A Study on Tool Path Error Control for Disk Cams in a Five-Axis CNC Machining Center

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Abstract: In this paper, we propose a simple but optimized NC code generating technique for disk cams by means of tool path error control in a five-axis CNC machining center. Using the geometric theorem of the triangle made between manufacturing points and error checkpoint, the tool path error has been studied for disk cams profile generation and an improvement in the profile has been obtained. Then, based on the present manufacturing approach a computer program is developed on C^{++} language to perform and to verify the shape design, the manufacturing simulation, and the optimized generation of the NC code.

Key Words: Tool Path Error, Disk Cam, five-Axis CNC Machining Center, NC Code

1. Introduction

Automation with cam mechanisms, although they offer a low degree of flexibility, are frequently used due to their low cost and to the fact that they provide the simplest way of achieving almost any desired follower motion. It has been widely or generally used the three-axis CNC machining center for the manufacturing of disk cams. For the case of manufacturing of combined disk cams (three or more disk cams) with single cam shaft, however it is not possible or difficult to manufacture such cams using the traditional three-axis CNC machining center. A five-axis CNC machining center is presently one of the most versatile machine tools available for such disk cams and they are becoming increasingly common. To increase the accuracy capabilities of such a machine, it is crucial to be able to study the geometric errors of the components and its effect on the quality of machined products.

It should be noted that the paper does not focus on the geometric error of the structural elements of the milling machine, such as positioning errors of the machine axes, spindle errors, thermally induced geometric errors, etc. We will confine ourselves to the influence of the specific geometric-kinematic factor, namely the particular tool path that guides the cutting tool. In other words, we investigate the extent to which the machining tool path evaluated by the CAD/CAM computer contributes to the inaccuracy of a machined disk cam.

To improve part quality with minimal machining time (i.e. to create the well-compensated NC code) for the disk cams in a five-axis CNC machining center, the control of tool path calculation with minimal error and its communication to the NC unit are imperative. Generally, the tool motion functions can be described utilizing linear, circular, polynomial or spline interpolation algorithms. The application of linear interpolation algorithms (first-degree functions), leads to follower velocity and acceleration discontinuities, which cause vibrations, mainly in high-speed mechanisms. The use of second-degree functions, as a basis for circular interpolation algorithms, eliminates the follower velocity discontinuities and may lead to satisfactory results regarding the dynamic behavior of the cam mechanism. Using a circular interpolation algorithm a certain number of cam profile points, regarding minimum distances between them, is required. Small increments between successive points may lead to undercutting and the NC code size increases considerably. Furthermore, a successive change of the curvature of the circular arcs from convex to concave is caused and significant deviations of the real transfer functions (velocity, acceleration, etc.) from the corresponding calculated ones occur. Using higher-degree functions, such as interpolation equations, like polynomials or splines, continuous second and higher order cam transfer functions can be achieved. The applicable spline degree depends on the interpolation facilities of the NC machine. To determine the number of the cam interpolation regions, the cam accuracy and the permitted transfer functions deviations have to be considered.

In the present paper, we propose a simple but optimized NC code generating technique for disk cams by means of tool path error control in a five-axis CNC machining center. Using the geometric theorem of the triangle made between manufacturing points and error checkpoint, the tool path error has been studied for disk cams profile generation and an improvement in the profile has been obtained. Then, based on the present manufacturing approach a computer program is developed on C^{++} language to perform and to verify the shape design, the manufacturing simulation, and the optimized generation of the NC code.

2. The Manufacturing of Disk Cam Mechanism

There are many kinds of cams with various followers. The general methods for the shape design of the cam include graphic layout method and analytic ones. In a way of the shape design of the cam, recently, Shin et al. [1-3] presented an approach to the shape design of disk cam based on the relative velocity of a follower versus a cam and the shape of the follower using the velocity graphics, and to determination of the curvature radius of disk cams using acceleration graphics. Following the above-mentioned researches [1-3], the entire shape of disk cams can be determined via coordinate transformation as follows (see Ref. [4] for more details)

$$\begin{aligned} C_{x1} &= Q_{x1}\cos\theta_c + Q_{y1}\sin\theta_c \\ C_{y1} &= -Q_{x1}\sin\theta_c + Q_{y1}\cos\theta_c \end{aligned} \tag{1}$$

where θ_c is an angle of cam rotation. Also Q_{x1} and Q_{y1} represent contact points on the shape design-coordinate, given by:

