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Methodology for In-Situ Visual Detection and Compensation of Profile Grinding Error

Nguyen Nhat Tan[1], Nguyen Anh Thang[1], Pham Ngoc Linh[2]*
[1]Vietnam-Japan Center, Hanoi University of Industry, Hanoi, Vietnam
[2]School of Mechanical and Automotive Engineering, Hanoi University of Industry, Hanoi, Vietnam
*Corresponding Author: linhpn@haui.edu.vn

Abstract**—***Profile grinding is widely used in machining of profile curve parts, such as kinds of complex precision molds and cutting tools. As a precision machining method for curve parts, optical enlargement-based profile grinding are broadly applied and the machining errors are inspected by manual vision and also manually compensated. With the development of imaging processing technology, machine vision was introduced into profile grinding in this paper. The grinding error was visual detected by with the advantages of no touch and high efficiency. A digital profile grinding method was presented. The in-situ machining error detection principle was proposed based a global visual image. A on line error direct detection methodology was put forward. The error compensation arithmetic was analyzed based on different error features. The simulation experiment was conducted and the result showed that the machining error was down by about 80 percentage compared to before compensation under the given ordinary machining conditions. It verified the feasibility of the proposed methodology for in-situ visual detection and compensation of profile grinding error.*

Keywords**—** *Profile grinding, image processing, error detection, error compensation.*

I. Introduction

Profile grinding is widely used in machining of profile curve parts, such as kinds of complex precision moulds and cutting tools. As a precision machining method for curve parts, it has become a crucial subject to improve the profile accuracy or form accuracy. Except for high-performance CNC machine tools developed by the state-of-the-art technology to meet the requirements, the compensation methodologies for reducing machining errors have been persistently investigated in a variety of manufacturing process, which has the advantages of low cost and effectiveness in accuracy improvement [1]. A traditional method to detect the profile error in profile curve grinding is to optically enlarge the profile of the machined component to the projection screen. The enlarged profile image is to be compared with the theoretical profile, and the profile error can be inspected and compensated manually by operator. This manual vision-based compensation method has the disadvantages of manual dependence and low efficiency. It becomes an urgent problem to seek a new generation of technology to replace the traditional profile grinding method. As an essential issue for improving the machining accuracy, the error compensation has variety depending on the error sources, such as geometric error of machine tools, thermal error, tool wear error, residual error, and form error. The geometric errors can be compensated by modelling the geometrical error of machine tools. Ramesh et al. [1] and Schwenke et al. [2] reviewed the geometric error measurement and compensation of machines. Thermal errors are the large contributor to the dimensional errors of a workpiece in precision machining [3-4]. Some researches focused on the overall consideration of both geometric and thermal errors in improving the machining accuracy. Li Proceedings of the 20th International Symposium on Advances in Abrasive Technology 3-6 December, Okinawa, Japanet al. [5] presented a comprehensive compensation method for the integrated geometric and thermal errors of machine tools, and the tests on a vertical machining center showed that the position accuracy of the machine tool could be significantly improved after compensation. Tool wear sometimes becomes a big factor to the dimensional or form errors of a workpiece [6-9]. Li et al. [6] studied the tool wear in contour grinding of optical components. A tool wear model was developed to predict tool profiles and an algorithm was designed to adjust the tool path. Zhang et al. [9] studied a wheel wear detection approach based on machine vision in precision curve grinding. Some compensation methods based on the residual error have also been reported. Liu et al. [10] presented a Taguchi method for eliminating the residual form error of an aspheric surface. Lee et al. [11] discussed a method for compensation of the residual form error due to tool de-centering in the ultra-precision machining of aspheric surfaces. More compensation methods directing at the form error have been discussed. Form error is usually regarded as a difficult issue among the main geometric features of size, form error and roughness. Huang et al. [12] proposed a discrete system model for form error control in surface grinding. Chen et al. [13] presented a profile error compensation approach in ultraprecision grinding of aspheric surfaces based on the on-machine displacement sensor measurement. The overall profile error was obtained and used to generate a new tool path for compensation grinding. Lin et al. [14] studied a grate parallel grinding of large aspheric mirror surface. A noncontact displacement laser sensor was used to on-machine measure the form error, and the result showed the error compensation can significantly improve the form accuracy.

