In-situ fast measurement of grinding wheel wear and compensation of wheel profile error

F.Fan[a *], L.M.Xu[b], Z.Zhang[c], X.J.Chao[d], W.C.Fan[e] and L.Shi[f]

School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China country

[a]m18817819218_1@163.com, [b]limingxu@sjtu.edu.cn, [c]sjtuzhangzhe@foxmail.com, [d]chaoxujia@outlook.com, [e]fanweicheng@sjtu.edu.cn, [f]shilun@sjtu.edu.cn

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Abstract. In-situ measurement of grinding wheel profile is of great significance for monitoring grinding wheel wear and wheel dressing accuracy. But it is difficult to achieve the application in engineering due to the poor machining conditions. In this study, a novel method for in-situ rapid vision measurement of grinding wheel profile and detection of wheel wear was investigated based on a digital profile grinding machine. An in-situ vision measuring system of grinding wheel profile was designed. The methodology for precision measurement of wheel profile and quantifying assessment of wheel wear was proposed. The reliability and measurement accuracy were experimentally testified. Finally, a segmented characterization of wheel profile error and error compensation method was proposed for wheel dressing process. The experimental results indicated that the proposed methodology can achieve in-situ fast measurement of grinding wheel wear, and the dressing accuracy of the wheel profile was effectively improved by using the proposed method.

1. Introduction

The demand for parts with complex contour curves increases rapidly with the development of manufacturing industry. This kind of parts is usually finished by precision profile grinding. The truing accuracy of grinding wheel will have a great influence on the contour accuracy of the machined parts. Hence, it is of great significance to quantitatively monitor grinding wheel wear and wheel truing accuracy in profile grinding.

Many studies have investigated the measurement of abrasive wheel profile and wheel wear. Furutani et al. [1] proposed an in-process method for measuring topography of grinding wheel by using hydrodynamic pressure. Further, pressure based automatic compensation for grinding wheel wear was developed to reduce the dimensional error [2], but it should work in wet grinding and it is not stable. Vibration and acoustic emission sensors are usually adopted. They can form a multiple sensor system and finish a sensor integration based judgement [3] or work independently to monitor the wheel condition [4]. In comparison, direct measurement method was seldom used in in-situ detection of wheel profile or wheel wear. Fan et al. [5] presented an in-situ and non-contact method for measuring the wear of grinding wheel with a CCD based vision system. Lachance et al. [6] developed an optical system mounted on the grinding machine to measure the wear flat of wheel surface and evaluated the state of wheel wear.

The paper is organized as following: Section 2 introduces the principle of profile grinding based on vision oriented open CNC. The design methodology for vision oriented CNC is proposed in section 3, which covers the hardware architecture and the software characteristics.

The experiments were conducted in section 4 to verify the effectiveness of the proposed methodology. Section 5 concludes the paper and the potential application of the findings.

2. Structure principle for in-situ measurement of wheel profile

The structure diagram for in-situ vision measurement of wheel profile in profile grinding was shown in Fig. 1. The grinding wheel was mounted in the electrical spindle, which can be servo controlled up and down along *Z* axis and servo driven along *U* and *V* axes in the horizontal plane. The workpiece was setup on the workbench, which can be servo driven along *X* and *Y* axis respectively. O_1-*XYZ* forms the workpiece coordinates. O_2-*UVZ* forms the tool coordinates and the wheel profile measurement coordinates as well.

