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Contour error compensation method for computer numerical controlled non-circular grinders

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Abstract: A contour error compensation method for computer numerical controlled (CNC) non-circular grinders is introduced. The compensation method collects set and actual positions of each axis from servo controllers during the dry run process and calculates compensation data for the interpolator of the CNC system. It can be executed quickly and iteratively without real grinding. It can also be integrated in existing CNC systems without modifying interpolation or servo control algorithms. Brief introductions to the servo controller simulation model and contour error displaying module when developing the compensation method are also given. Grinding results demonstrate high contour accuracy of a cam workpiece and efficiency of the compensation method.

Keywords: contour error, compensation, CNC, servo controller, non-circular grinder

1 INTRODUCTION

The manufacture of non-circular workpieces is nowadays completed by the computer numerical controlled (CNC) grinding process. The mechanical structure of a CNC non-circular grinder is illustrated in Fig. 1 [**1**]. Through the simultaneous movements of translational and rotational axes the workpiece is ground. Their set positions must be calculated in the numerical controlled (NC) system according to the workpiece's contour and its tangential velocity.

Each axis is driven by its servo controller, which has a following error mainly related to axis velocity and position control gain of the servo controller [**2–4**]. Following errors of two simultaneously moving axes will cause a velocity-dependent path error, called the dynamic path error. The latter will finally result in the contour error of workpieces.

Different compensation methods have been developed in order to improve the contour accuracy. The most common way is to grind several testpieces before mass production and then measure their contours on a coordinate measuring machine (CMM) or cam measuring machine [**5–7**]. By comparing the measured contour to the programming contour, compensation data are calculated and inputted to the CNC controller manually. For a new workpiece, this process might need to be repeated several times. It is therefore time consuming and costly. Another way is to modify servo control algorithms to decrease the following errors and thus reduce the contour error [**8–13**]. All of them require a precise knowledge of the dynamic behaviour of the axial drive system.

In this paper, a new and efficient compensation method of contour error for non-circular grinders is introduced. The set and actual positions of each axis are collected from servo controllers during the dry run process and used to calculate the compensation data. This is independent of CNC systems and can thus be applied on a machine without modifying the interpolation or servo control algorithms. The method of contour programming, a simulation model of servo controllers, and a contour error displaying module for developing the compensation method are also introduced. Finally, the compensation method is integrated in a cam grinder CNC system, and grinding results show that it can reduce the contour error effectively.

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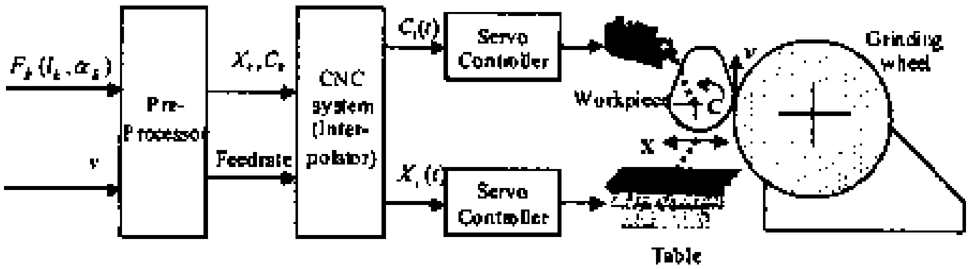


Fig. 1 Basic structure of CNC non-circular grinders

2 CONTOUR PROGRAMMING METHOD OF NON-CIRCULAR WORKPIECES

The contour of a non-circular workpiece is defined in the form of a roller lift table, which consists of a series of polar points $F_k(l_k, \alpha_k)$ along the roller's centre, as shown in Fig. 2. Here l_k is the polar radius and α_k is the polar angle; k takes values of 1, 2, ..., N, where N is the number of polar points. The normal angle θ_k of each polar point is calculated from two consecutive polar points around it under the supposition that the three points form an arc. From θ_k and radius R_g the grinding wheel position (X_k, C_k) is obtained. These positions are coordinate values in the NC program [**1**]. The calculating work is finished by the preprocessor shown in Fig. 1. The tangential velocity v of the grinding wheel contact points must be kept constant, in order to achieve good surface roughness. Given coordinates of the grinding wheel position (X_k, C_k) and tangential velocity, the CNC system interpolates set positions $X_i(t)$ and $C_i(t)$ at every interpolation cycle and outputs them to servo controllers. Servo controllers drive the motors of two axes in order to move them simultaneously in actual positions.