(Case 1) Translating roller follower:

$$\begin{aligned} Q_{x1} &= \varepsilon + r_r\cos(\phi - 90) \\ Q_{y1} &= h + r_r\sin(\phi - 90) \end{aligned} \tag{2}$$

(Case 2) Translating flat-faced follower:

$$\begin{aligned} Q_{x1} &= e \\ Q_{y1} &= h + (e - \varepsilon)\tan(\phi - 90) \end{aligned} \tag{3}$$

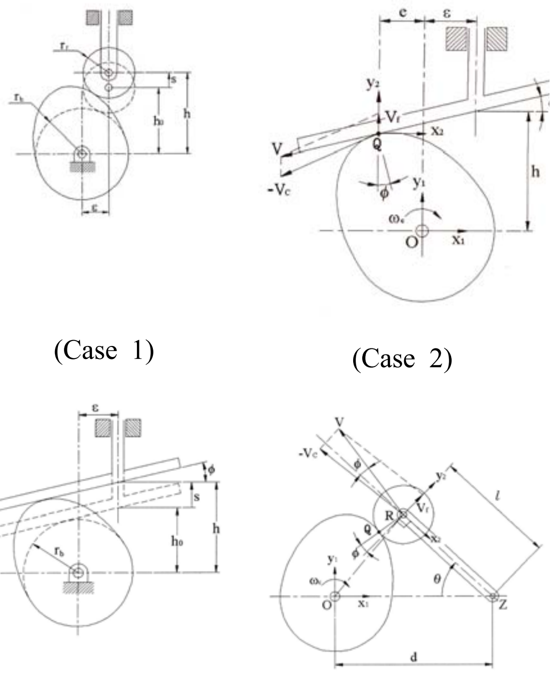
(Case 3) Oscillating roller follower:

$$\begin{aligned} Q_{x1} &= d - l\cos\theta + r_r\cos(\phi - \theta - 90) \\ Q_{y1} &= l\sin\theta + r_r\sin(\phi - \theta - 90) \end{aligned} \tag{4}$$

(Case 4) Oscillating flat-faced follower:

$$\begin{aligned} Q_{x1} &= d + \varepsilon\sin\theta - l\cos\theta \\ Q_{y1} &= \varepsilon\cos\theta + l\sin\theta \end{aligned} \tag{5}$$

where the notations in Eqs. (2)-(5) can be found in Fig. 1.



(Case 1) (Case 2)

(Case 3) (Case 4)

Fig. 1 Various types of disk cam

A 5-axes machine tool has the ability of simultaneously positioning and orienting the cutting tool in some coordinate system defined in the work space. This makes such a machine tool very versatile. The configuration of the 5-axes CNC machining center can be assembled in several ways. In this study, horizontal 5-axes machining center is used, which consist of the usual three translation motion axes (Z_2, Z_3, Z_4) and two rotation axes (Z_0, Z_1), as shown in Fig. 2.

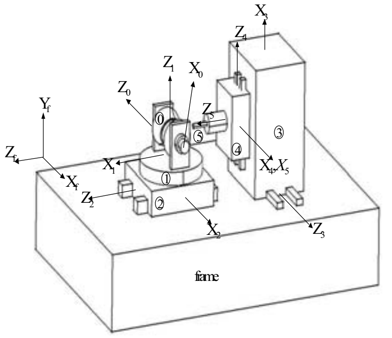


Fig. 2 A 5-axes CNC machine center configuration set-up

From the shape design data, the tool location of rough and finishing manufacturing with general tools is defined in Fig. 3.

The cutter location is calculated from the shape data of the disk cam, given by:

$$T^0_{xi} = Q^d_{xi} \tag{6}$$

$$T^0_{yi} = Q^d_{yi} \tag{7}$$
$$T^0_{zi} = \xi + TD/2 \tag{8}$$

where $\{Q^d\}$ represent contact points of Eqs. (2)-(5) in the shape-design-coordinate, $\xi = i \times TD$ ($i = 1,2,3 \cdots n$) and TD is a tool diameter.