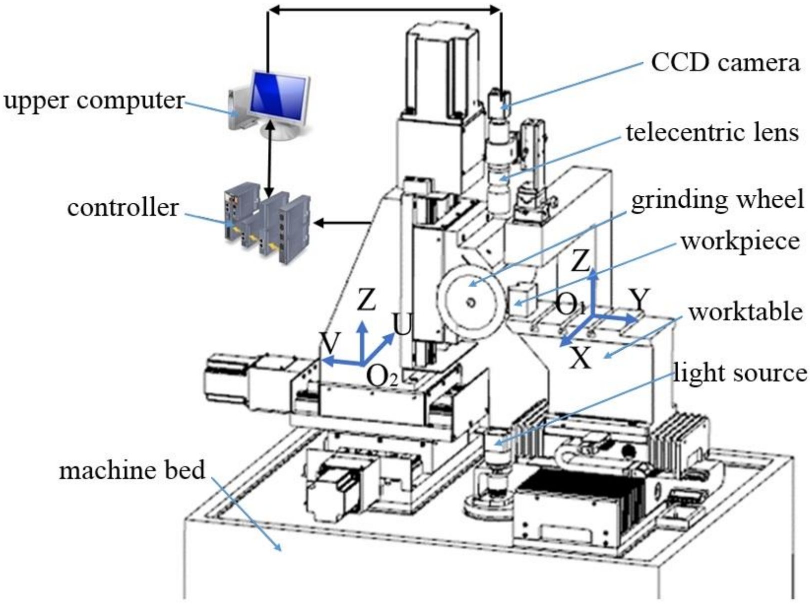


Fig. 1 Structure diagram for in-situ vision measurement of wheel profile in profile grinding

In the case of measuring the wheel profile or detecting the wheel wear, move the grinding wheel away from the workpiece and stop running of the spindle. The wheel can be controlled to move into the central field of camera view, and then be servo adjusted along *Z* axis to ensure the measured wheel profile in the scope of the depth of field. The image acquisition can then be triggered and the clear wheel edge profile can be captured.

3. Methodology of in-situ measurement of wheel wear

3.1 Experimental design

In the vision system, the camera model is GC2441M. It is characterized by 2/3" CCD in size, 15fps in frame rate, 5 mega-pixels in resolution. The telecentric lens is characterized by 0.02% in distortion, 3mm in depth of focus, 150mm in object distance and 0.5 in enlargement factor. The light source is blue LED and parallel back light with 5W in power.

In order to measure the wheel profile, a high-quality image of wheel profile should be firstly captured by the vision system. Then Edge detection of wheel profile was conducted based on Canny operator.

Due to that one shot can only capture one image of wheelprofile in section at certain circumference position, the test was designed to measure the wheel edge profile at different positions by rotating the wheel an equal angle each time. The different wheel profiles can be obtained and the corresponding profile parameters can be calculated and analyzed.

The typical grinding wheel used in profile grinding is a thin double bevel wheel with circular edge in section. Its profile is composed of two oblique lines and one arc. In order to fit the curve of the wheel profile based on the extracted edge pixels, a contour segmentation algorithm was developed. The edge pixels were divided into three parts corresponding to the geometric features of edge profile. The lowest edge point can be located and the edge points for arc can be defined and fitted to calculate the arc center. Further algorithm can be developed to calculate the intersections $P_1(x_1,y_1)$,$P_2(x_2,y_2)$ of line L_1, L_2 and arc, which is also the point of tangency. The center point of arc is $O(x_0,y_0)$ and the lowest point of arc is $P(x_p,y_p)$.

The central angle α can be calculated by Eq. 1

$$\alpha=180° - (\beta1+\beta2) \quad (1)$$

where $\beta1$ and $\beta2$ are the included angle of centerline L and $L1$, $L2$ respectively.

The curve fitting results based on least square method is shown in Fig.2 for a wheel edge extraction case.

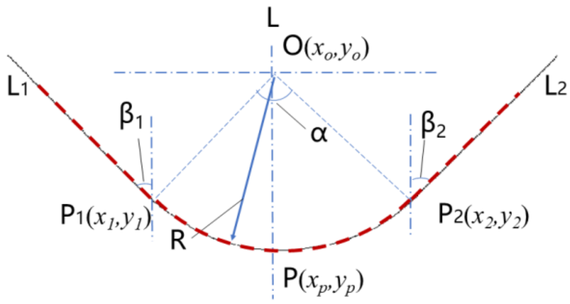


Fig. 2 Edge extraction and curve fitting for wheel profile

The wheel profile parameters should be designed first according to the profile feature of the workpiece and the wheel can be dressed accordingly. The parameters can then be measured based on the presented method. The wheel edge contour in each radial section can be compared with theoretical one and the wheel profile accuracy can be synthetically evaluated.

