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Kinematical smoothing of rotary axis near singularity point

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Abstract. This paper deals with singular configurations of a 5-axis machine tool in high speed milling which may lead to the appearance of large incoherent movements of rotary axes near singularity points. These movements generate slowdowns of the actual feedrate during the execution of the tool path, which affect quality and productivity. Thus, this paper proposes a method to detect these behaviors during machining simulation and correct the tool path. Unlike the literature methods, this correction consists in modifying the tool axis orientation by going through the singularity point while respecting maximum velocity, acceleration and jerk of the rotary axis. For that purpose, the initial articular positions of the rotary axis near the singularity point are fitted with B-spline curves, modified and finally discretized for linear interpolation. Experimental investigations on a test part are carried out to show the efficiency of the method.

Introduction

The use of 5-axis machining allows profits in productivity by optimizing tool trajectories and by minimizing the number of part setups. The continuous orientation of the tool axis relative to the surface allows to machine more complex parts. Besides, the technology of the machines has also been greatly improved, particularly at the CNC equipment and drive axis level. Axes are more dynamic, especially with the use of linear motors for translation axis and torque motors for rotation axis. Hence, lots of research improves the trajectory in order to reach the kinematic performance of axis without going over it [1]. For that purpose, tool orientation has a key role in the efficiency and quality of 5-axis machining. The main objective is to define the tool orientation at each cutter contact point in order to minimize machining time within tolerances [2]. Nevertheless, 5-axis machining requires a better expertise than 3-axis machining. The problems are related to solutions for forward and inverse kinematics transformation, especially the positioning of the machine axes near a kinematic singularity. Indeed, near these singular positions, the strategy of the tool axis orientation may lead to incoherent movements, generating slowdowns of the actual feedrate during the execution of the trajectory and affecting the part quality and productivity.

Many papers deal with the smoothness of the motion by limiting the jerk in the trajectory planning to produce a soft motion [3] [4]. The aim is to find a velocity profile which respects all the kinematical constraints for a given tool path and a given machine tool. In the literature, two different approaches are used to solve this problem of singularity: to avoid the singularity or to pass by the singularity. For instance, to avoid the singularity, Jung et al. propose to retract the tool along the tool axis [5]. However, this method does not improve production time. Affouard et al. define a cone near the singularity, which has to be avoided [6]. Their method consists in deforming the tool path described as two native polynomial curves in order to avoid the tool transition in the singular cone while respecting the machining tolerances. Another method for reducing the machining error is to identify all possible tool orientation combinations and to choose the one which minimize the machining error

[7]. Yang et al. detect the singularity and modify the B-Spline tool path to make it C^3 continuous [8]. Soerby et al. proposes to modify the axis rotation position near the singularity such as the new position pass exactly by the singularity point [9]. Tournier et al. analyze the tool path in the (i,j) plan and propose a method to modify the orientation of the tool to remove or soften the incoherent movements [10]. Nevertheless, all these methods improve performances but they are not optimized to smooth the tool path while respecting kinematic performances of the machine used.

The present work introduces a new method to detect incoherent movements of rotary axes near singularity point and correct the tool path. In the second section, the problems linked to the kinematical transformation between part frame and machine frame in 5-axis machining are exposed. A specific attention is done on singularity configurations, which create incoherent movements on rotary axes and cause slowdowns during machining. Then, a proposed modification of the tool path near singularity is detailed in the third section. The last section is dedicated to the experimental validation of the proposed method on a test part.

5-axis machining and kinematics transformation

Numerical chain in 5-axis milling. In 5-axis milling, tool path are defined in CAM software from CAD definition of the part. The tool path is expressed in the part frame with 6 coordinates: 3 for the driven point (X_p, Y_p, Z_p) and 3 for the projections of the tool axis direction (i, j, k) . However, the different movements are realized by the 5-axis structure in the articular space with 3 translation axes (X_m, Y_m, Z_m) and 2 rotation axes (A, C) in the present case. The description of the tool path can be transmitted to the Numerical Controller (NC) unit with the coordinates in the part frame (X_p, Y_p, Z_p, i, j, k) or with the coordinates in the machine frame (X_m, Y_m, Z_m, A, C) or even with hybrid coordinates by combining the two previous coordinates (X_p, Y_p, Z_p, A, C) (Figure 1). The first program has the advantage of being the same whatever the machine tool structure used. The last two programs are more difficult to manage since the effective relative movements between the tool and the part and each axis velocity have to be controlled. The post-processing of these programs can allow improving kinematic performances of the machine tool.