From the above review studies [1-14], it is found that lots of error detection and compensation methods have been researched but most of them focused on indirect and on machine measurement. Very few studies are aimed to describe the profile grinding process for direct profile error detection and compensation, which is especially crucial for profile curve grinding.

In this study, a digital profile grinding method was presented to reform the traditional manual vision based profile curve grinding process. The profile error can be directly in-situ detected based on the machine vision to overcome the disadvantages of manual dependence and low efficiency. The principle for in-situ visual detection of profile error in profile curve grinding was analyzed. The methodologies for direct measuring and compensation of profile error were proposed. The simulation experiments were conducted to verify the proposed profile grinding methods.

II. Profile Curve Grinding and Error Detection System

The machine vision based digital profile grinding of curve parts was performed on a self-developed 5-axis precision machine tool. The schematic diagram for the grinding system is shown in Fig. 1. A few profile grinding methods can be designed based on the testbed. In this study, a global visual image based digital profile grinding method was introduced to in situ detect the profile error. The workpiece settled on the worktable and the vision system fixed on the testbed remain stationary during grinding, while the machining profile of curve part is in the field of view of camera. After finishing the clamping of the workpiece, the position of machined profile is also fixed in the acquired picture, which can be matched to the theoretical profile position through tool setting. The arc grinding wheel with double bevel edge rotates in programmed speed under the motion controller. Meanwhile, the wheel conducts interpolated feed motions in x and y directions, and reciprocating servo feed motion in z direction.

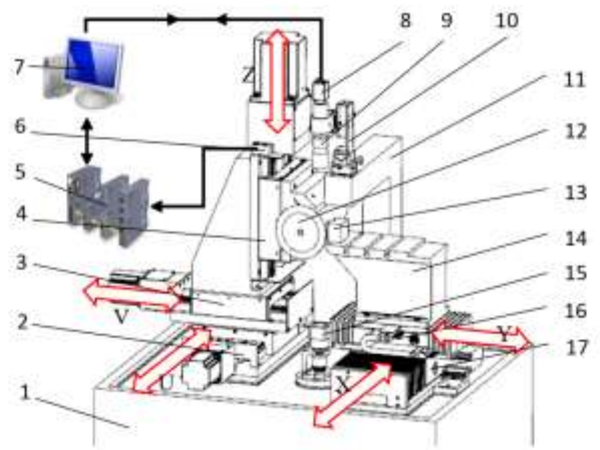

Fig. 1. Machine vision based form error detection for profile grinding
1. base; 2. U slide; 3. V slide； 4、 Z slide; 5. motion controller; 6. position sensor; 7. Computer; 8. camera; 9. telecentric lens; 10. optical bench; 11; camera support; 12. grinding wheel; 13. workpiece; 14. worktable; 15. light source; 16. Y slide; 17. X slide

The profile curve grinding performs a sort of dry point-grinding, in which the wear debris can be collected by the vacuum cleaner. When the wheel moves to the top position in z direction, the camera takes a picture of the machined profile of the workpiece. The acquired image has the advantage of better edge sharpness due to the shooting conditions such as noncontact between wheel and workpiece, less grinding spark, less disturbance exerted on the profile image by wheel. The actual ground profile of workpiece can be extracted on line through image processing and be compared with the theoretical one. The profile error can then be calculated by the design of error detection algorithm.

The error detection system consists of high precision area CCD camera, telecentric lens, directional backlight, computer, controller and sensors. The image acquirement can be software based internal triggered. Computer is in charge of image acquirement and transfer, image processing, sending command to controller and monitoring of grinding process.

