International Journal of Machine Tools and Manufacture 128 (2018) 33–40

Contents lists available at ScienceDirect

International Journal of Machine Tools and Manufacture

journal homepage: www.elsevier.com/locate/ijmactool

Accurate three-dimensional contouring error estimation and compensation scheme with zero-phase filter

Chuxiong Hu [a,b,*], Ze Wang [a,b], Yu Zhu [a,b], Ming Zhang [a,b]

[a] State Key Lab of Tribology, Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China
[b] Beijing Key Lab of Precision/Ultra-Precision Manufacture Equipments and Control, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Keywords:
Contouring motion control
Newton algorithm
Position compensation
Contouring error
Three-axis system

ABSTRACT

Contour following is an important research topic for multi-axis CNC systems. In this paper, to simultaneously meet the challenges of accurate contouring error estimation and high-performance contouring control those are very significant for three-dimensional contouring following tasks, a numerical calculation based contouring error estimation and contour compensation scheme is proposed. Unlike any existing geometric approximation methods, the proposed scheme calculates the contouring error through a numerical calculation algorithm. Specifically, a cost function is defined as the spatial distance between the actual point and the point located on the reference contour. When the minimum value of the cost function is obtained through the numerical calculation, accurate contouring error vector can be obtained even under extreme contouring tasks with high-speed, large-curvature and sharp-corner. Then, the calculated contouring error is projected to each axis. After a zero-phase filter with low-pass characteristic, the axial contouring error is fed back to the corresponding axis as a kind of contour compensation. The added filter can effectively suppress the high-frequency noise widely existing in contouring error signal. Moreover, our proposed contour compensation scheme can be realized iteratively for further improvement of contouring performance. Various comparative experiments are performed to verify the effectiveness of the proposed contouring error estimation and compensation scheme. The results demonstrate that in comparison with traditional position loop CCC method, the proposed scheme can achieve not only nearly perfect contouring error estimation but also obvious promotion of contouring accuracy.

1. Introduction

In advanced machining process, contour following of multi-axis motion system is one of the most important tasks [1–3]. Contouring error, which is defined as the shortest distance between the actual position and the reference contour, is an important index in contouring motion tasks [4]. To improve the tracking accuracy of individual axis, there exist many advanced tracking control strategies such as ZPETC [5], optimal feedforward control [6], adaptive control [7,8], learning control [9,10], and so on. However, due to the dynamics incompatibility between different axes, the tracking accuracy improvement of each axis cannot guarantee the contouring error reduction [11]. In order to further consider the coordination between different motion axes, cross coupled control (CCC) for biaxial systems was proposed by Koren [12,13]. In CCC, the contouring error is estimated according to geometrical relationship between the axial tracking errors and the reference contour. Based on the estimated contouring error, additional control actions are generated to improve the actual contouring performance. Based on the thought of CCC, many kinds of contouring control strategies have been reported, such as CCILC [14], fuzzy logic CCC [15], adaptive CCC [16] and so on. In the aspect of contouring error estimation, the tangent-line approximation approach is widely used in not only above CCC based strategies but also some other contouring control schemes, i.e., tangential-contouring control [17] and task coordinate frame (TCF) [11]. This approximation approach can achieve effective contouring error estimation, but its estimation accuracy deteriorates significantly in some extreme cases such as high feedrate and large contour curvature [18]. To cope with this problem, various attempts were proposed, such as curvature circle based contouring error estimation method [19], point-by-point comparison method [20], contour index [21], task polar coordinate frame [22], global task coordinate frame (GTCF) [23], numerical calculation methods [24] and so on. In order to enlarge the application range of CCC in biaxial motion systems, some position loop CCC schemes were also proposed [25,26], in which CCC controller could

* Corresponding author. State Key Lab of Tribology, Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China.
E-mail address: cxhu@tsinghua.edu.cn (C. Hu).

https://doi.org/10.1016/j.ijmachtools.2018.01.001
Received 10 November 2017; Received in revised form 22 November 2017; Accepted 11 January 2018
Available online 31 January 2018

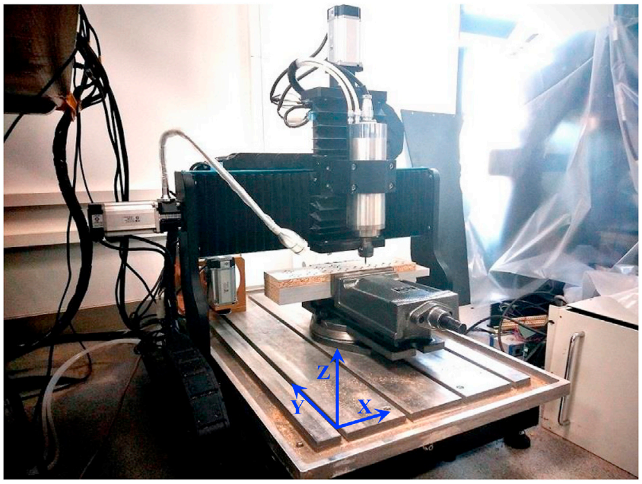

Fig. 1. The industrial three-axis mechatronic motion system.

Table 1
PID Parameters of each axis.