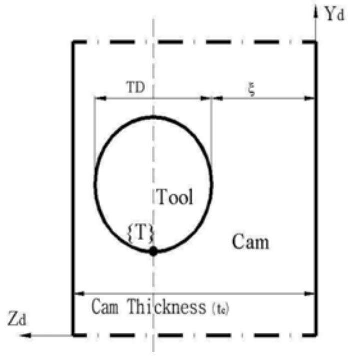


Fig. 3 Cutter location with respect to contact point of the disk cam

To extract NC-code data in a 5-axes machining center, the tool path position and orientation will be defined via coordinate mapping technique. In performing a manufacturing, it is necessary to coincide the machining point with design-coordinate X_d. It is possible to perform a rotational transformation between tool-coordinate $t(X_t, Y_t)$ and design-coordinate $d(X_d, Y_d)$. Also, to obtain the translation motion data, we map work-coordinate f into shape-design-coordinate d (see Figs. 4 and 5).

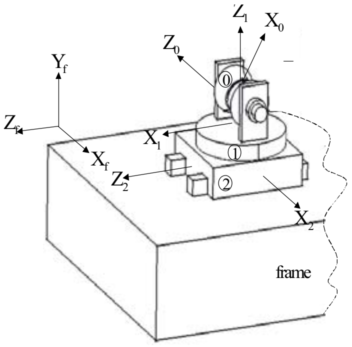


Fig. 4 Coordinate systems of workpiece on a 5-axes CNC machining center

After such a consideration, we lead to the following NC-code generation equation

$$\{N\} = [R^f_d][R^t_d]\{T^0\} \tag{9}$$

where

$$[R^t_d] = \begin{bmatrix} \cos\theta_c & \sin\theta_c & 0 & 0 \\ -\sin\theta_c & \cos\theta_c & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{10a}$$

$$[R^d_f] = \begin{bmatrix} \cos 90 & 0 & \sin 90 & 0 \\ 0 & 1 & 0 & 0 \\ -\sin 90 & 0 & \cos 90 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{10b}$$

Therefore, the NC-code for the above four types of the disk cam can be expressed as

$$\begin{aligned} N^T_X &= T^0_{zi} \\ N^T_Y &= -T^0_{xi}\sin\theta_c + T^0_{yi}\cos\theta_c \\ N^T_Z &= -T^0_{xi}\cos\theta_c - T^0_{yi}\sin\theta_c \\ N^R_A &= \theta_c \\ N^R_B &= \alpha + \delta \end{aligned} \tag{11}$$

where α is the rotation angle of the tool which is dependent of the cam type, and here δ is the interference corrected angle to avoid tool interference under the consideration of the negative curvature.

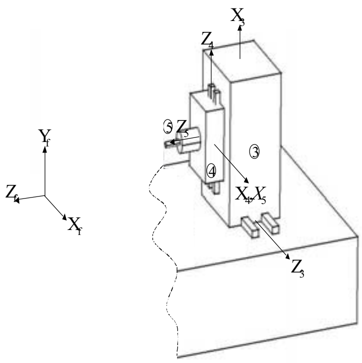


Fig. 5 Coordinate systems of spindle on a 5-axes CNC machining center

3. Tool Path Error Control by Biarc Algorithm

In programming the tool path of CNC machinery, fewer arc segments can help to improve the production efficiency by reducing the number of instructions and tool motions. In particular, the quality of cam depends upon the machine tool errors. A biarc [5] can be described as two connected circular arcs with an identical tangent at the connecting point. At the connecting point, C^1 tangent continuity is maintained. Furthermore C^2 curvature continuity can be improved if the difference between two curvatures at the connecting point is minimized. The tolerance constraint can be specified as the largest deviation distance between the curve and the approximating biarcs. From the machining point of view, circular interpolation is the basic function in most NC machines. Therefore, biarcs are suitable for tool-path generation and NC code generation.