III. Principle and Methodology for Profile Error Detection

The schematic diagram for the detection of profile grinding error one time during grinding is shown in Fig. 2. According to the cutter radius compensation theory, the path planning of the cutter location point can be determined based on the theoretical profile of part and the radius of wheel arc. Due to the conditions that the camera and the workpiece are both fixed and the theoretical position of machining profile is also unchanged in the image coordinate system, the actual position of machined profile should overlap the theoretical profile position in the same in the same image coordinate. Nonoverlap of the two profiles means that there exists the profile errors. The grinding profile error comes from multiple factors such as the wear of grinding wheel arc, the geometric errors of machine tools, the thermal deformation of grinding carriage or worktable, which can all cause the deviation between actual machining point and the theoretical one. The deviation determines the grinding accuracy of curve profile and the amount of profile error. Therefore, the profile error is kind of comprehensive error which includes variety of errors including the wheel wear, the geometric errors and the thermal error. The direct detection of the profile grinding error can provides the foundation for the synthetical compensation of the different kinds of errors. During grinding process, read the current positions of wheel location point C and the corresponding programmed grinding point Mi at any moment from the numerical control system, as shown in Fig. 2.

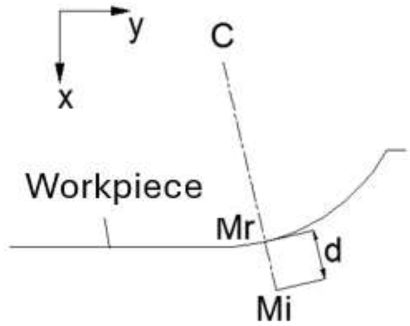

Fig. 2. Schematic diagram for detection of profile grinding error

The actual machined workpiece profile can be obtained by edge extraction of the captured workpiece image. Connect

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point C and Mi, the line CMi intersects the actual extracted workpiece profile at point Mr. The error compensation is to make Mr come as closer to point Mi as possible. The distance d between Mr and Mi can be regarded as the current machining deviation. Three criterions for determining compensation are discussed below with respect to the relationship between d and the defined error threshold e.

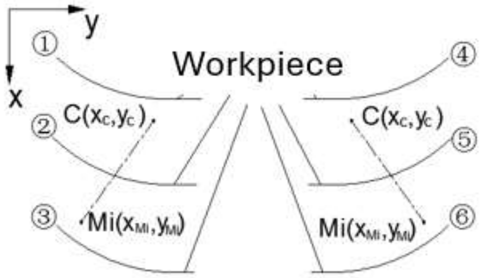

Fig. 3. Schematic diagram for detection of profile grinding error

Criterion 1: if $d \leq e$， the error is acceptable, no compensation needed；

Criterion 2: if $d > e$， and Mr is between C and Mi， or on the extension line of Mi C, the wheel feed amount is insufficient;

Criterion 3: if $d > e$， and Mr is located on the extension line of CMi， the wheel feeding is excessive.

The distance d is calculated every time when the grinding wheel finishes one reciprocation in the grinding process. The compensation can be determined depending on the criterions discussed above. Assume $p(xp, yp)$ is one point on the actual workpiece profile, the distance from point p to line CMi is $d_p{-}C_{Mi}$, and the distance from Mr to line CMi is $d_{Mr}{-}C_{Mi}$, then Eq. 1 can be concluded for searching the point p.

$$d_{Mr}{-}C_{Mi} = \min d_p{-}C_{Mi} \quad (1)$$

In order to improve the efficiency for searching point Mr, the searching strategy can be designed in accordance with the relative positions of point C, Mi and the actual machined profile, as shown in
Fig. 3. Seven cases can be classified and discussed below.

Case 1. If $y_c > y_{Mi}$， and the actual curve profile is above C: Search point ps $(yp = yc)$ on the actual profile. Count $d_p{-}C_{Mi}$ from p_s along the profile in the direction of y increase. M_r can be located when d_{p-CMi} starts to increase.

Case 2. If $y_c > y_{Mi}$, and the actual curve profile is between C and Mi : Search point ps $(y_p = y_c)$
and pe $(y_p = y_{Mi})$ first on the actual profile. M_r is the point on the profile between p_s and p_e, and meets the condition that $d_{p-CMi} = \min(d_{p-CMi})$.

Case 3. If $yc > yMi$, and the actual curve profile is below Mi : Count d_{p-CMi} from p_s $(y_p = y_{Mi})$ along the profile in the direction of y decrease. Mr can be located when d_{p-CMi} starts to increase.

