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ORIGINAL ARTICLE

Method for graphically evaluating the workpiece's contour error in non-circular grinding process

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Abstract To find and compensate the dynamic contour error of workpieces on CNC non-circular grinder, a graphic display and evaluation method is introduced. The programmed set and actual contours of workpiece are displayed through the outlines of grinding wheel at a series of set and actual positions. The dynamic contour error can be recognized directly on CNC control screen without extra measuring equipments as usual. The set and actual positions of grinding wheel related to workpiece are collected from the CNC controller and servo drives and further evaluated. This process is carried out after a dry-run cycle on the machine. Based on this method, a display and evaluation software module has been developed and integrated in the controller of a CNC non-circular grinder. It helps to find contour error and generate the compensation data. Grinding an eccentric test piece shows good result and advantage of the proposed method.

Keywords CNC grinding · Non-circular workpiece · Contour error

1 Introduction

High precision non-circular parts such as cam and crankshaft must be finished on CNC non-circular grinder in order to obtain high accurate contour and good surface roughness. A CNC non-circular grinder, as shown in Fig. 1, consists generally of CNC system, servo controllers, translational axis X, rotational axis, and grinding wheel. When the workpiece rotates about C axis, the table on which the workpiece locates traverses back and forth on X axis. Through their simultaneous movements, the contour of workpiece is formed. The programmed set positions (X_k,C_k) of X and C axes are calculated in CNC system according to workpiece's contour function $F_k(l_k,\alpha_k)$ and its tangential velocity ν.

X and C axes are driven by servo controller and motor, i.e., servo loop. Following error occurs in the servo loop when axis moves. It is related to axis velocity, axis acceleration, gain of servo loop, etc. [1–4]. When the translational and rotational axes of a CNC grinder move simultaneously, their following errors will cause velocity-dependent dynamic path error, which will finally result in the contour error of workpiece, especially during acceleration and deceleration phase of the contour [5].

Contour error must be obtained in order to eliminate it with proper compensation data on controller. The most common way is to use a coordinate measuring machine or specialized cam measuring system (CMS) [6, 7]. Their working principles are the same, as shown in Fig. 2. The non-circular workpiece locates on the main shaft of CMS and rotates with it. A rotary encoder is connected to the main shaft to record rotating angles of the workpiece. The measuring head, locating on a sliding guide way, touches the workpiece's surface radially and traverses back and forth as it rotates. Its position is recorded by a linear encoder. Based on the recorded rotational and translational positions, the actual contour is calculated by the computer. Then, the contour difference to the programmed set contour will be determined.

Several test pieces have to be ground and then measured on CMS in order to get the dynamic contour error and calculate compensation data. For a new workpiece, this

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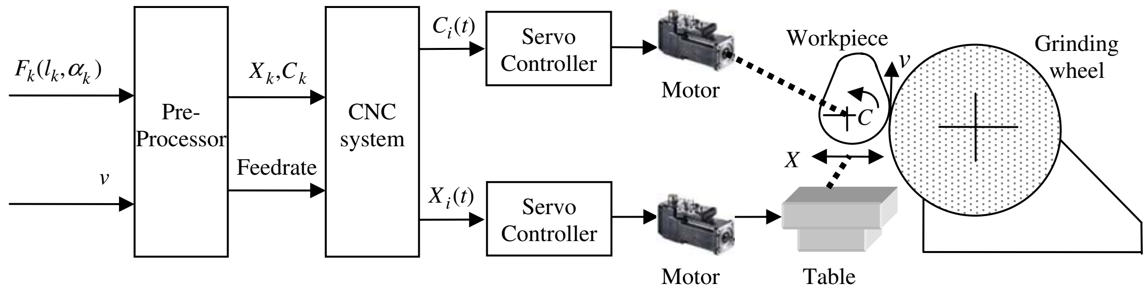


Fig. 1 Basic structure of CNC non-circular grinder

process might need to be repeated several times before mass production. Therefore, it is time consuming and inefficient.

Some researchers developed online methods [8–11], which make it possible to carry out the measurement directly on the same grinder by applying a measuring probe or measuring device. Contour error can be derived by the measured data and through complex algorithms. However, extra hardware is still needed.