A circular arc can be defined by a center, a start point, and an end point. Two circular arcs can be linked if the end-point of the first arc and the start point of the second arc are connected. If the tangents of the two circular arcs are the same at the connecting point, then two circular arcs composes a biarc.

In the present study, we adopted the biarc algorithm by proposed by Bolton [5]. In Fig. 6, a biarc composed of two circular arcs is illustrated.

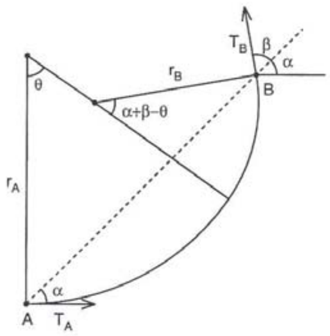


Fig. 6 A biarc matching G^1 Hermite data

As shown in the figure, using the geometric theorem of the triangle the following equation can be made

$$P^2 - 2P(R_1C_1 + R_2C_2) + 2R_1R_2(S_1S_2 + C_1C_2 \pm 1) = 0 \tag{12}$$

where $P = |P_1 - P_2|$ is the chord length, C_i and S_i $(i=1,2)$ denote $\cos\theta_i$ and $\sin\theta_i$, respectively. Also the sign ± in the last term of left hand side of equation means the unimodal (C-shape) and inflection (S-shape) biarcs, respectively.

If we set R_1, the radius R_2 can be evaluated as follows

$$R_2 = \frac{P^2 - 2PR_1C_1}{2PC_2 - 2R_1(S_1S_2 + C_1C_2 \pm 1)} \tag{13}$$

Using Eq. (13), tool path error can be controlled by standard permitted tool path error. Figure 7 shows tool path error defined by vertical distance between real tool path and linear tool path.

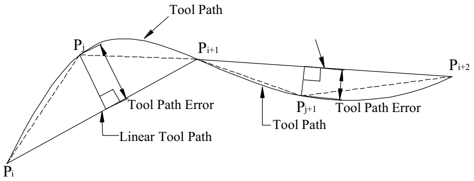


Fig. 7 Definition of tool path error

A tool path error at an arbitrary point P_j can be evaluated by using the Pythagorean theorem of the triangle as follows (see Fig. 8):

$$\text{ERROR} = \sqrt{a^2 - \left(\frac{a^2 + c^2 - b^2}{2c}\right)^2} \tag{14}$$

where

$$a = \sqrt{(P_{xi} - P_{xj})^2 + (P_{yi} - P_{yj})^2 + (P_{zi} - P_{zj})^2} \tag{15a}$$

$$b = \sqrt{(P_{xj} - P_{xi+1})^2 + (P_{yj} - P_{yi+1})^2 + (P_{zj} - P_{zi+1})^2} \tag{15b}$$

$$c = \sqrt{(P_{xi} - P_{xi+1})^2 + (P_{yi} - P_{yi+1})^2 + (P_{zi} - P_{zi+1})^2} \tag{15c}$$

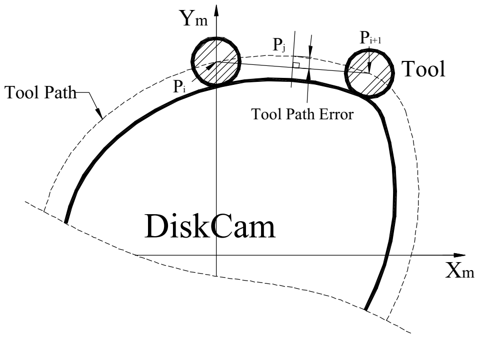
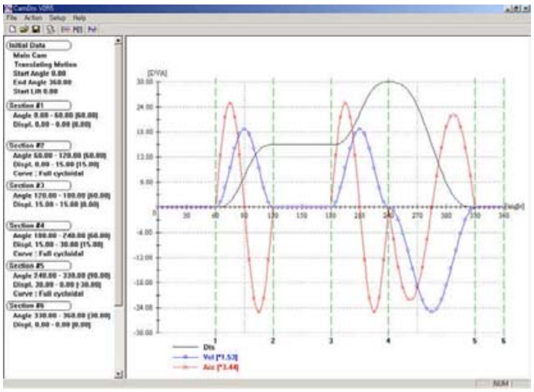


Fig. 8 Tool path error control in disk cam

4. Numerical Examples

A CAD/CAM program, DiskCam , is developed on C^{++} language. This program can perform the shape design, the simulation of the manufacturing procedure and the kinematics simulation, which can make the integral NC-code for the 5-axis CNC machining center.