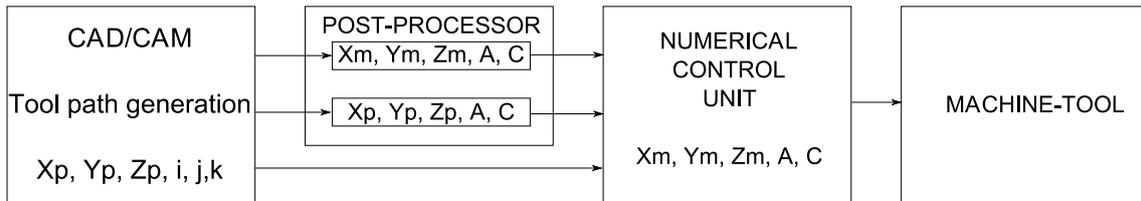


Figure 1: Numerical chain in 5-axis milling

Inverse kinematics and singularity point. The forward and inverse kinematics transformations provide a link between tool positions expressed in the part frame and tool positions expressed in the articular frame. Switching from part frame to machine frame can be realized thanks to the inverse kinematical transformation. Thus, for a RRTTT machine tool structure with rotations on A and C axis, the tool axis components can be expressed as a function of A and C:

$$\begin{cases} i = \sin(C) \cdot \sin(A) \\ j = -\cos(C) \cdot \sin(A) \\ k = \cos(A) \end{cases} \quad (1)$$

System (1) has two domains of solutions corresponding to $A > 0$ or $A < 0$, and solutions vary in function of the (i,j,k) values (Table 1) [10].

	$i < 0$	$i = 0$	$i > 0$
$j < 0$	$A_1 = \text{acos}(k) \quad C_1 = -\text{atan}(i/j)$		
	$A_2 = -\text{acos}(k) \quad C_2 = -\text{atan}(i/j) + \pi$		
$j = 0$	$A_1 = \text{acos}(k) \quad C_1 = -\pi/2$	$A=0$ C undefined (singular point)	$A_1 = \text{acos}(k) \quad C_1 = \pi/2$
	$A_2 = -\text{acos}(k) \quad C_2 = \pi/2$		$A_2 = -\text{acos}(k) \quad C_2 = -\pi/2$
$j > 0$	$A_1 = \text{acos}(k) \quad C_1 = -\text{atan}(i/j) + \pi$		
	$A_2 = -\text{acos}(k) \quad C_2 = -\text{atan}(i/j)$		

Table 1: Domains of solutions ($A1, C1$) and ($A2, C2$)

Special issues associated with the inverse kinematics transformation are the problem of singular configurations on the one hand and solution space swapping on the other hand. According to Table 1, the case $i = 0$ and $j = 0$ is the singular configuration.

The passage from j negative to j positive corresponds to a solution space swapping. That means that swapping from $[A1 = \text{acos}(k) ; C1 = -\text{atan}(i/j)]$ to the solution $[A2 = -\text{acos}(k) ; C2 = -\text{atan}(i/j)]$ involves a main discontinuity. When the ratio i/j is of a high negative value, $C1$ is close to 90° , whereas when i/j is of a high positive value, $C2$ is close to -90° . This generates a discontinuity of 180° in the worst case on the C -axis when passing through $j = 0$ when i is not null. As established in [10], this movement appears very locally and strongly slows down the machining process which can generate marks on the part.

Thus, the aim of this paper is to eliminate the incoherent movements of the C -axis while respecting maximum velocity, acceleration and jerk of the rotary axis. For that purpose, the proposed approach is to modify the tool path in order to go through the singularity point.

Modification near singularity points

Criterion: respecting maximum velocity, acceleration and jerk of the rotary axis C. Kinematical performances of machine tools are limited by the maximum velocity, acceleration and jerk of each axis. Considering these kinematical limits, the tool path geometry, especially discontinuities or high curvatures, can cause slowdowns of the actual feedrate during the execution of the trajectory. Thus, the aim is to modify the C -axis position near the singularity point in order to prevent it from being the axis, which limits the actual feedrate.

