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Three-axis linked contour error coupled-control approach for column cams machining

Abstract*. A three-axis linked contour error coupled-control approach for column cams machining is researched in the paper, which computes contour error and contour error correction quantity with high-accuracy for linked linear axis and rotation axis on each sampling period. The contour error coupled-control experimentation results show that the introduced approach can improve matching degree among each axis and enhance profile precision further.*

Streszczenie. *Zbadan o trzyosiowy układ krzywkowy oraz urządzenie sterowania. Urządzenie oblicza błąd dopasowania do konturu krzywki i wprowadza korekcję.* (***Trzyosiowy układ sterowania mechanizmem krzywkowym***)

Keywords: column cam, contour error, coupled-control, profile precision
Słowa kluczowe: mechanizm krzywkowy, układ sterowania.

Introduction

The column cams can be manufactured with linked X linear axis, Y linear axis and A rotation axis in the vertical NC milling machine with rotary working-table [1]. CNC machine tool has complicated servo driving equipments, and the CNC system parameters may change in practical machining. Consequently, all of the linked axes actual dynamic performances don't match well, which reduces the profile precision markedly. The research results show that it is more effective to enhance profile precision, which computes the contour error and adopts appropriate contour error compensation approach on each sampling period in parts machining [2,3].

Contour error is the minimum distance from current actual cutter position to cutter path instruction curve [4]. The contour error is easy to describe, compute and compensate when linear axes linked machining. But the contour error is difficult to describe, compute and compensate when linear axis and rotation axis linked machining. The existing research productions about contour error coupled-control are applicable to two or three linear axes linked machining, but can't be applied directly in linear axes and rotation axis linked machining.

For instance, after introducing contouring error transfer function, Syh-Shiuh Yeh transforms the multi-axis cross-coupled control to a single-input-single-output system, and defines the distance of actual cutter position to the tangent on reference cutter path curve current position as contour error when three linear axes machining [5]. Myung-Hoon LEE puts forward a multi-axis contour controller based on a contour error vector using parametric curve interpolation when three linear axes machining, which is a vector from the actual tool position to the nearest point on the desired path [6]. Peng Chao-Chung introduces a new contour index (CI) aimed to arc and line profile, which can be looked as an equivalent contour error such that a reduction in CI implies a reduction in contour error [7]. By establishing a Frenet coordinate frame on a desired trajectory as the task coordinate frame, Liu Yi puts forward that contour error can be approximated by the normal component of tracking error in the task coordinate frame [8]. Zhao Ximei and Guo Qingding achieve three-axis linked contour error control on basis of calculating XY, YZ, XZ axes plane coupling model [9]. Gong Shihua deduces a cam contour error expression in camshaft grinding process in polar coordinates aimed to one linear axis and one rotation axis linked, but the contour error model is abstract and complicated [10].

As a result, in the column cam parts machining, how to compute contour error and contour error correction quantity with high-accuracy for linked linear axis and rotation axis on each sampling period, is much significant to improve matching degree among each axis and enhance profile precision. Accordingly, a three-axis linked contour error coupled-control approach for column cams machining is researched in detail in the paper, which is verified in the end on the developed three-axis linked CNC test table.

The three-axis linked contour error coupled-control flow for column cams machining

Comparing to plane cams mechanism, the column cams mechanism with compact structure, satisfied rigidity and reliable driving torque, have a remarkable superiority on intermittent dividing movement and big movement lift range [1]. However, it is difficult to describe and compute contour error under the machine tool coordinate system when manufacturing column cams with linked A axis, X axis and Y axis.

Consequently, besides the machine tool coordinate system, the space rectangular coordinate system Oxyz is built up in the paper. The contour error is described and computed under the introduced space rectangular coordinate system Oxyz, then is transformed to machine tool coordinate system to correction control.

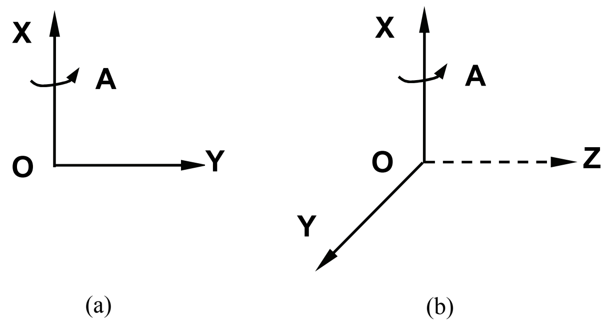

Fig.1. The coordinate system when A axis, X axis and Y axis linked machining

As shown in Fig.1(a), in the machine tool coordinate system, the X linear axis is vertical to Y linear axis, and the A axis rotates round X axis when manufacturing column cams with linked A axis, X axis and Y axis; As shown in Fig.1(b), besides the linked X linear axis and Y linear axis, the Z linear axis is introduced in the developed space rectangular coordinate system Oxyz, and the X axis, Y axis and Z axis accord with right hand rectangular Carstesian coordinate system.