3.2 Experimental results

Multi-section contour measurement tests for grinding wheel were conducted. The grinding wheel profile in each section was captured every 45° wheel rotation and the according profile parameters were measured. The results of calculated profile parameters as well as the mean values and ranges are listed in table 1.

By analyzing the data in table 1, it can be found that the max-min for arc center coordinates x and y were 0.001mm and 0.011mm respectively, which indicated that there exited certain radial runout error of spindle. The average of roundness errors in different radial sections is 0.022 mm and the max-min is 0.004. The max-min of arc radii in different radial sections is 0.009 mm and the standard deviation is 0.003 mm. It indicated that the contour shapes of different sections were highly consistent. It can be explained that the wheel dressing and grinding are based on one installation, which avoids repeat positioning error and also eliminates the effect of spindle runout error on the shape of different radial section contours, i.e., ensures the consistency of different sectional contours. Therefore, the envelope profile parameters of grinding wheel can be obtained by measuring any contour of wheel radial cross section in the case of in-situ visual profile measurement.

Table 1 Wheel profile parameters in radial sections of different wheel rotational angles

Rotational angles [°]	Arc radius R[mm]	Circle center O x_o	y_o	Central angle α[°]	Roundness error [mm]
45	2.146	7.339	7.711	90.27	0.023
90	2.144	7.339	7.716	90.42	0.022
135	2.151	7.339	7.722	90.41	0.024
180	2.150	7.338	7.722	90.36	0.021
225	2.146	7.338	7.719	90.22	0.020
270	2.142	7.338	7.718	90.37	0.021
315	2.147	7.338	7.720	90.40	0.024
Mean value	2.147	7.338	7.718	90.35	0.022
Max-Min	0.009	0.001	0.011	0.20	0.004

4. Precision assessment of in-situ measurement of wheel profile

4.1 Methodology of precision assessment

Board duplication method was adopted to verify the in-situ vision based measuring accuracy. The board made of carbon fiber was firstly fixed on the worktable. The grinding wheel rotated and ground the carbon fiber plate up and down along Z axis while feeding at a certain speed along V axis as shown in Fig. 1 until the entire wheel edge profile was duplicated to the board.

The duplicated wheel profile in the board contains the information of all contours in different radial section of wheel edge, which represents the envelope profile of the grinding wheel. The profile parameters can be obtained by measuring the profile duplication. In the experiment, the board is 5mm in thickness with duplicated profile shown in Fig. 3.

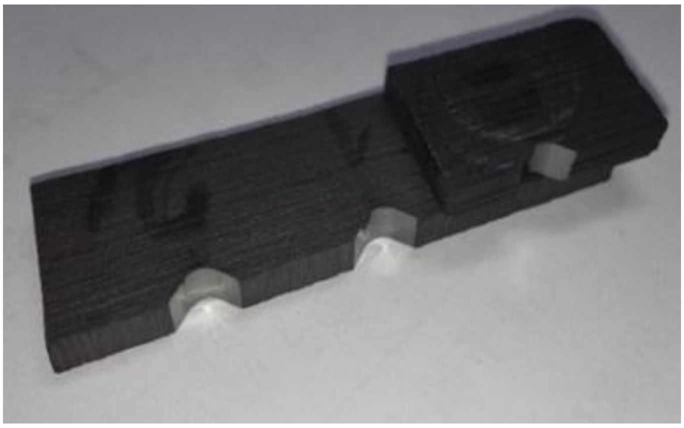


Fig. 3 Test board with duplicated profile

4.2 Measurement of duplicated wheel profile

4.2.1 In-situ visual measurement of duplicated profile

The board used for profile duplication was fixed on the worktable and moved to ensure the duplicated wheel edge profile was in the field of view of CCD.The image edge was extracted and profile parameters can be calculated according to the method proposed in section 3.

4.2.2 Profiler measurement of duplicated profile

The 3D surface optical profiler KS1100 was used to measure the duplicated wheel profile. The measurement range of the instrument is 100×100mm,the repositioning accuracy is ±0.5μm, and the absolute accuracy is 4μm.