In this paper, a new and efficient method to graphically evaluate the dynamic contour error in non-circular grinding process is introduced. The set and actual contours of workpiece are displayed through the outlines of grinding wheel at a series of set and actual positions. The dynamic contour error can be recognized directly on the CNC control screen without extra measuring equipments as usual. The set and actual positions of grinding wheel related to workpiece are collected from the CNC controller and servo drives and further evaluated. This process is carried out after a dry-run cycle on the CNC machine. In this paper, the generation process of programmed set axis positions, collection process of actual axis positions, and graphic evaluation of set and actual contour are explained in detail. Based on this method, a display and evaluation software module has been developed and integrated in the controller of a CNC non-circular grinder. It helps to find contour error and create the compensation data efficiently.

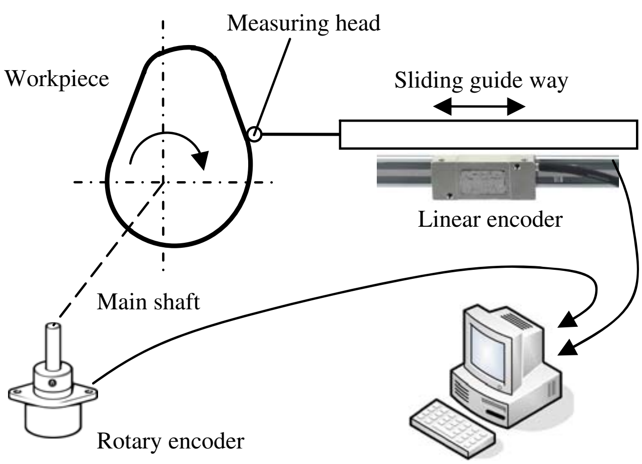


Fig. 2 Measuring principle of CMS

2 Generation of programmed set positions

The contour of non-circular workpiece is normally defined in the form of roller lift table, which consists of a series of polar points $F_k(l_k,\alpha_k)$ along the roller's center, as shown in Fig. 3. Here, l_k is the polar radius between the workpiece rotating center O_w and roller's center O_r, and α_k is the polar angle (k=1, 2,…,N, where N is the number of polar points). γ is the radius of roller.

In the grinding process, the grinding wheel generates workpiece's contour. Referring to Fig. 3, the grinding point P, roller's center O_r, and grinding wheel's center O lie on a straight line whose normal angle is θ_k. R is the radius of grinding wheel. X_k and C_k are the position of translational and rotational axes. The workpiece rotates about C axis and traverses on X axis on the grinding machine. In order to calculate the control data, it is assumed that the grinding wheel rotates about C axis and traverses on X axis. The difference between the assumption and real process is the reverse of C axis. Then, (X_k,C_k) is the coordinate value in NC program.

The normal angle of each polar point θ_k is calculated from two consecutive polar points near it, under the supposition that three points form an arc.