The developed three-axis linked contour error coupled-control flow for column cams machining is shown in Fig.2. Above all, on the basis of A axis, X axis and Y axis linked interpolate column cams profile cutter path, measure the A axis, X axis and Y axis working-table actual positions under the machine tool coordinate system on each sampling period, and compute the contour error $\varepsilon'(\varepsilon_x', \varepsilon_y', \varepsilon_z')$ under the space rectangular coordinate system Oxyz; Secondly, obtain the corresponding contour error $\varepsilon(\varepsilon_A, \varepsilon_x, \varepsilon_y)$ and contour error correction quantity under the machine tool coordinate system; Finally, add the contour error correction quantity to following error position controlled quantity for A axis, X axis and Y axis each other, and send the superimposing results to servo driving mechanism to achieve contour error coupled-control.

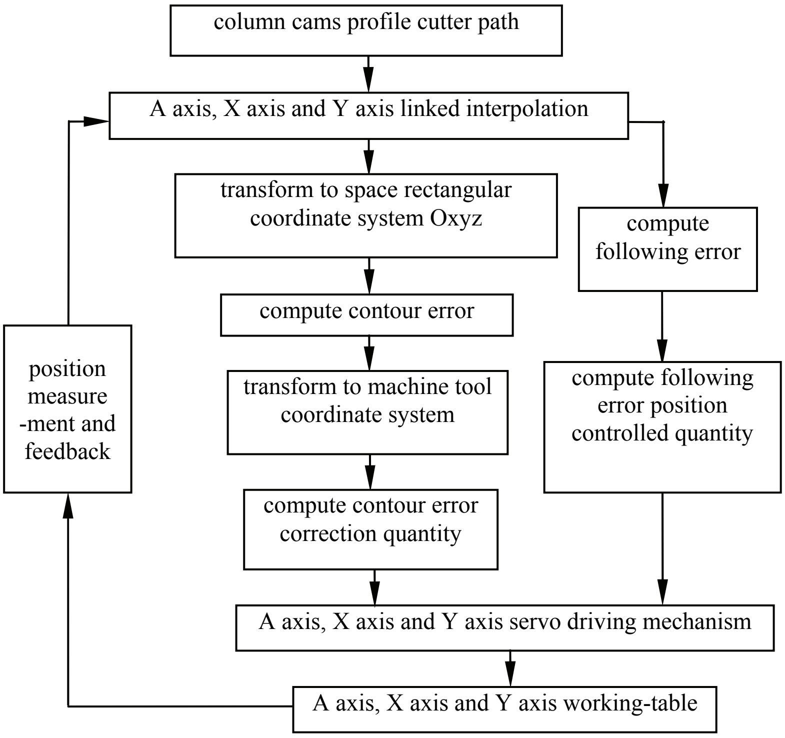

Fig.2. The three-axis linked contour error coupled-control flow for column cam machining

Contour error computing model

On each sampling period when A axis, X axis and Y axis linked interpolate column cams profile cutter path, the A axis, X axis and Y axis working-table actual positions are measured under the machine tool coordinate system with round grating sensor or linear grating sensor, and the current cutter position dot $R(R_A, R_x, R_y)$ can be obtained; Then the corresponding cutter position dot $R'(R_x', R_y', R_z')$ under the space rectangular coordinate system Oxyz can be computed:

(1) $$R_x' = R_x$$

(2) $$R_y' = R_y$$

(3) $$R_z' = R_y \cdot tgR_A$$

As shown in Fig.3, under the space rectangular coordinate system Oxyz, suppose one of the column cam profile cutter paths be L, the actual cutter position dot be R'. Above all, find the two interpolation dots Pa and Pb on the cutter path L, which are nearest to actual cutter position R'; Then the contour error under the space rectangular coordinate system Oxyz can be obtained with Equation (4):

(4) $$\varepsilon' \approx R'M$$

Suppose the intersection of R'M and cutter path L be dot N, and the maximum interpolation error be FG. Because MN≤FG, the calculation error of contour error computing model with Equation (4) is less than or equal to the maximum interpolation error.

Decompose the contour error ε' along X axis, Y axis and Z axis and obtain ε_x', ε_y' and ε_z' respectively.