The sensor measured the distance in *Z*-direction of each scanning point by scanning step 2μm in the X direction and 0.1mm in the Y direction. In this way, the space coordinates of the points in the measured surface can be obtained which represented the profile point set. The measuring point cloud of duplicated profile is shown in Fig. 4.

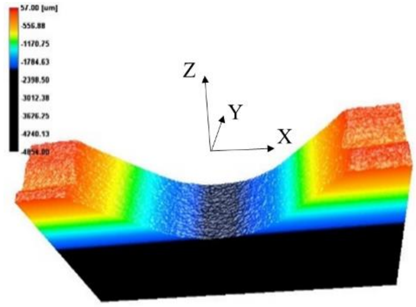


Fig.4 3D profiler measurement result of duplicated profile

4.3 Measurement results and evaluation

The results of three measurement methods are shown in Fig. 5. The calculated edge profile parameters are listed in table 2.

(a) (b) (c)

Fig. 5 The results of three measurement methods for measuring of wheel edge profile: (a)In-situ visual measurement of wheel profile;(b)In-situ visual measurement of duplicated wheel profile; (c) Profiler measurement of duplicated wheel profile.

Table 2 Wheel profile parameters by three measurement methods

Methods	Profile parameters		
	Edge arc radius R[mm]	Central angle α[°]	Roundness [mm]
In-situ measuring of wheel profile	[2.142, 2.151]	[90.22,90.42]	[0.020, 0.024]
In-situ measuring of duplicated wheel profile	2.153	90.22	0.032
Profiler measuring of duplicated wheel profile	2.161	90.33	0.034

By analyzing the calculated profile parameters of grinding wheel based on different measuring methods, it can be concluded that:

(1)By comparing the results of in-situ visual measurement and profiler measurement of duplicated profile, it is found that the related error of two edge arc radii obtained by the two methods is 0.37%, the related error of two central angles is 0.12%, and the absolute error of two arc roundness is 2μm. It indicates that the two measurement results had high consistency, and the in-situ visual measurement accuracy was high enough to be used to replace the profiler measurement.

(2)By comparing the results of in-situ visual measurement of actual wheel profile and duplicated wheel profile, it is found that the related error of edge arc radii obtained by the two methods is between 0.1%～0.51%, the related error of two central angles is between 0～0.22%, and the absolute error of two arc roundness is between 0.008 ～0.012mm. The high results consistency indicates that the in-situ visual measuring of arbitrary cross section profile of wheel edge can obtain the results as same as the measurement of duplicated wheel profile.

5. Compensation of wheel dressing error

5.1 Segmented representation of wheel profile error

The wheel wear condition can be evaluated by on machine measuring the profile accuracy of grinding wheel and the dressing time can then be determined. The schematic diagram for diamond roller dressing of grinding wheel is shown in Fig. 6. The cutting point of dressing roller changes the position constantly as the normal direction of dressed point of grinding wheel constantly changes. Assume P_1 and P_2 are two wheel dressing positions. When wheel is located in P_1, the dressed point A_1 is coincided with cutting point B_1, which is responsible for dressing all the profile points with the same normal direction as point B_1. The segment A_1A_2 of wheel profile is dressed only by segment B_1B_2 of the roller profile when the dressing position changes from P_1 to P_2.

