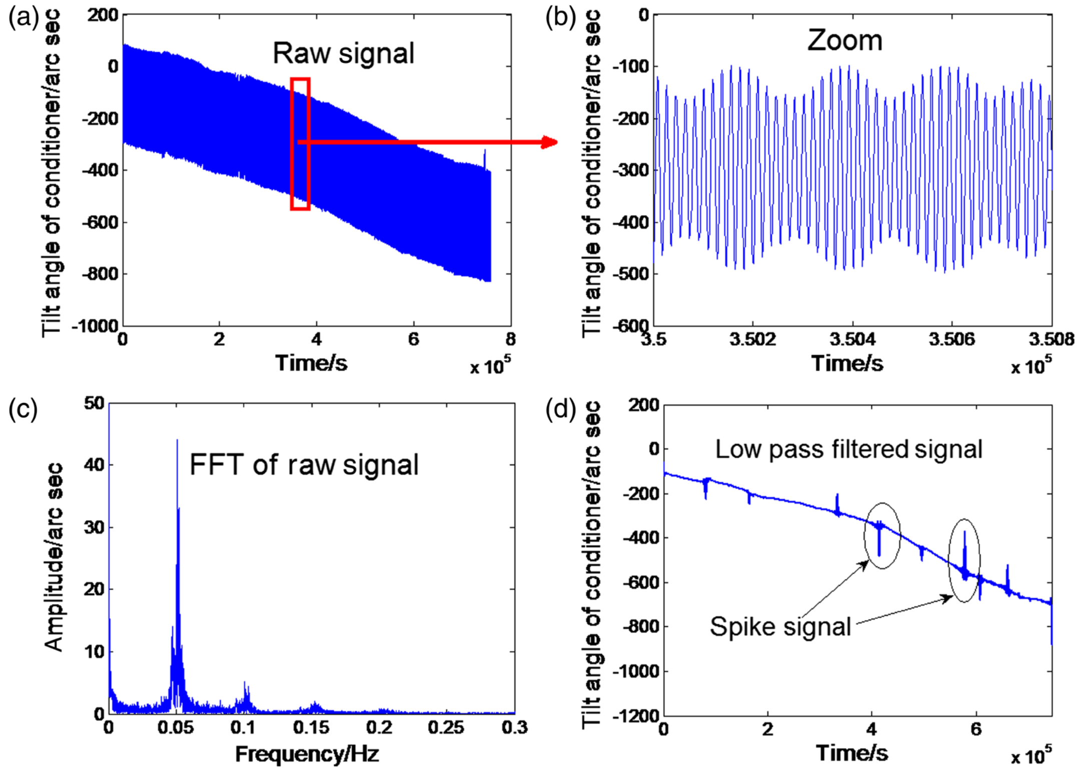

Fig. 9 (a) Raw signal, (b) drawing of partial enlargement, (c) FFT of raw signal, and (d) low pass filtered signal.

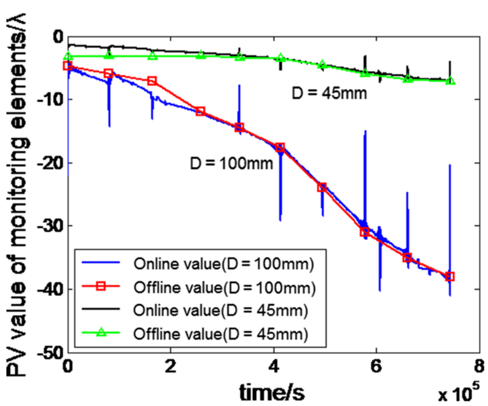

Fig. 10 Comparison of online and offline measurements of the surface shape of the workpiece.

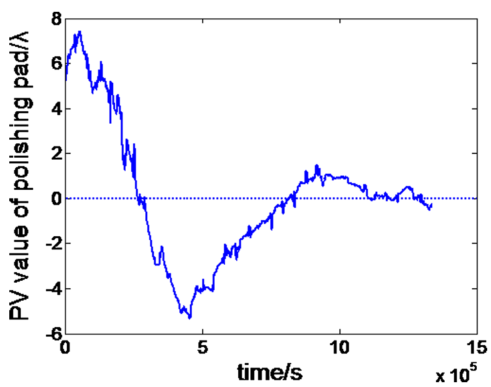

Fig. 11 Changes in the surface shape of the polishing pad through computer control.

Figure 11 shows the experimental result of the automatic adjustment of the surface shape of the polishing pad through computer control. The surface shape of the polishing pad converges stably. The surface shape of a workpiece processed by such a polishing pad is shown in Fig. 12. It must be noted that the surface of the polishing pad will have a slight fluctuation after a long period of time due to the changes in environmental and other factors. If the fluctuation range exceeds the preset permissible error, the surface shape of the polishing pad still should be repaired according to the computer control flow to achieve another optimal plane.

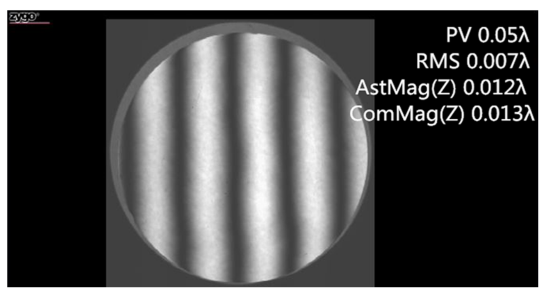

Fig. 12 Surface shape of monitoring element ($D = 100$ mm).

4 Summary and Conclusions

In this paper, we established a simplified model of continuous polishing and chose the tilt angle of the conditioning plate as the characteristic parameter. An online surface shape monitoring and controlling system with a high-precision goniometer has been demonstrated successfully. Compared with the traditional offline monitoring method, our new method ensures that the surface shape of the polishing pad converges stably without the need for an interferometer with a large diameter to measure the surface shape of the monitoring element frequently. Experimental results show that the surface shape of the polishing pad measured offline by a Zygo interferometer is highly consistent with the online monitoring results. The surface shape of the polishing pad converged in only a few iterations to 0.05λ, PV, as measured on a 100-mm monitoring element without human intervention. The accuracy of the system can meet the processing requirements very well in continuous polishing.

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