Transform the contour error $\varepsilon'(\varepsilon_x', \varepsilon_y', \varepsilon_z')$ from the space rectangular coordinate system Oxyz to the machine tool coordinate system, the A axis, X axis and Y axis corresponding contour error $\varepsilon(\varepsilon_A, \varepsilon_x, \varepsilon_y)$ can be obtained:

(5) $$\varepsilon_A = arctg\frac{\varepsilon_z'}{\varepsilon_y'}$$

(6) $$\varepsilon_x = \varepsilon_x'$$

(7) $$\varepsilon_y = \varepsilon_y'$$

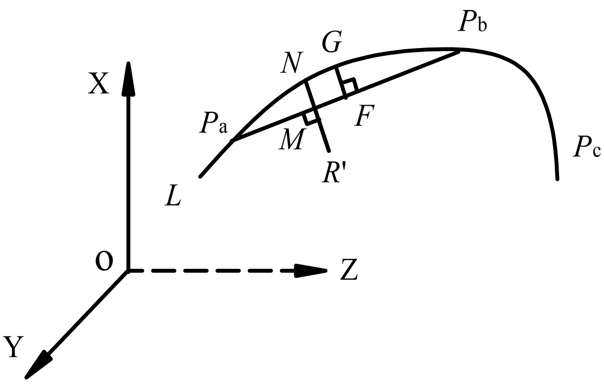

Fig.3. The contour error computing model

Contour error correction quantity computing approach

Define the controlled coefficients in A axis feeding system following error PID position controller are K_{pA}, K_{iA} and K_{dA}; The controlled coefficients in X axis feeding system following error PID position controller are K_{px}, K_{ix} and K_{dx}; The controlled coefficients in Y axis feeding system following error PID position controller are K_{py}, K_{iy} and K_{dy}. What's more, introduce the scale zoom coefficient w to compute the A axis, X axis and Y axis correction quantity:

(8) $$C_{\varepsilon A} = \varepsilon_A \cdot K_{pA}$$

(9) $$C_{\varepsilon x} = \varepsilon_x \cdot K_{px} \cdot w$$

(10) $$C_{\varepsilon y} = \varepsilon_y \cdot K_{py} \cdot w$$

Where w∈(0.9,1.1).

Contour error coupled-control experimentation

The A axis, X axis and Y axis linked CNC test table hardware framework is shown in Fig.4. The CNC controller is made up of Industrial Personal Computer (IPC) and programmable DSP control card. The IPC and DSP control card communicate through USB2.0. Both the interpolation period and sampling period are 4ms. The X axis and Y axis adopt AC servomotors and ball screw transmission, and make use of linear grating sensors to measure working-table actual position on each sampling period; The A axis adopts AC servomotor and worm-gears transmission, and makes use of round grating sensor to measure working-table actual position on each sampling period. And the interpolation arithmetic, position control and contour error coupled-control function are carried out on the programmable DSP control card.

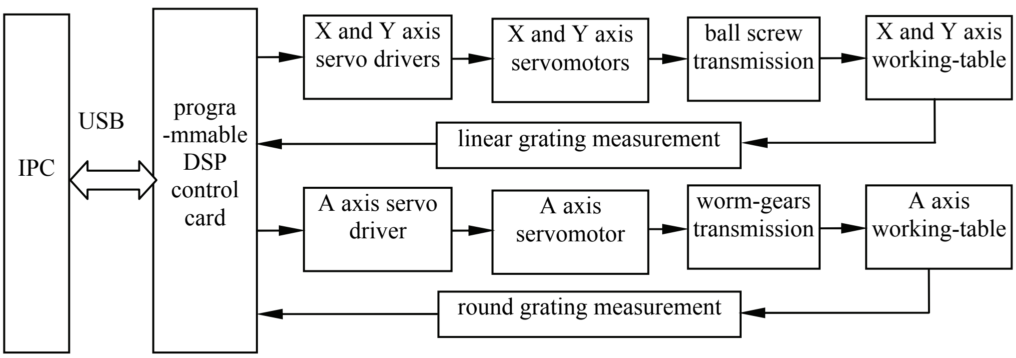

Fig.4. The A axis, X axis and Y axis linked CNC test table hardware framework

The column cam profile cutter path shown in Fig.5 is described with parameter curve form. The expression under machine tool coordinate system with linked A axis, X axis and Y axis is as follows:

$$\begin{cases} x = 100t \\ y = 35\cos 2\pi t, (0 \le t \le 1). \\ A = 2\pi t \end{cases}$$

The expression under the space rectangular coordinate system Oxyz shown in Fig.2 is as follows:

$$\begin{cases} x = 100t \\ y = 35\cos 2\pi t, (0 \le t \le 1). \\ z = 35\sin 2\pi t \end{cases}$$

The contour error curve when interpolate the above-mentioned cutter path is shown in Fig.6 and Fig.7. And the Fig.6 shows the contour error curve when not adopting the developed contour error coupled-control approach, where the contour error maximum is about 0.107mm; At the same working circumstance, the Fig.7 shows the contour error curve when adopting the developed contour error coupled-control approach (w=1.05), where the contour error maximum is about 0.067mm.