A cam provided by a motor manufacturer has been used for this research. Its shape and dimension are shown in Fig. 3. The cam contour consists of line and arc segments (1) to (5). On segment (1) the angular interval of the programming polar points $F_k(l_k, \alpha_k)$ is 0.5°, while on other segments it takes the value 1°. There are 541 programming polar points available for the preprocessor.

3 SIMULATION MODEL AND CONTOUR ERROR DISPLAYING MODULE

When developing the compensation method, a simulation model of servo controllers was developed. It is a simplified three-order system, as shown in Fig. 4 [**1**]. Since models of X and C axes are the same, only the schema of the X axis is illustrated.

Referring to Fig. 4, $X_i(t)$ is the set position of axis X, and e_{xi} is its following error; K_v is the position control

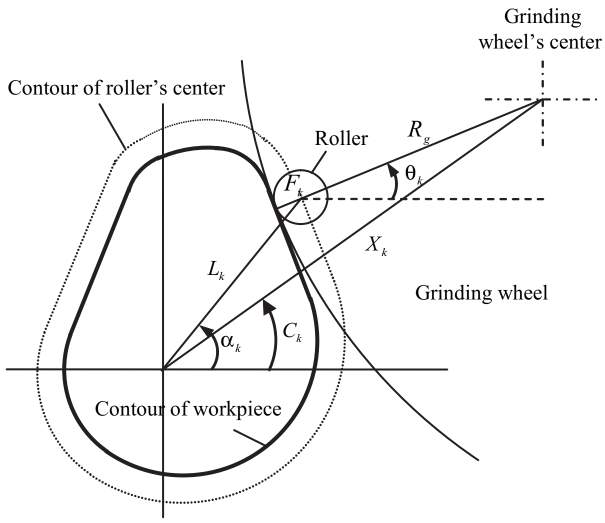


Fig. 2 Contour programming method

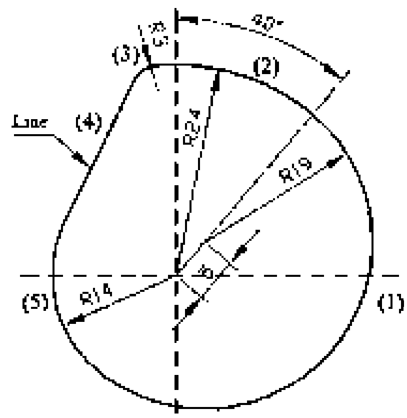


Fig. 3 The shape and dimension of a cam

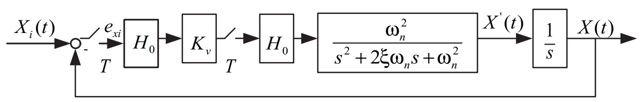
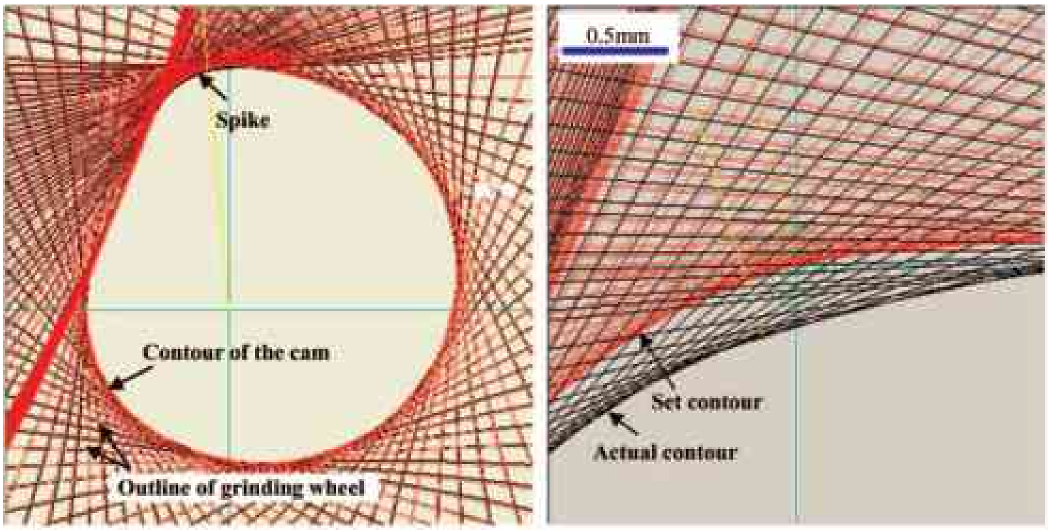