By noting q the axes position, for a path displacement s , the velocity of the axes \dot{q} can be expressed as a function of the geometry q_s multiplied by a function of the motion \dot{s} (Equation 2). This formula is valid for each axis of the machine (X, Y, Z, A, C). The acceleration \ddot{q} and jerk $\ddot{\ddot{q}}$ of the axes are obtained in the same manner (Equation 3 and 4).

$$\dot{q} = \frac{dq}{dt} = \frac{dq(s)}{ds} \cdot \frac{ds}{dt} = q_s(s) \cdot \dot{s} \quad (2)$$

$$\ddot{q} = q_{ss}(s) \cdot \dot{s}^2 + q_s(s) \cdot \ddot{s} \quad (3)$$

$$\ddot{\ddot{q}} = q_{sss}(s) \cdot \dot{s}^3 + 3 \cdot q_{ss}(s) \cdot \dot{s} \cdot \ddot{s} + q_s(s) \cdot \ddot{\ddot{s}} \quad (4)$$

Focusing on the approximation of the upper limit of the feedrate, tangential acceleration and tangential jerk along the tool path can be neglected in the areas of interest, that is to say when the feedrate is greatly decreasing and then increasing [4]. Hence an approximation of the actual feedrate respecting the kinematic constraints is given by Equation 5:

$$\dot{s} \leq \min_{i=\{X,Y,Z,A,C\}} (F_{prog}, \frac{\dot{q}_{max}^i}{|q_s^i|}, \sqrt{\frac{\ddot{q}_{max}^i}{|q_{ss}^i|}}, \sqrt[3]{\frac{\ddot{\ddot{q}}_{max}^i}{|q_{sss}^i|}}) \quad (5)$$

Where:
- i represents each axis X, Y, Z, A, C
- F_{prog} : programmed feedrate

- \dot{q}_{max} , \ddot{q}_{max} , \dddot{q}_{max} : maximum axis velocity, acceleration and jerk
- q_s , q_{ss} , q_{sss} : geometrical derivatives

Equation 5 allows knowing which axis is the limiting one to reach the programmed feedrate. Besides, near singularity points, it allows to know how to modify C-axis positions to prevent it from being the axis, which limits the actual feedrate.

Proposed algorithm

From the G1 CL file of the tool path, singular points can be detected when the articular value of the A-axis changes from a positive value to a negative near zero (or vice versa). In this case, j goes through zero. In order to avoid the area with an important gradient of C-axis position, the tool axis orientation has to be modified in order to go through $C = 0$ or $C = 180$ while respecting maximum velocity, acceleration and jerk of all axis. This modification is possible because in the case of ball-end cutter tool milling, for a given position of the tool center point, any orientation of the tool axis keeps the tangent contact between the tool and the surface. Thus, it is possible to modify C-axis position without changing the trajectory of the tool center point.

For that purpose, the initial articular positions of C-axis are fitted by two cubic B-spline curves: one before (*Curve_b*) and one after the singular points (*Curve_a*). The aim is to connect these two curves by a cubic B-Spline smoothing curve (*Curve_s*) under jerk constraints and interpolating the singularity point. The use of cubic B-spline instead of the original G1 points allows to calculate velocity, acceleration and jerk with a smaller sampling step. The choice of the sampling step depends on sampling frequencies of the NC unit and programmed feedrate. It is the product of the cycle time for interpolation and the programmed feedrate. Thus, each interpolation in the algorithm precedes a finer sampling in order to compute discrete derivatives. The proposed algorithm is described in Figure 3, illustrated on Figure 5 and detailed hereafter.

After having resampled both *Curve_b* and *Curve_a*, the first step consists in an iterative test of each sampled point starting from the singular points to be candidate for the connection. While the kinematical constraints are not respected at the connection, the algorithm simultaneously tests each point P_i backward along *Curve_b* and forward along *Curve_a*. As jerk constrained smoothing involve a third order continuity at the connection between *Curve_s* and both *Curve_a* and *Curve_b*, four successive points on each curve ($P_i, P_{i+1}, P_{i+2}, P_{i+3}$) are considered to evaluate the C^0, C^1, C^2 and C^3 continuity.

At the end of this stage, the jerk limited smoothing is guarantee at the connection between *Curve_s* and both *Curve_b* and *Curve_a* but not along the introduced smoothing curve *Curve_s*. Thus the next stage is to go further backward along *Curve_b* and forward along *Curve_a* until the kinematical constraints of the C-axis are respected all along the smoothing curve. During this second stage, the shape of the smoothing curve is becoming slender, q_s, q_{ss} and q_{sss} (Equation 2, 3, and 4) are decreasing (Figure 3). At the end, the final smoothing curve is used to project the initial G1 points to obtain the new position of the C-axis in order to be used with linear interpolation.