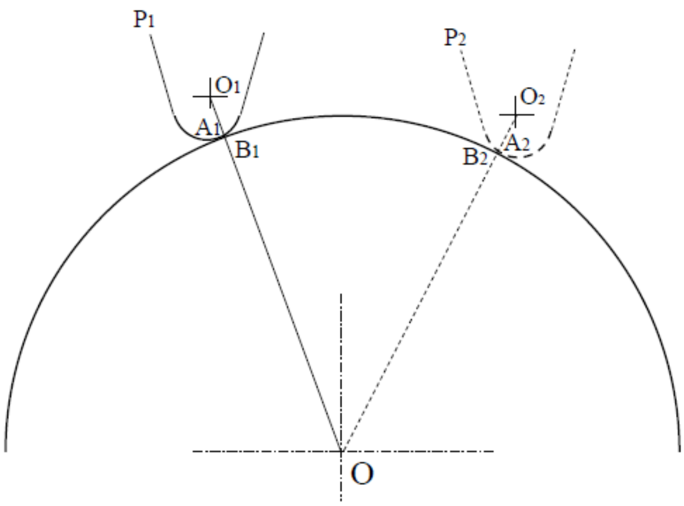


Fig. 6 Schematic diagram for diamond roller dressing of grinding wheel

A segmented representation of wheel profile error was proposed. The arc roundness of the wheel profile was evaluated after measuring of the wheel profile parameters. The wheel arc will be divided and characterized in segments if the roundness is larger than the set threshold. The profile error of each point in the wheel arc was defined as the displacement from the point to the least square circle along the direction of the line between the point and the center of least square circle.

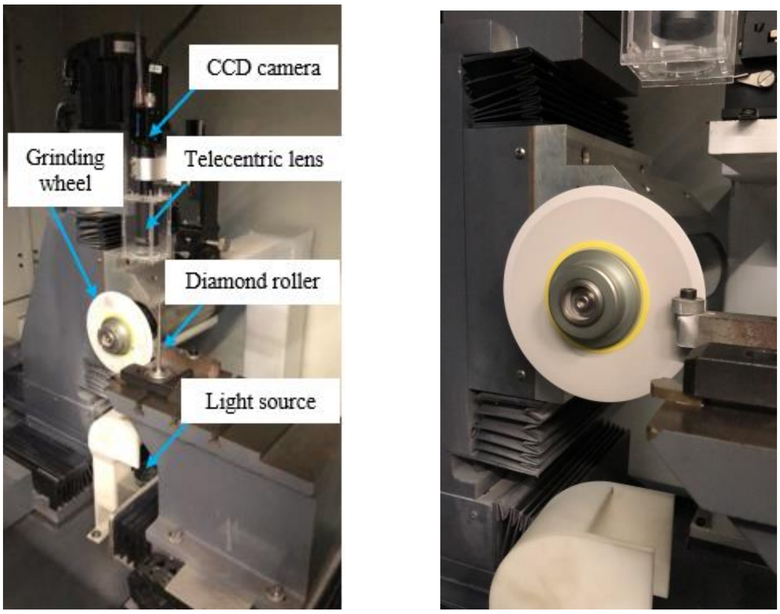
5.2 Virtual axis based online error compensation

Based on the segmented representation of wheel profile error, a segmented error compensation method was proposed. In the process of second wheel dressing, the calculated representative values for each segment are used as compensation values to be superimposed upon dressing movements.

The online compensation was realized by virtual axis based motion-superposition principle, i.e., superimposing the motion of virtual axis on the motion of physical axis. In this study, the compensation amount was decomposed into the movements of two virtual axis, which were superimposed on the movements of axes U and V, respectively.

5.3 Experiement

The diamond roller with 80 ANSI mesh abrasive and 20mm in diameter was used in the experiment. The roller had uneven wear because of dressing the same shape of wheels for a long time. The vitrified bond grinding wheel was comprised of single-crystal corundum abrasive with ANSI 150 mesh size, 150 mm in diameter and 6 mm in thickness and 1 mm in corner radius. The testbed for dressing and measurement is shown in Fig. 7. The wheel rotates at the speed of 3000rpm and the wheel feedrate is 0.02mm/s for dressing.



(a) (b)

Fig. 7 Experiment platform: (a)Self-developed profile grinding testbed; (b) Wheel and dresser in ressing.

A fixed-step compensation strategy was taken in the dressing process. In the first dressing process, the wheel was trued according to the the theoretic tool path. After dressing , the camera captured the wheel profile image and the profile edge was extracted. The least-square circle was obtained as the theoretic profile based on the least square. The wheel arc profile can be divided into 7 segments based on the proposed method in Section 5.1 to characterize the profile errors of each segment. The radius compensation values ε is listed in Table 3.