Fig. 4 The simulation model of the servo controller



(a) The overview of a cam's contour (b) An enlarged view of the contour around spike

Fig. 5 Set and simulated actual contour of a cam

gain; ω_n and ξ are respectively the natural frequency response and damping ratio of the servo motor; T is the sampling time of the servo controller, which equals the interpolation cycle; $X'(t)$ is the actual speed of the servo motor; and $X(t)$ is the actual position. Consider a middle-sized grinding machine. The values of those parameters are: $K_v = 15\,\mathrm{s}^{-1}$, $\omega_n = 80\,\mathrm{s}^{-1}$, $\zeta = 0.7$, and $T = 4$ ms.

The above model is used to get the actual positions $X(t)$ and $C(t)$ from the interpolated positions $X_i(t)$ and $C_i(t)$ through computer simulation. The contour error can then be graphically evaluated with a contour error displaying module.

In the contour error displaying module it is assumed that the grinding wheel rotates about the C axis and traverses on the X axis. With this assumption the set and actual contours of a non-circular workpiece are displayed through outlines of the grinding wheel at a series of set and actual positions. Figure 5(a) illustrates the set and simulated actual contours of the cam workpiece. An enlarged view around the spike is shown in Fig. 5(b). Since no compensation action is taken, large contour errors exist. The situation is especially worse around the spike where the X axis traverses with high acceleration and deceleration.

4 COMPENSATION METHOD

In order to generate compensation data automatically, the CNC controller samples actual positions of X and C axes from servo controllers at each interpolation cycle T during the dry run process. The set and actual XC paths of the grinding wheel centre are shown in Fig. 6(a).

The set path is defined by connecting all polar positions $P_k(X_k, C_k)$ with lines, while the actual path is by all the sampled actual positions $Q_i(X(iT), C(iT))$. For each polar position $P_k(X_k, C_k)$, there is always a point on the actual path with the same C value. Let $Q_k(X_k(t), C_k(t))$ be that actual point; then the following equation holds

$$C_k(t) = C_k \tag{1}$$

Suppose that the point Q_k locates between two consecutive actual positions $Q_{m-1}(X((m-1)T), C((m-1)T))$ and $Q_m(X(mT), C(mT))$; then $X_k(t)$ can be calculated as

$$X_k(t) = \frac{X((m\ -)T) + X(mT)}{2} \tag{2}$$

The difference of the X value ΔX_k between two points P_k and Q_k is

$$\Delta X_k = X_k - X_k(t) \tag{3}$$

which is the compensation value for the polar position P_k.

The data flow of the compensation method is shown in Fig. 6(b). The compensation analysing module collects set and actual positions and calculates the compensation data ΔX_k for each X_k; ΔX_k is then fed back to the input of the interpolator.