Case 4. If $y_c < y_{Mi}$, and the actual curve profile is above C: Count d_{p-CMi} from ps $(y_p = y_C)$ along the profile in the direction of y decrease. Mr can be located when d_{p-CMi} starts to increase.

Case 5. If $y_c < y_{Mi}$, and the actual curve profile is between C and M_i : The search algorithm is same as Case 2.

Case 6. If $y_c < y_{Mi}$, and the actual curve profile is below Mi : Count d_{p-CMi} from ps $(y_p = y_{Mi})$ along the profile in the direction of y increase. Mr can be located when d_{p-CMi} starts to increase.

Case 7. If $yc = yMi$, Mr is the point p $(yp = yC)$ on the actual profile.

IV. ON LINE COMPENSATION OF PROFILE ERROR IN PROFILE GRINDING

According to the presented criterions above, it is necessary to execute compensation when the detected machining error d exceeds the error threshold e. In some cases, the theoretical compensation amount was determined by d, but identification of the compensation direction was a tough work that can't be simply judged by the position of current cutting point. The direction and magnitude of error compensation were discussed in this section. The theoretical center of wheel circular arc can be identified in the image coordinate at one moment in profile grinding. The theoretical circular area of wheel arc was formed based on the ideal wheel arc radius and the identified center of wheel arc. The working allowance inside the theoretical circle should be removed assuming that there was no machining error. And there was no workpiece image inside the circle area. If there was grinding error due to the insufficient wheel feeding caused by the reasons such as wheel wear, the image of workpiece would enter into the theoretical circle because the working allowance wasn't removed by grinding, as shown in Fig. 4. The direction of line connecting wheel arc center and the theoretical machining point is also the normal direction of the machining point in the theoretical profile.

Fig. 4. Theoretical circle under insufficient feed

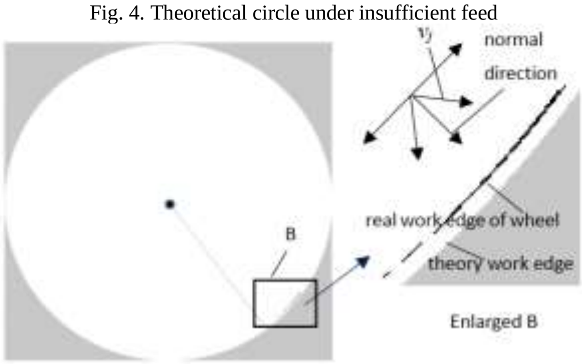

Fig. 5. The circle image subtraction for twice machining under insufficient feed

If the wheel feed is insufficient judged by Criterion 2 in section 3, an image subtraction based method was proposed to figure out the direction and magnitude of grinding error. In first grinding reciprocation, capture the image of theory circle for wheel arc when insufficient feed happens. Then capture the next image of theory circle in the second grinding cycle. The subtraction of the adjacent two images presents the removed part of materials by the second cycle. The subtraction image also indicates the real profile position of grinding wheel, as shown in Fig. 5. When the position deviation between real wheel arc and theoretical one occurs in direction v, as shown in Fig. 6, define the distance from the point pi(i=1,2,…n)， on the real wheel profile (or called edge) to the theory wheel profile (or called edge) is d_{v-pi} in direction v, then we obtain Eq. 2 as follows.

$$d_{v-p1} = d_{v-p2} = \ldots = d_{v-pn} \quad (2)$$

The real working edge of wheel is obtained by image subtraction and shown in box B in Fig. 5. The working edge points of wheel were the set of each point $p_i(i=1,2,\ldots n)$ at the lowest of each column of the real working edge. In the angle range of normal direction of theory grinding point plus or minus 90 degrees, compute $d_{vj-pi}(i = 1,2, \ldots n)$ in different direction of $v_j(j=1,2,\ldots m)$. The standard deviation can be calculated by Eq. 3.

$$S_j = \sqrt{\sum_{i=1}^{n}\left(d_{v_j-p_i} - \overline{d_{v_j-p_i}}\right)^2} \quad \left(\overline{d_{v_j-p_i}} = \frac{1}{n}\sum_{i=1}^{n} d_{v_j-p_i}\right) \quad (3)$$

Choose vj as error direction where Sj reaches the minimum. The average distance value $\overline{d_{v_j-p_i}}$ can be used as the size of error in this direction.