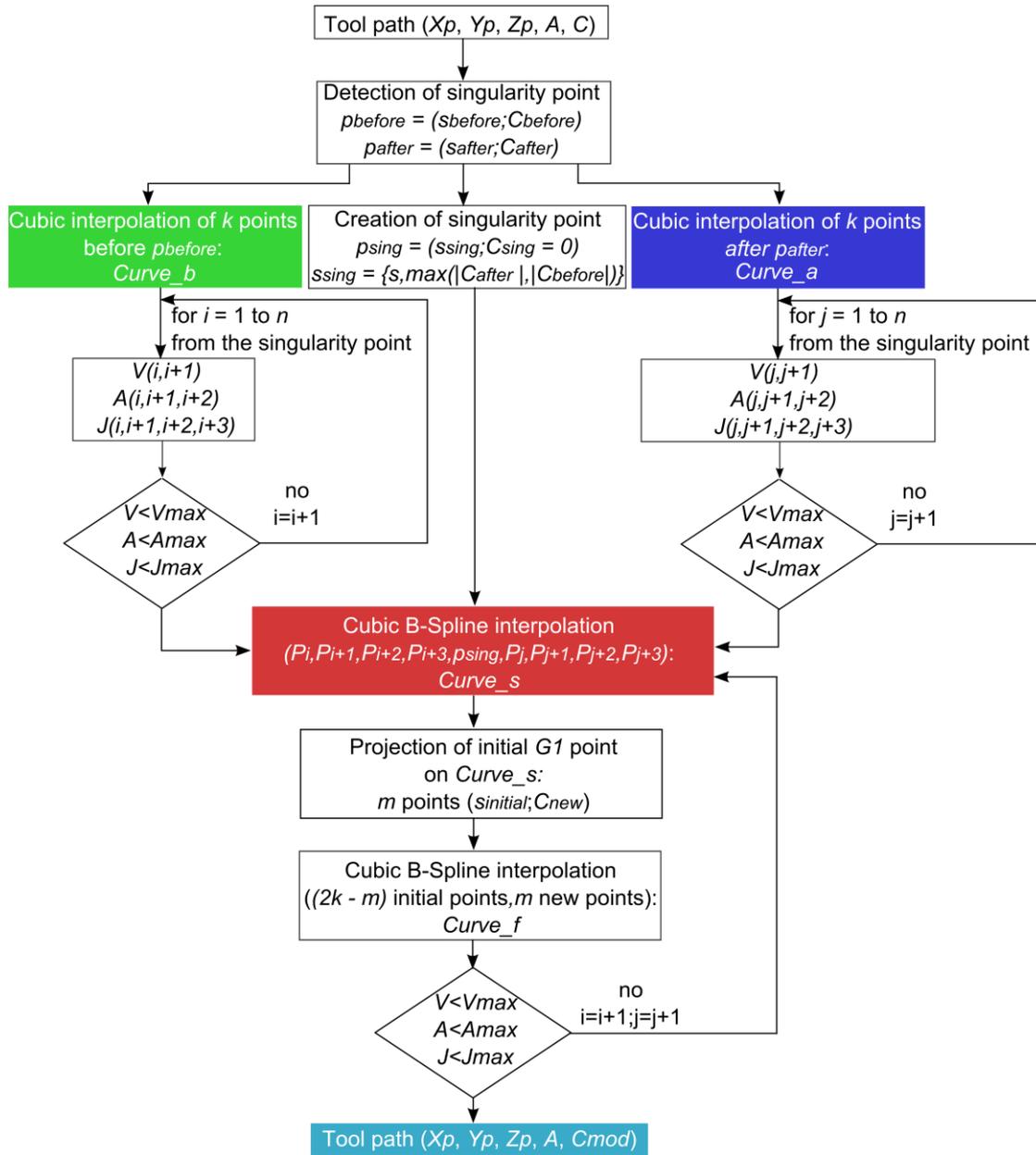


Figure 3: Proposed algorithm to modify C while respecting kinematical constraints

Experimental investigations

Test part. The proposed test part is extracted from previous experiments done by Tournier et al [10]. It is an aluminum test part that presents an evolutionary curvature along the leading edge. The finishing milling of the part is based on a tool guiding according to iso-parametric curves of the surface (Figure 4). A fixed tilt angle of 5 degrees is used with a 5 mm radius ball end mill. This finishing operation generates the problem highlighted above. Indeed, incoherent C-axis movements are observed when the tool is close to the singularity point, that is to say when the tool is on the leading edge of the part. This movement appears very locally for each path but with different amplitudes, and strongly slows down the milling. The NC code corresponding to the tool path shows a discontinuity of the C-axis evolution for each path. By using the algorithm presented in section 3, a new NC code can be created. The objective is to reach 1m/min all along the tool path.