The compensation process can be iterative until contour accuracy meets the requirement. The previous displaying module can be used to evaluate the contour error graphically using sampled actual

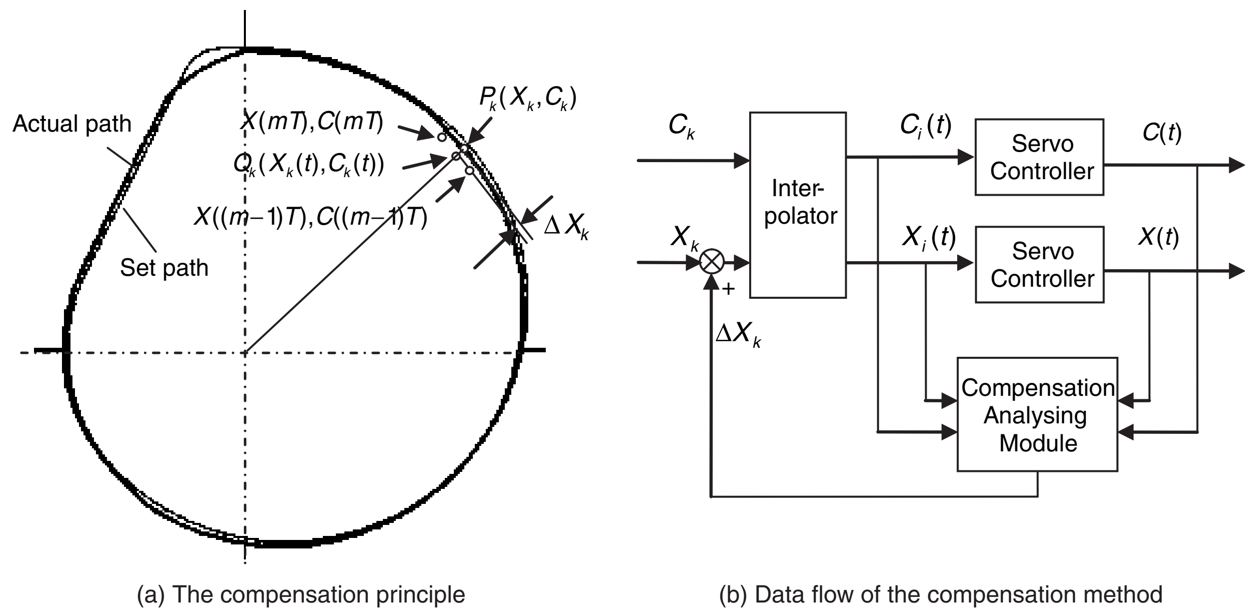


Fig. 6 The compensation method

Table 1 Maximal contour errors of each segment before and after twice compensation

Segments	(1)	(2)	(3)	(4)	(5)
Polar angle α_k (deg)	20	70	96	130	200
Before compensation (mm) (evaluated during the dry run process)	−0.036	−0.005	−0.21	0.07	0
After twice compensation (mm) (measured on the cam measuring machine)	−0.01	0	−0.03	0.02	0

positions during the dry run process instead of simulated actual positions.

The compensation analysing module was successfully integrated in a cam grinder CNC system developed by the authors. A preprocessor to calculate coordinate values (X_k, C_k) from the roller lift table is also integrated.

The workpiece shown in Fig. 3 is ground. The interpolation interval T and tangential velocity v are respectively 4 ms and 2000 mm/min. Three dry run processes are iteratively carried out on the grinder to generate the compensation data. With final compensated set points, the cam is ground and then measured on a cam measuring machine. The maximal contour errors of each segment before and after twice compensation are listed in Table 1, where the minus sign means that the cam is overcut here. It can be seen that the compensation method can reduce the contour error and satisfy the accuracy requirements.

5 CONCLUSION

This paper proposes a new and efficient contour error compensation method for CNC non-circular grinders. Unlike other existing methods, this one can be executed very quickly during a dry run process and integrated in CNC systems without looking deeply into the interpolation or servo control algorithms. Grinding results demonstrate that the compensation method can reduce contour errors effectively.