In order to calculate the distance d_{vj-pi}(i = 1,2, … n) in direction vj, firstly search the intersection point $q_i(i=1,2,\ldots n)$ of the line passing through point $p_i(i=1,2,\ldots n)$ with the theoretical wheel profile. Then compute the distance between point p_i and q_i. Suppose one special situation that in first grinding cycle, the wheel feed is judged insufficient by Criterion 2, but there is no material removing due to the grinding error in the second grinding cycle. In such case, the real cutting position can’t be located by the presented method. We can take the normal direction of theory grinding point as the direction of compensation and the detected deviation in the first grinding cycle as the amount of compensation.

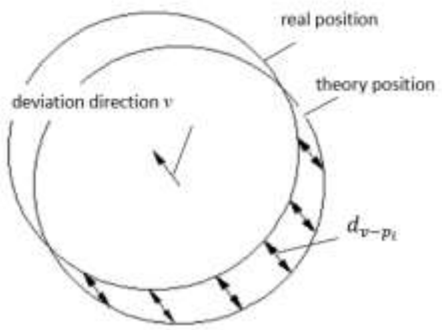

Fig. 6. Schematic diagram for deviation of wheel position

If the wheel feeding is excessive judged by Criterion 3 in section 3, the wheel should return a certain distance to avoid the overcutting in the next grinding processing. The normal direction of theoretical grinding point can be taken as the return direction, and the calculated deviation can be taken as the return distance.

V. SIMULATION EXPERIMENT

According to the proposed methodology for error detection and compensation in profile grinding, the simulation experiment was conducted based on the openCV, the open source computer vision library. Microsoft Visual Studio was used as simulation language environment. The simulation flow chart is shown in Fig. 7.

First, create an image of semi-finished workpiece to be profile ground based on the theoretical profile. The math expression of the theory profile can be written in Eq. 4.

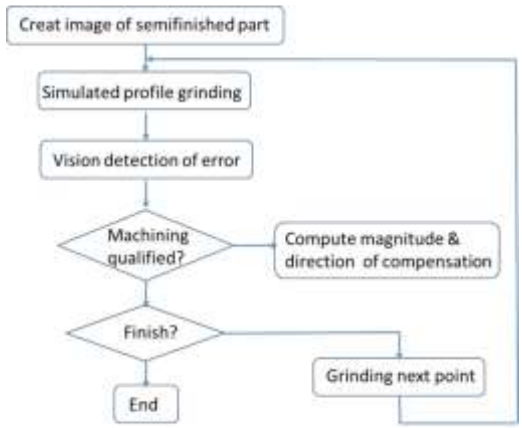

Fig. 7. Flow chart of profile grinding simulation

$$f(x) = \begin{cases} 0 & x \in [0, 0.875] \\ -\sqrt{0.563-(x-0.875)^2}+0.75 & x \in [0.875, 1.405] \\ 0.993x - 1.176 & x \in [1.405, 1.790] \\ \sqrt{0.563-(x-2.5)^2}+0.25 & x \in [1.970, 3.146] \\ -1.783x + 6.238 & x \in [3.146, 3.854] \\ -\sqrt{0.563-(x-4.5)^2}-0.25 & x \in [3.854, 5.030] \\ 0.993x - 5.778 & x \in [5.030, 5.595] \\ \sqrt{0.563-(x-6.125)^2}-0.75 & x \in [5.595, 6.125] \\ 0 & x \in [6.125, 7] \end{cases}$$

The image size of the created semi-finished part is 7500 × 4000 resolution. The pixel pitch is 1μm. The simulation position of the part can be obtained by offsetting the theoretical part profile upward by 50μm.