	K_p	K_i	K_d
X	62.5	500	0.1
Y	36	400	0.1
Z	100	1200	0.3

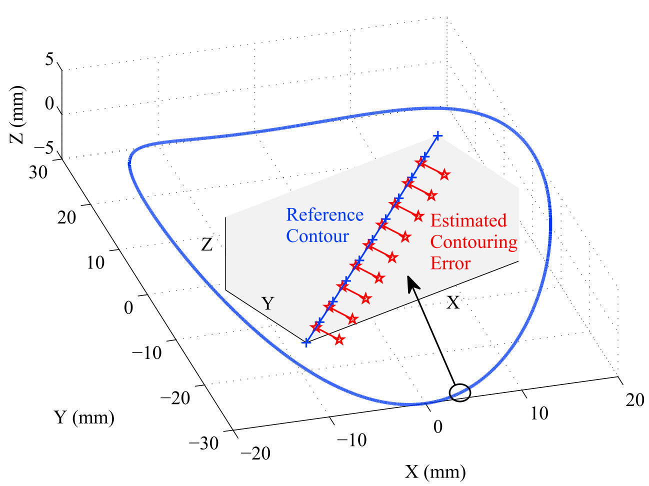

Fig. 2. Reference contour and contouring error estimation of C3 in Case I.

be viewed as a kind of simple reference compensation in the position loop [27]. Therefore, these methods can be effectively utilized in servo systems with built-in motion controllers. In summarize, there are many effective methodologies focusing on biaxial contouring control [28]. However, for contouring tasks in three-dimensional space, the kinematics relation between different axes should be further considered.

In [29], traditional CCC method was expanded to three-axis systems. Specifically, the estimated contouring error vector lies on the plane expanded by the tracking error vector and the tangential vector at the desired point. The estimated contouring error vector is also orthogonal to the tangential vector. In this three-axis CCC method, the drawback of biaxial CCC algorithm is further enlarged, i.e., both large tracking error and large curvature of the reference contour would severely affect the accuracy of the contouring error estimation. On the other hand, the contouring error is controlled by a single contouring controller and the control action is then allocated to three axes. As the kinematics characteristic of the three-axis system is more complicated than that of the

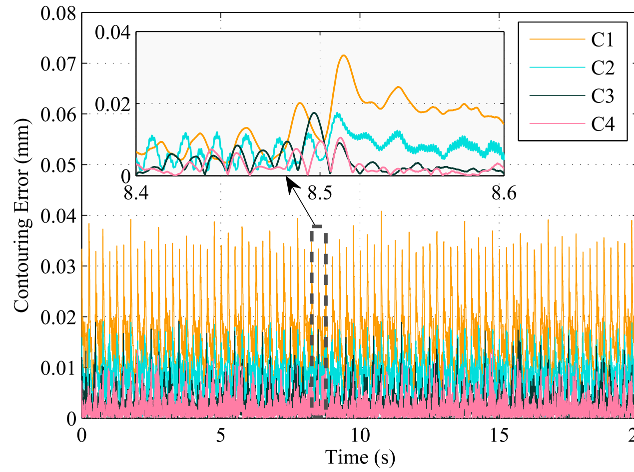

Fig. 3. Contouring errors in Case I.

biaxial one, the single contouring control is actually hard to design. To make contouring controller design more flexible, a two-layered CCC was proposed in [4]. In this method, two components of the estimated contouring error, i.e., the component in the X-Y plane and the component perpendicular to the plane, are controlled separately. Therefore, contouring error is controlled by two different controllers, which can be designed reasonably according to the dynamic characteristics of different components. Similarly, the decoupled contouring error and the tangential error can be individually controlled by the TCF method presented in [11]. To further facilitate the application of CCC in motion systems with more than three axes, many researches inherit the idea of position loop CCC in biaxial systems [25]. For example, an online point-by-point scheme was utilized in [30,31] to estimate contouring error, and then the component of the contouring error along each individual axis could also be obtained. After a simple proportional gain, all the components are fed back to the position loop of different axes to improve the contouring performance. This method is easy to realize, but the estimation accuracy of the contouring error is limited. In addition, there exists unavoidable high-frequency noise in the components of the contouring error, which is adverse to the smoothness of the reference trajectory. If the above feedback gain is high enough, unsmoothed reference trajectory will cause unexpected vibration of CNC systems. To suppress the above high-frequency noise, simple proportional gain used in [31] was supplanted by a specially designed compensator [32]. However, the stability of this compensator is based on the assumption that the position loop servo of each individual axis is a linear-time-invariant system, which is usually difficult to satisfy in practical situations.

It can be concluded that, the main issues of existing contouring control methods lie in two aspects, i.e., accurate contouring error estimation and effective contouring error control. To address these two problems for three-axis motion systems, a numerical computation based accurate contouring error estimation method and the corresponding position loop compensation strategy are proposed in this paper. Specifically, a cost function is defined to represent the distance between the actual position and the reference contour in three-dimensional space. The Newton algorithm [33] is then carried out to calculate the minimum value of the cost function which is defined as the contouring error. The convergence of the proposed Newton algorithm is proved theoretically. Compared with other geometrical relationship based contouring error estimation algorithms, contouring error with extraordinary accuracy can be obtained in the proposed numerical calculation method. Before being fed back to the position loop, the components of the contouring error are filtered by a low-pass filter which can suppress the high-frequency noise effectively. With the purpose of avoiding unexpected phase lag, the filter is designed as a zero-phase filter. Inspired by the thought of iterative learning control [34], the above position compensation scheme can be