Table 3 Segment compensation value under fixed-step mode

Segment	1	2	3	4	5	6	7
Radius [μm]	1094.78	1091.57	1091.76	1087.44	1089.26	1102.94	1096.42
ε [μm]	7.34	4.13	4.32	0	1.82	15.49	8.97

In the second dressing, virtual axis based error compensation was triggered when the wheel reached the begining point of each segment. The speed ratio of virtual axis vs physical axis is 3.

5.4 Experimental results

After finishing dressing, the wheel profile was in-situ measured to calculate the parameters of wheel profile and contour error of each point of in the profile, which was defined as the distance of the point to the least square contour in the normal direction. The contour error distributions of grinding wheel before and after compensation are illustrated in Fig. 8; in this figure, a positive value means that the point is above the theoretical contour and a negative value means that the point is below the theoretical contour.

The results indicated that the PV value decreased by 32% from 0.031mm to 0.021mm, and the RMS value decreased by 40% from 0.005mm to 0.003mm, the roundness decreased by 39% from 0.031mm to 0.019mm before and after compenastion, respectively. It can be concluded that the proposed compensation method can effectively improve the dressing accruacy of the grinding wheel. Better compensation effect is expected to obtain under the condition of increasing the number of segments to reduce the compensation step.

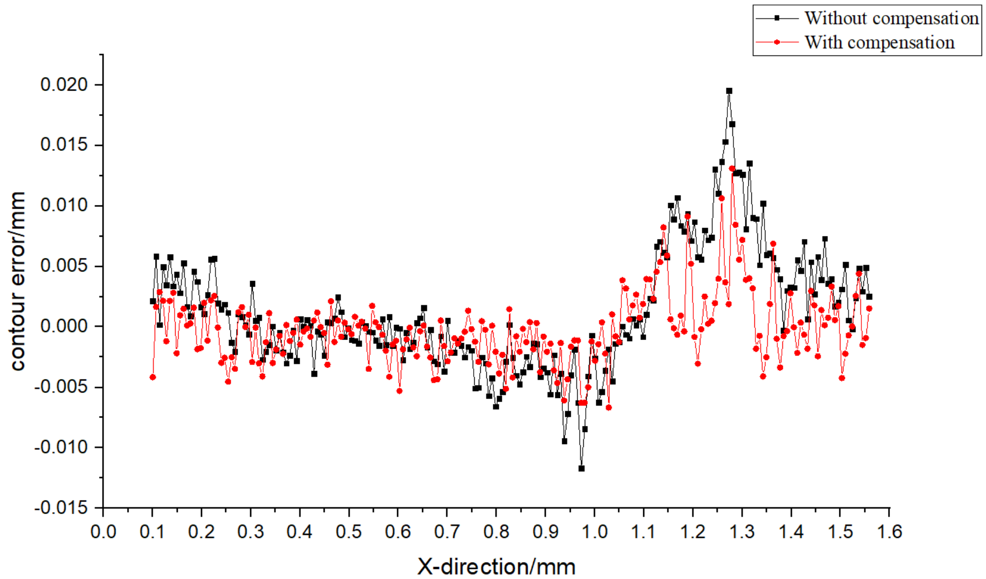


Fig. 8 Contour error distribution of grinding wheel before and after compensation

6. Conclusion

(1) The proposed methodolgy can realize in-situ and fast vision measurement of grinding wheel profile. One positioning for both dressing and in-situ measurement helps implement measuring the envelope profile of grinding wheel by measuring the single-section contour parameters of wheel, which improves measuring efficiency and ensures measuring accuracy as well.

(2) The in-situ direct measurement of wheel profile is highly consistent with the results of offline profiler measurement of duplicated profile. It demonstrates that the proposed method can replce the traditional offline and indirect profile measurement method and obtain a satisfactory measuring accuracy as well.

(3) Based on the segmented quantitative representation of wheel profile error, the proposed wheel dressing error compensation method can be used to segment and quantify the contour error of the wheel and realize the virtual axis based online compensation of the dressing error, which effectively improved the profile accuracy of the dressed wheel.

(4) The proposed in-situ direct measurement of wheel profile can be used in fast on-machine monitoring of the wheel wear condition and wheel dressing accuracy, which provides an

effective support for improving both accuracy and efficiency in profile grinding of contour surface.

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