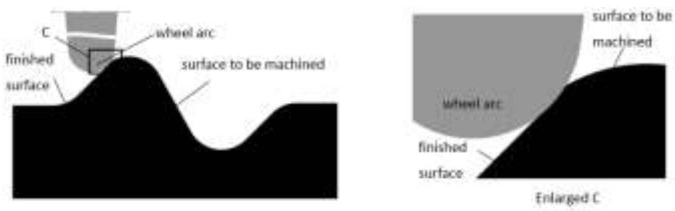

Fig. 8. Schematic diagram for simulating profile grinding

The schematic diagram for simulating profile grinding is

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shown in Fig. 8. The cutter location point is determined by the processing parameters including the wheel federate, reciprocating speed, and the radius of wheel arc. In the experiment, suppose the radius of wheel arc is 0.5mm, and the interval of two adjacent location points is 5μm. The removed material of workpiece is the intersection of the theoretic wheel arc area with the semi-finished part while grinding the certain point of profile.

The error detection was conducted after finish a certain reciprocation grinding cycle in grinding processing. If the detected result was qualified, move on grinding the next point. If the detected error was over proof, the amount and direction of error compensation can be computed based on the presented algorithm in section 4, and do the compensation in the next cycle. Giving consideration of both accuracy and efficiency, choose normal direction of theory grinding point, the normal direction plus or minus 30°, 60°, 90° as the traverse direction based on the direction search algorithm when insufficient feeding happened.

The profile error was simulated by making a coordinate offset for theory cutter location point. Five simulation experiments were designed by setting five coordinate offsets for five theory cutter location points respectively. It means that from that point on, the following points on the part profile, which are corresponding to the wheel reciprocating cycles, all have the coordinate offset. Error detection and compensation were conducted with the proposed methodology above. The profile errors before and after compensation were shown in Fig. 9(a) and Fig. 9(b) respectively with the condition that the

Fig. 8 Schematic diagram for simulating profile grinding finished surface wheel arc surface to be machined C. Enlarged C wheel arc finished surface surface to be machined coordinate offset starts from No. 760 cycle by setting offset value (-7, 7). It's found that the largest profile error was 11.2 pixels before compensation and reduced to 2.2 pixels after compensation. Table 1 lists the results of five simulation tests. The results showed that the average profile error dropped by 80% after compensation. The machining accuracy was within 3 pixels.

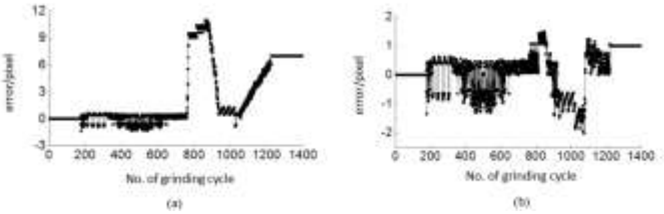

Fig. 9. Comparison of errors before and after compensation (a) before compensation, (b) after compensation

TABLE 1. Error compensation results of simulation experiments

Exp	N (start cycle with offset)	Coordinate offset [pixel]	Error before comp. [pixel]	Error after comp. [pixel]
1	100	(-8, -6)	11.1	1.8
2	300	(-9, -3)	10.5	2.1
3	600	(-10, 2)	11.5	2.8
4	760	(-7, 7)	11.2	2.2
5	950	(-10, 10)	10.1	1.7

VI. CONCLUSION

1. A novel principle was presented for digitalized profile grinding of curve workpiece based on machine vision. Compared with traditional curve grinding, it can realize in situ detection of profile error and online error compensation.
2. A new methodology for in situ detection of profile machining errors was proposed based on entire visual image. The detected profile errors can comprehensively reflect the machining errors caused by wheel wear, geometrical errors of machine tool and the thermal deformation of worktable or grinding head.
3. The error compensation method based on different detected error characteristics was studied and the corresponding compensation algorithms were put forward. The simulation indicated that the average profile error dropped by 80% after compensation under the given grinding conditions, which testified the feasibility of proposed methods for profile error detection and compensation.
4. It should be noted that this study has examined only by simulation. The further experimental research will be conducted based on the development of grinding testbed.

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