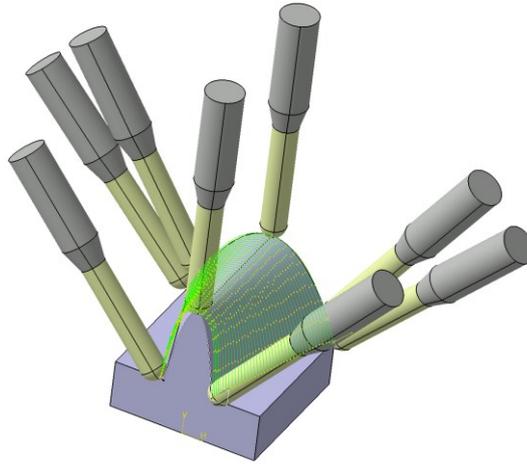


Figure 4: Test part machining

Tool path modifications. Figure 5 shows the different steps in order to modify the NC code close to the singularity according to the algorithm presented in Figure 3. The algorithm is used to correct each path of the program and a new NC code is generated in linear interpolation.

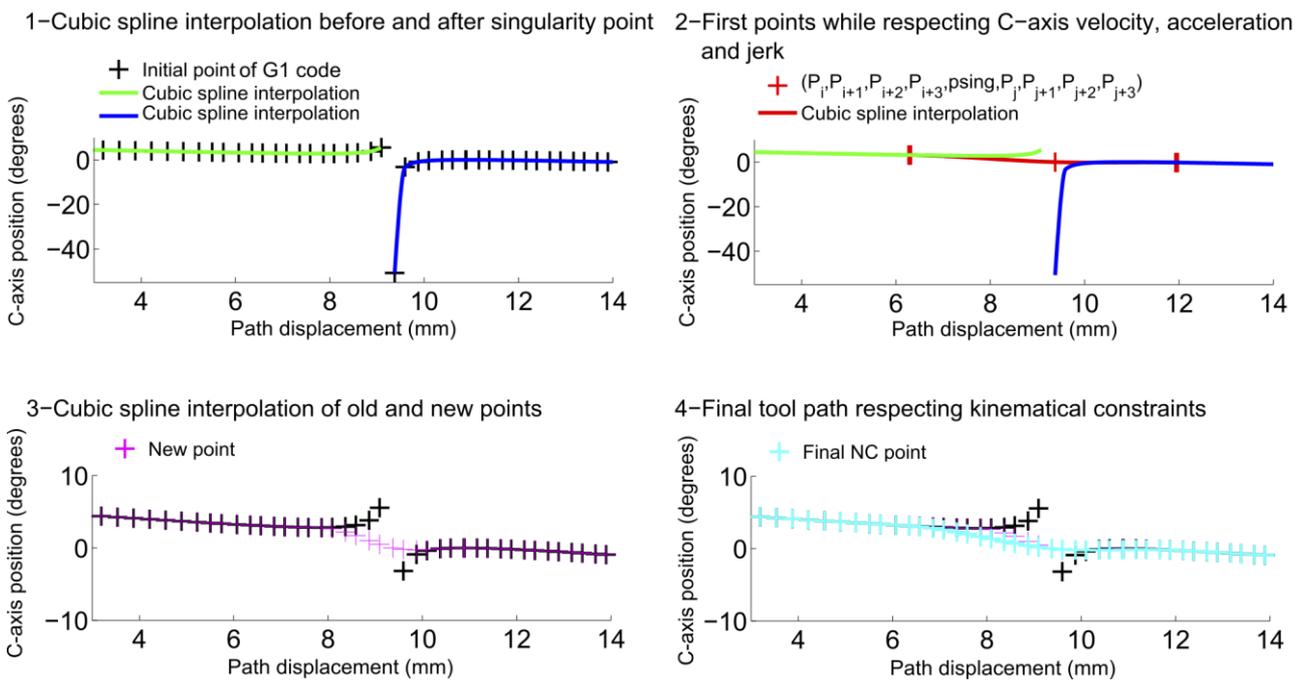


Figure 5: Steps to obtain a new NC code near singularity point

Experimental results. Tests are carried out on the Mikron UCP710 with the numerical controller Siemens 840D which offers the possibility of monitoring axis characteristic during machining of one path. A tool path with a large C-movement has been selected to show the benefit of the proposed algorithm. The original C-axis behavior is depicted in red on figure 6 and presents amplitude of movement close to 40° . After modification of the tool path, a smooth geometrical evolution of C-axis is achieved with the proposed method. Regarding the kinematical behavior, the feedrate of the initial tool path is set to 1m/mn but the effective feedrate is much slower due to acceleration and jerk constraints. After optimization, the new evolution of C-axis velocity, acceleration and jerk allows respecting the programmed feedrate. A video is available online to show the efficiency of the method (<https://www.youtube.com/watch?v=g7p1umVBQ08>). However, smoothing other axes involved in the 5-axis movement could increase the relative feedrate between the tool and the part. As illustrated in figure 6, the effective