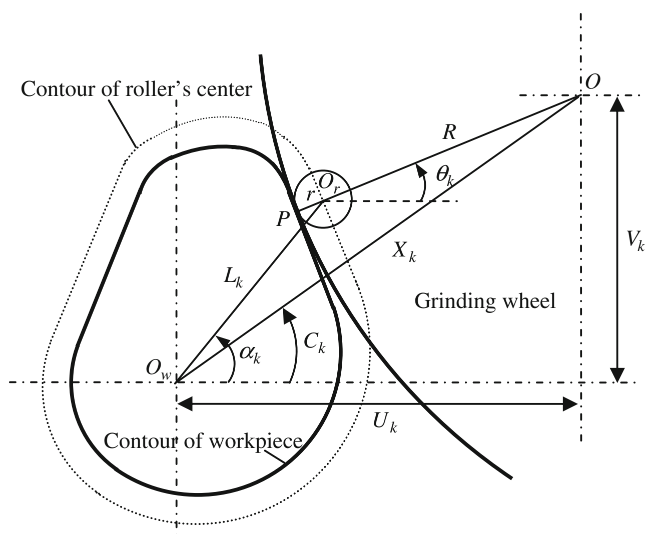


Fig. 3 Calculating principle of set positions

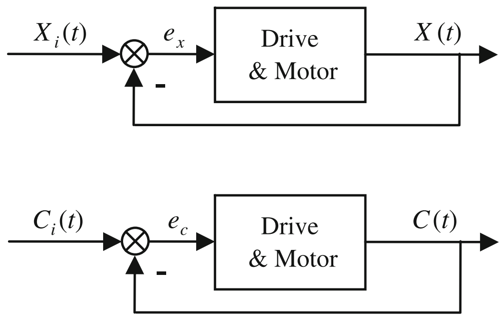


Fig. 4 Set and actual positions to be collected

Given l_k, α_k,θ_k, γ, and R, the position of grinding wheel (X_k,C_k) can be calculated. If U_k and V_k are the position of the grinding wheel's center in workpiece coordinates system, the following equations hold,

$$\begin{aligned} U_k &= L_k \cos\alpha_k + (R-r)\cos\theta_k \\ V_k &= L_k \sin\alpha_k + (R-r)\sin\theta_k \end{aligned} \tag{1}$$

then

$$X_k = \sqrt{U_k^2 + V_k^2} \tag{2}$$

$$C_k = \arctan\frac{V_k}{U_k} \tag{3}$$

Furthermore, the tangential velocity of the grinding point must keep constant in order to achieve good surface roughness. According to the coordinates of grinding wheel X_k and C_k and the tangential velocity, CNC controller outputs the set positions of X and C axes, $X_i(t)$ and $C_i(t)$ (i= 1, 2,…, M, where M is the number of interpolated positions) to servo controllers at every interpolation cycle T. Servo controllers drive the motors of two axes to move simultaneously in actual positions $X(t)$ and $C(t)$, as shown in Fig. 4.

3 Collection of actual positions

Due to following error e_x and e_c, actual positions of grinding wheel $X(t)$ and $C(t)$ differ from set positions. This difference leads to the dynamic contour error of workpieces. Therefore, actual positions of each axis are used to evaluate and display the contour error.

Actual positions $X(t)$ and $C(t)$ are measured by linear and rotary encoders of servo loop. They are used to build position control loop. The CNC controller developed by authors