REFERENCES

1 **Ma, W.** *Study on the path error simulating and compensating method of the noncircular grinding machine.* Thesis, Beijing University of Aeronautics and Astronautics, 2002.
2 **Huan, J.** and **Ma, W.** A method based on MATLAB for calculating the dynamic path error of NC machine tools. *J. Beijing Uni. Aeronaut. Astronaut.*, 2003, **29**(4), 299–302.
3 **Ramesh, R., Mannan, M. A.,** and **Poo, A. N.** Tracking and contour error control in CNC servo systems. *Int. J. Mach. Tools and Mfg*, 2005, **45**, 301–326.
4 **Flores, V., Ortega, C., Alberti, M.,** *et al.* Evaluation and modeling of productivity and dynamic capability in high-speed machining centers. *Int. J. Adv. Mfg Technol.*, 2007, **33**, 403–411.

5 **Jywe, W. Y., Chou, C. T., Chen, C. J.,** *et al.* Development of a three-dimensional contouring measuring system and error compensation method for a CNC machine tool. *Proc. IMechE, Part B: J. Engineering Manufacture*, 2007, **221**(12), 1755–1761.

6 **Chiu, H. C.** and **Lin, T. R.** A novel reverse measurement and manufacturing of conjugate cams in a diesel engine. *Int. J. Advd Mfg Technol.*, 2005, **26**, 41–46.

7 **Jywe, W.** The development and application of a planar encoder measuring system for performance tests of CNC machine tools. *Int. J. Advd Mfg Technol.*, 2003, **21**, 20–28.

8 Siemens AG, SINUMERIK 840D/840Di/810D extended functions, 2004.

9 **Shieh, Y. S., Lee, A. C.,** and **Chen, C. S.** Cross-coupled biaxial step control for CNC EDM. *Int. J. Mach. Tools and Mfg*, 1996, **36**(12), 1363–1383.

10 **Mo, J. P. T., Squires, M. R.,** and **Brien, G. C.** Real-time automatic statistical control for the grinding process. *Proc. Instn Mech. Engrs, Part B: J. Engineering Manufacture*, 1997, **211**(3), 233–237.

11 **Tönshoff, H. K.** and **Hinkenhuis, H.** Adaptive Prozeβführung beim Konturschleifen. *wt Werkstattstechnik*, 1998, **88**, 129–134.

12 **Lechniak, Z., Werner, A., Skalski, K.,** and **Kedzior, K.** Methodology of off-line software compensation for errors in the machining process on the CNC machine tool. *J. Mater. Processing Technol.*, 1998, **76**, 42–48.

13 **Sartori, S.** and **Zhang, G. X.** Geometric error measurement and compensation of machines. *CIRP ann. – Mfg Technol.*, 1995, **44**, 599–609.

APPENDIX

Notation

C	rotational axis
$C(t)$	actual position of the C axis
$C_i(t)$	set position of the C axis
$C_k(t)$	C value of Q_k
$C(iT)$	C value of Q_i
$C((m-1)T)$, $C(mT)$	C value of Q_{m-1}, Q_m
C_k	C value of P_k
e_x	following error of the X axis
e_{xi}	following error of the X axis at the set position $X_i(t)$
e_y	following error of the Y axis
F_k	polar point in the roller lift table
H_0	zero-order holder
i	index number
K_v	servo gain
l_k	polar radius
k	index number
M	total number of interpolated positions
N	total number of polar points
P_k	point on the XC set path
Q_i	point on the XC actual path
Q_k	point on the XC actual path with the same C value with P_k
Q_{m-1}, Q_m	certain point on the XC actual path around Q_k
t	time point
T	interpolation cycle or sampling time of the servo controller
X	translational axis
$X(t)$	actual position of the X axis
$X'(t)$	actual speed of the X axis
$X_i(t)$	set position of the X axis
$X_k(t)$	X value of Q_k
$X(iT)$	X value of Q_i
$X((m-1)T)$, $X(mT)$	X value of Q_{m-1}, Q_m
X_k	X value of P_k
Y	translational axis
$Y(t)$	actual position of the Y axis
$Y_i(t)$	set position of the Y axis
α_k	polar angle
ΔX_k	compensation value for P_k
ε	path error
θ_k	normal angle of the polar point F_k
ξ	damping ratio
ω_n	natural frequency response