feedrate is oscillating for both old and new code. This is an effect of the real time polynomial interpolation of the G1 NC code done by the NC controller. Finally, this result shows the efficiency of the method to avoid incoherent movements and improve productivity.

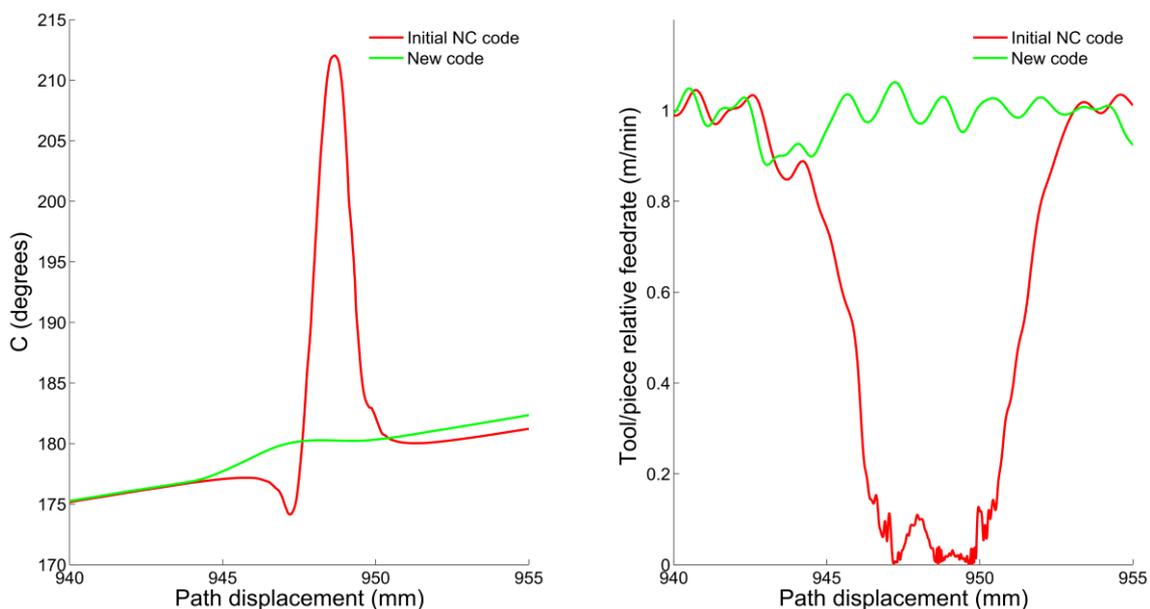


Figure 6: Measure of C-axis position and relative feedrate

Conclusions

The use of 5-axis high speed machining allows to machine more complex parts by optimizing tool trajectories. However kinematical performances are not always optimized because of difficulties linked to the structure of the machine. Incoherent movements of rotary axis can appear near singularity points, which cause slowdowns. Consequently, the aim of this paper was to propose a method to deform rotary axis articular movement while respecting maximum velocity, acceleration and jerk of the rotary axis. For that purpose, the initial positions of the rotary axis are fitted by two cubic B-spline curves: one before and one after the singularity. The aim is to rely these two curves by a cubic B-Spline curve while imposing the passage by singularity point and while respecting maximum velocity, acceleration and jerk of the rotary axis. A discretization of this curve creates new positions of the axis position and the new code with (X_p, Y_p, Z_p, A, C) coordinates can be used with linear interpolation. Incoherent movements are eliminated after rotary axis deformation and the kinematical performances of the machine tool are improved.

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