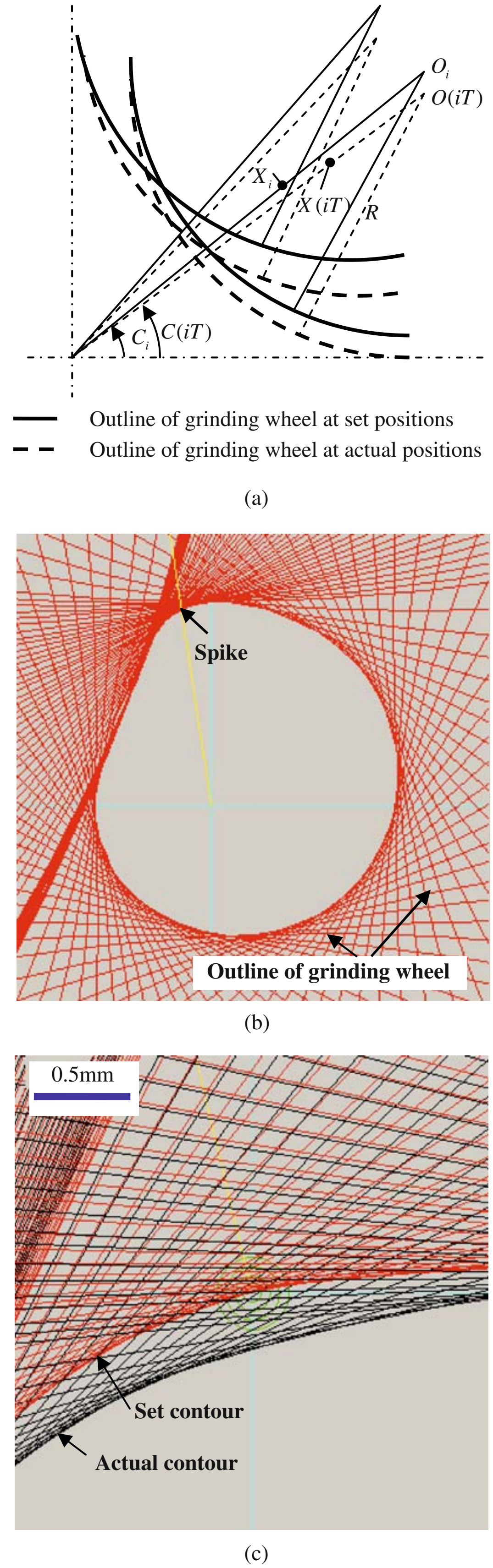


Fig. 5 Displaying method of contour error of workpiece. **a** The principle to display the contour error of workpiece. **b** The set contour of a cam. **c** The enlarged contour error of a cam

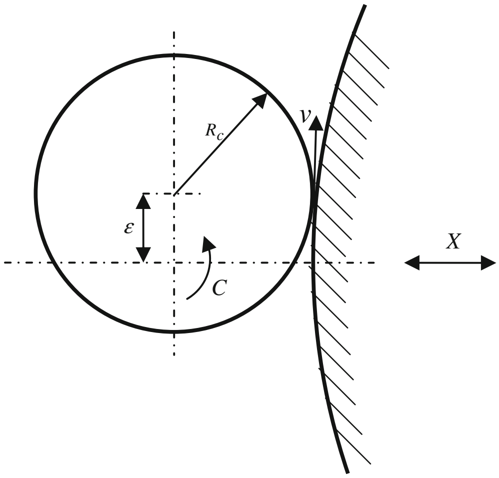


Fig. 6 Eccentric circle test piece

provides interface to collect and store actual positions, which can be further evaluated for graphic display.

4 Method for graphically evaluating the contour error

Since the contour of workpiece is formed by grinding wheel in real grinding process, contour error of workpieces can be graphically evaluated through the outlines of grinding wheel at a series of set and actual positions.

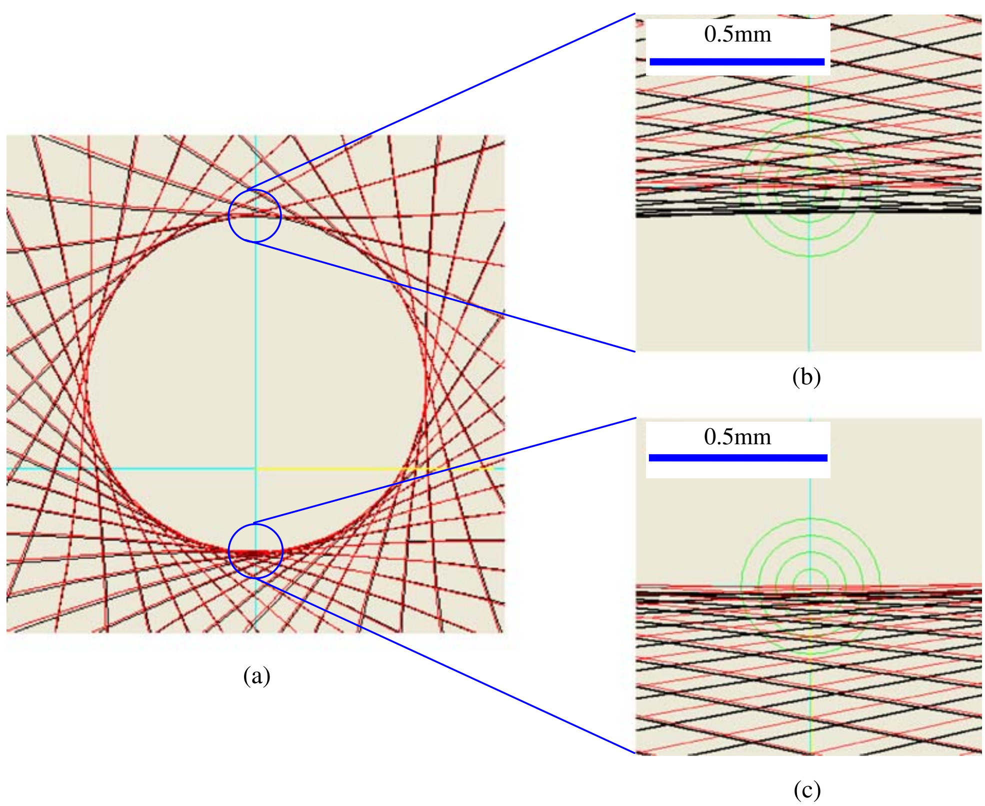
Figure 5a shows the generation process of a workpiece contour. At certain moment $t(t=iT)$, the grinding wheel's center O_i has set position (X_i, C_i). Due to following errors, the actual position $(X(iT), C(iT))$ lags behind (X_i, C_i). $O(iT)$ is the actual position of grinding wheel. The outline of actual grinding wheel deviates from outline of set grinding wheel. If they are plotted in proper interval, the set and actual contours of workpiece are shown by enveloping arc of grinding wheel. The contour error of workpieces can be further enlarged for a better view.

