Analysis and Compensation Strategy of Non-linear Error in Five-Axis CNC Machining

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Abstract. This paper presents a new strategy of analysis and compensation of non-linear error. Non-linear error is an important source of machining error in multi-axis numerical controlled machining and it is unavoidable. In view of tool positions optimization in five-axis CNC machining of complex surface, this paper presents a strategy for non-linear error compensation in five-axis machining: Firstly, non-linear error caused by the change of tool axis vector is analyzed and the non-linear error model is established, in order to get the maximum non-linear error of interpolation segment; Then, the tool position that meets the machining accuracy is obtained; Finally, Simulation and analysis of the model show that the proposed method is effective and greatly improves the geometric accuracy.

Introduction

Five-axis CNC machining plays a pivotal role in the complex and high-precision machining fields, because of its high flexibility, high compound and excellent cutting tool position profile [1]. Five-axis CNC control systems generally use linear interpolation. However, the actual movement trajectory between two adjacent cutter locations is a space curve rather than the ideal programming line, which can cause the processing error. The processing error contains linear error and non-linear error. Non-linear error in five-axis CNC machining is first proposed by Takeuchi.Y in 1992, but its definition is still confusion. Che-Hua She and some person called that non-linear error is a deviation between theoretical linear interpolation trajectory and free curve trajectory. At present, this definition is One of the most common explanation [2]. Through the analysis of CNC machine inverse kinematic chain, O.Remus Tutunea-Fatan and His-Yung Feng made a detailed elaboration of the generation and influence of non-linear error [3].

The previous research methods for nonlinear error, mainly comes two types: (1) Real tool path replaced by arc or chord to approach theoretical tool path, and then, each tiny line segment is investigated: each chord projection projects on 2d plane and chord height is calculated. Finally, chord height error is regarded as nonlinearity error. (2) Approximation error and rotation error of tiny line segment is separately compensated, chord height error is calculated before the rotation error calculation, and then the rotation error is calculated [4,5].

It exits two kinds of ways to control non-linear error [6]: one is to control non-linear error in the NC system, in other words, to control it in the pre-processing; the other one is to control it in the post-processing. This paper is to make a deep study on post-processing method. Non-linear error is a specific error for five-axis CNC machining. Machining accuracy of complex surface and non-linear error are deeply bonded. So how to control non-linear error effectively is a key issue for complex surface in five-axis CNC machining.
Analysis and control of the machining error in five-axis CNC machining

The non-linear error analysis. As shown in figure 1, because of the uncertainty of cutter contact point on the tool envelope surface in the actual interpolation processing, CNC system can only choose fixed tool position point on the tool or fixed machine axes position. The change of the tool position and tool direction in the interpolation process are all linear, but the theoretical tool path non-linear, so the actual tool contact point trajectory deviates from the theoretical tool contact point trajectory. The maximum distance between the two trajectory above is non-linear error $\delta_n$. Non-linear error only exists during machine translation axis and machine rotary axis move together. It is also closely depended on the choice of linear interpolation points in CNC system.

As shown in figure 2, It is easy to find that the influence of non-linear error on machining precision relates to the concavity and the convexity of curve and surface. When the normal curvature of machining surface along the feed direction is greater than zero, the machining error is the sum of linear $\delta_l$ and non-linear errors $\delta_n$, which is called undercutting; on the contrary, it is named as less cutting.

In the state of less cutting, the non-linear error $\delta_n$ is included in the linear error $\delta_l$, which decreases the processing error. In the state of undercutting, the existence of the non-linear error increases the machining error. Therefore, the non-linear detection and the tool path control of convex surface portion needs to be considered in the tool posture optimization.

The non-linear error detection and compensation. Given the low overall efficiency of CNC programming system, the optimization model is required to be as simple as possible to detect the non-linear error. As shown in figure 3, in the convex surface machining, the processing error was always larger than the maximum permissible error all the time by using cutter location point interpolation method. So the traditional cutter location point interpolation method is not applicable to non-linear error control. In this paper, the non-linear error is controlled in post-processing stage. Therefore, the non-linear error compensation method can be improved with considering the tool section information and the surface geometry information.

Because of the continuous surface between the adjacent cutter contact points, the curvature of each point on theoretical contour lines changes continuously. Non-linear error is caused by rotation axis. It is not evenly distributed through inserting with the intermediate tool orientation during interpolating. In this paper, according to the method of normal vector sum on the adjacent tool contact points, the cutter contact position on the theoretical contour line can be calculated conversely. And this point is
used as the interpolation cutter contact point of the non-linear error compensation. Meanwhile the tool orientation of the point is assumed to be the sum of adjacent tool orientation. According to the surface geometry information and the cutter orientation, the cutter position of the compensation point can be calculated. Algorithm process is shown in figure 4.

The tool contact position is inserted by non-linear error compensation:

$$P_{\text{iter}} = P(n_i + n_{i+1})$$

The intermediate tool orientation is inserted by non-linear error compensation:

$$T_{\text{iter}} = T_i + T_{i+1}$$

Fig. 3 The cutter location point interpolation method and The Curvature midpoint interpolation method

Fig. 4 The flow chart of non-linear error compensation

The tool contact position is inserted by non-linear error compensation:

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The intermediate tool orientation is inserted by non-linear error compensation:

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The example analysis

The non-linear error compensation strategy is verified in this example by non-linear error detection and non-linear error compensation of tool position. Figure 5 is a 3D simulation renderings, which is established through Rosen gradient projection method. This example uses a flat rounded end mill, with 10 mm radius “R” and 2 mm corner radius “r”, Feed trajectory is planned through equal section method; tool contact sequence is divided through equal step method; the track line spacing l is 18 mm; and the residual maximum height δ is 0.1 mm.
As shown in figure 6, the red dots line indicates the distribution of processing error before the non-linear error compensation. By reason of the convexity and concavity of surface and curve, the processing errors of all points on convex surface portion are larger than the maximum permissible error δ=0.1mm. But all the processing errors of concave surface are below the maximum permissible error. The black line represents the distribution of processing errors after the non-linear error compensation, which is strictly controlled within the range of permissible error. Therefore, the tool contact point interpolation method can solve the non-linear error distribution problem that caused by the tool axis rotation.

Conclusions

This paper studies on the special non-linear error and the tool position optimization in the five-axis CNC machining of complex surface. Firstly, the non-linear machining error of complex surface in five-axis CNC machining is analyzed; then, the non-linear error control strategy is developed through the cutter contact points on theoretical contour line, the cutter contact points is generated by inverse operation of adjacent tool orientation midpoints on the convex surface. Finally, the non-linear error is strictly controlled by work above. From figure 6, the machining error gets lower through non-linear compensation.

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