Fig. 9 displays the displacement, velocity and acceleration curves for the disk cam mechanism.


Initial Data
Main Cam
Translating Motion
Start Angle 0.00
End Angle 360.00
Start Lift 0.00

Section #1
Angle 0.00 - 60.00 [60.00]
Displ. 0.00 - 0.00 [0.00]

Section #2
Angle 60.00 - 120.00 [60.00]
Displ. 0.00 - 15.00 [15.00]
Curve : Full cycloidal

Section #3
Angle 120.00 - 180.00 [60.00]
Displ. 15.00 - 15.00 [0.00]

Section #4
Angle 180.00 - 240.00 [60.00]
Displ. 15.00 - 30.00 [15.00]
Curve : Full cycloidal

Section #5
Angle 240.00 - 330.00 [90.00]
Displ. 30.00 - 0.00 [-30.00]
Curve : Full cycloidal

Section #6
Angle 330.00 - 360.00 [30.00]
Displ. 0.00 - 0.00 [0.00]

Fig. 9 Displacement, velocity and acceleration curves for cam mechanism

Fig. 10 depicts the integral simulation for assembled process of disk cam mechanism and five-axis CNC machine center

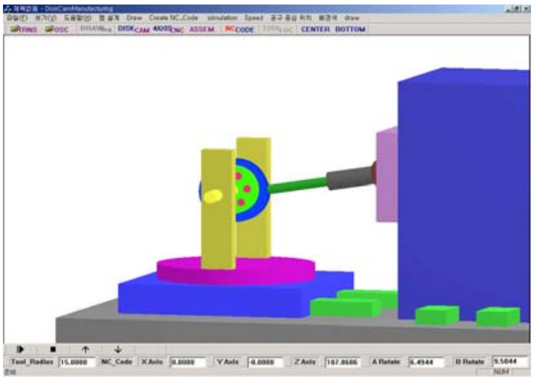


Fig. 10 Integral simulation for assembled process in a 5-axes CNC machine center

5. Conclusions

This paper proposes an approach for the shape design and manufacturing of the disk cam via tool path error control in a 5-axes CNC milling machine. The following conclusions can be drawn.

(1) The cutter location and cutter orientation are defined for the manufacturing of the 5-axes machining center from the shape data based on the relative velocity method.
(2) The integral NC code for multi-axis CNC machining center is proposed using the coordinate transform method from the data of location and orientation of cutter path on a horizontal 5-axes machining center which is consist of three linear motion axes and two rotation axes.
(3) To improve the quality of the cam, the tool path error is controlled by biarc algorithm and geometric theorem of the triangle.
(4) A CAD/CAM program, DiskCam , is developed on C^{++} language. This program can perform shape design, manufacturing and kinematics simulation, which can make integral NC code for multi-axis CNC machining center.

References

[1] Shin, J.H., Kang, D.W., Kim, J.S. and Kim, D.W., 2000. A study on shape design approach of disk cams using relative velocity of followers. J. of the Korean Society of Precision Engineering, 17 (2), 185-192.
[2] Shin, J.H., Kang, D.W., Kim, J.S. and Kim, D.W., 2000. A study on curvature determination approach of disk cams using relative velocity of followers. J. of the Korean Society of Precision Engineering, 17 (8), 113-119.
[3] Shin, J.H., Kang, D.W., Yoon, Y.H. and Zhang, Y.H., 2001. An approach to shape design of disk cams using relative velocity of followers. Proceedigns of the International Symposium on Mechanical Transmissions, 1, 347-351.
[4] Kang, D.W., 2000. A study on design automation technology of complex mechanisms with disk cams and cylindrical cams for multi-axis motion control. Ph.D. Thesis, Changwon National University, Korea.
[5] Bolton, K.M., 1975. Biarc curves, Computer Aided Design, 7(2), 89-92.