Figure 5b shows the set contour of a cam workpiece. Here, only the set contour is displayed. It can be used to check if the calculated coordinates (X_k, C_k) in NC program are correct.

Figure 5c shows the set and actual contours of the cam, which are enveloped by the outlines of grinding wheel at a series of set and actual positions. Since X and C axes have great acceleration and deceleration near the spike, large contour error occurs here. Therefore, the contour around this area is enlarged so that the set and actual outlines of grinding wheel can be clearly separated. With help of scale, the contour error is easily estimated.

Based on this method, a display and evaluation software module is developed and integrated in the controller of a CNC non-circular grinder. The set and actual positions are collected during dry-run process from the servo loop and stored in CNC controller. The software module evaluates

Fig. 7 Contour error of an eccentric circle. **a** The enveloped workpiece's contour. **b** Contour error at C_i=90°. **c** Contour error at C_i=270°



these data and plots the contours on screen. The contour error can be easily recognized and analyzed. It helps to generate a proper compensation data set. The process can be repeated until the contour accuracy meets requirement. Comparing to usual compensation process of non-circular grinding, no extra measuring equipment is needed by using this method. And it is easily to integrate the method into a contour error compensation system [12–15].

5 Grinding test

In order to examine the proposed method, an eccentric circle test piece has been finished on the CNC grinder developed by author. Its structure is shown in Fig. 1. The test piece, as shown in Fig. 6, has a radius R_c of 20 mm and eccentricity ε of 10 mm. It is fixed on C axis. The grinding of this eccentric circle is similar to a cam, but it is much easier to get the real contour error by measuring the roundness with a micrometer gauge. Comparing the roundness of finished test piece with contour error on CNC screen, the advantage of the proposed method is proved.

Tangential velocity ν is 4,000 mm/min, while C axis speed varies from 17 to 32 rpm.

The programmed set positions are calculated according to Eqs. 2 and 3, while actual positions are collected from servo controller during the first dry-run process. Figure 7a shows the test piece's set and actual contours on CNC screen. The maximal contour error occurs at C_i=90° where the test piece is over ground. An enlarged view of this area is shown in Fig. 7b. The thicker arcs represent grinding wheel at actual positions, while thinner arcs show set positions. The contour error is about −0.07 mm. The test piece is less ground at C_i=270° where the contour error is about +0.02 mm. Using the estimated contour error, the automatic contour error compensation module calculates the compensation data for each set positions.

With the compensated set positions, another dry-run test is done. The contour error at C_i=90° is reduced to −0.01 mm, and contour error at C_i=270° is almost fully compensated. Then, the eccentric circle is ground on the grinder. The roundness measured by micrometer gauge is 0.016 mm. The contour error evaluated by the proposed method is proper to the real roundness of finished test piece.

6 Conclusion

Dynamic contour error resulted from following error of servo loop is the main error source of CNC non-circular grinding process. It must be eliminated with compensation data, which are generated after a measuring and evaluating process. The proposed method in this paper can graphically evaluate and display dynamic contour error on CNC controller and helps to generate compensation data. No extra measuring equipment is needed. A software module has been developed and integrated in a CNC non-circular grinder of authors. The grinding test gives good result and shows the advantage of the proposed method.

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