The experimental results show that the developed A axis, X axis and Y axis linked contour error coupled-control approach can reduce contour error effectively, enhance profile precision further and improve A axis, X axis and Y axis linked matching degree.

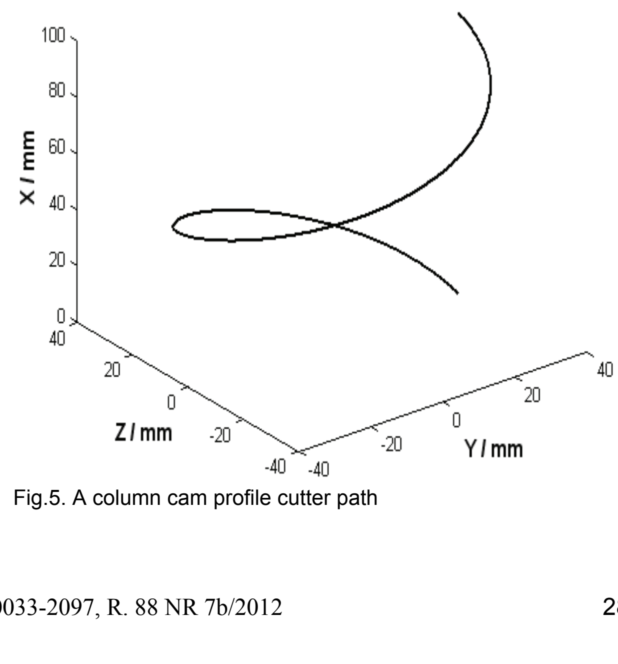

Fig.5. A column cam profile cutter path

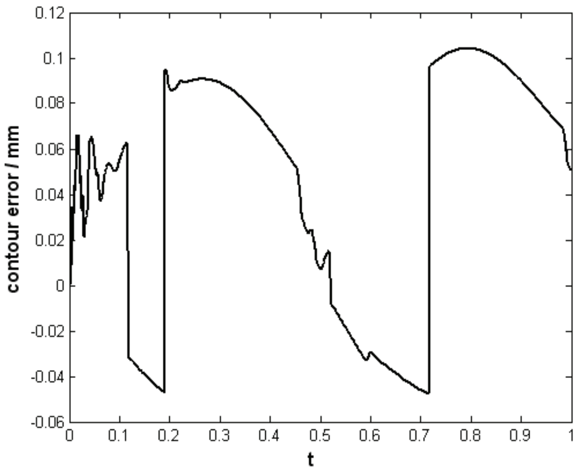

Fig.6. Contour error curve when not adopting the developed contour error coupled-control approach

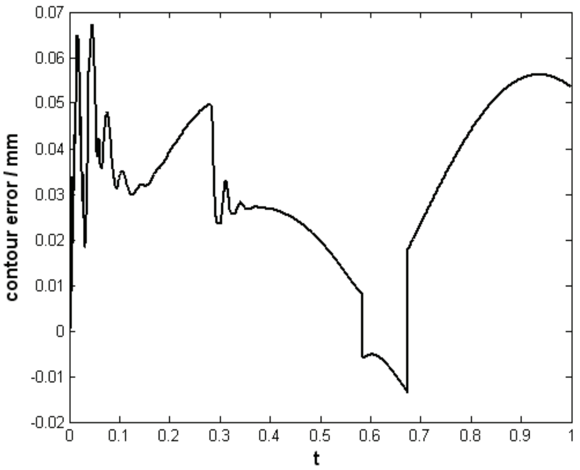

Fig.7. Contour error curve when adopting the developed contour error coupled-control approach

Conclusions

Column cams belong to spatial cams, which can be divided into linear follower column cams and swing follower column cams according to follower movement mode.When manufacturing column cam parts with linked A rotation axis, X linear axis and Y linear axis, the abstract contour error under machine tool coordinate system is transformed to the developed space rectangular coordinate system Oxyz to describe in the paper; The introduced contour error computing model which makes use of the actual cutter position and the two interpolation dots on the cutter path that are nearest to actual cutter position, has a high calculation-precision, and the calculation error of contour error computing model is less than or equal to the maximum interpolation error; The contour error correction quantity computing approach is easy and effective, which uses the introduced scale zoom efficient and the proportion efficient in following error PID position controller of each axis.

The developed contour error coupled-control approach in the paper is fit for rotation axis and linear axis linked control, and can be applied and generalized in CNC system and CNC machine tool for column cam parts machining.

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