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► **To cite this version:**

Sylvain Lavernhe, Yann Quinsat, Christophe Tournier, Claire Lartigue, René Mayer. NC-simulation for the prediction of surface finish in 5-axis High-Speed Machining. 3rd CIRP International Conference on High Performance Cutting, Dublin(Ireland), Jun 2008, Dublin, Ireland. pp.387 - 396. hal-00999715

**HAL Id: hal-00999715**

**<https://hal.science/hal-00999715>**

Submitted on 3 Jun 2014

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# NC-simulation for the prediction of surface finish in 5-axis High Speed Machining

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**Abstract:** This paper deals with simulation models allowing predictions of the surface finish and the actual velocity during machining. To simulate material removal in 5-axis machining, we propose an N-buffer based model integrating the Inverse Kinematics Transformation. This model can be coupled with the NC-simulation model we have previously developed, and which has been validated for several sets of NC/machine tools. The tooth track is thus linked to the velocity giving the surface topography resulting from actual machining.

**Keywords:** 5 axis machining, axis kinematical behaviour, surface finish prediction

## 1 INTRODUCTION

Within the fields of automotive or mould and die industries, 5-axis High Speed Machining is now widely used as it facilitates the machining of complex surfaces. As the tool trajectory is the input data of the 5-axis digital chain, CAM systems must generate optimal tool trajectories to maximize process performance.

Currently, CAM systems calculate the tool trajectory as a set of tool postures without taking the set NC/machine tool into account. Therefore, during machining actual velocity does not exactly match the programmed one. Actually, due to physical and numerical limits, the NC unit performs adaptations such as reducing the relative tool-surface velocity to accommodate each axis performance. Furthermore, although the calculated trajectory is collision free, collisions may appear due to the changes of configurations. Indeed, in multi-axis machining the coordinate transformation is not unique: the machine tool can have two possible configurations corresponding to one given tool posture. Hence, the machined surface does not exactly match the desired surface, due to both the actual trajectory and the actual relative tool/surface velocity. As result, the 3D micro-geometry of the surface may be altered. For applications such as mould machining for plastic injection, the control of the 3D surface finish is essential as it conditions following applications of polishing. Due to difficulties in measuring the surface topography for complex surfaces, the need in models or simulations of the 3D surface finish is real. Some studies proposed in literature investigated the prediction of 3D surface micro-geometry. Kim described the texture found in ball end milling using

numerical simulations [Kim *et al.*, 1999]. This effort sought to refine the standard model that correlates scallop height with transverse step by integrating the influence of the feed rate. Bouzakis incorporated the influence of tool orientation and focused on the cutting edge motion. Simulations showed the influence of tool orientation, transverse step and feed rate on surface quality [Bouzakis *et al.*, 2003]. Toh has complemented this work by defining the best direction for machining an inclined plane [Toh, 2004]. More recently a number of theoretical models have also been proposed to describe 3D topography obtained in ball end milling [Quinsat *et al.*, 2008]. However, the case of 5-axis machining with filleted end-tool is little analysed. Furthermore, the influence of feed rate modifications during machining is seldom investigated.

Within this context, this paper aims to propose a simulation model allowing predicting the surface finish and the actual velocity during machining. The model for material removal relies on a N-buffer simulation integrating the Inverse Kinematics Transformation. This model can be coupled with the NC-simulation model previously developed, and which has been validated for several sets of NC/machine tools. The tooth track is thus linked to the velocity giving the surface topography resulting from actual machining. With such a model, the link between the surface finish, the tool trajectory and the kinematics of the machine tool on which the 5-axis machining is carried out is clearly emphasized.

## 2 3D SURFACE FINISH PREDICTION IN 5-AXIS MACHINING

The proposed model simply simulates the machining process, from the trajectory execution to the actual surface machining. The simulation process consists of 2 main steps. From the CNC file, and for a given CNC machine tool, the first step leads to the prediction of the actual tool trajectory (set of tool postures and corresponding feedrates). The second stage is the geometrical simulation of the cutting process considering the actual trajectory. Results are the 3D surface topography and actual machining time. Note that in the proposed simulation, mechanical and dynamical effects are assumed to be negligible (or not taken into account). Both steps of the model are detailed in the next sections.

### 2.1 Prediction of actual trajectory processing

This part of the model concerns the modelling and the simulation of the CNC treatments performed to adapt the trajectory to the CNC machine tool capacities [Lavernhe *et al.*, 2007]. The four main stages are summarised in figure 1.

Input data are the set of tool postures and corresponding feedrates given by the CNC file. Thanks to the IKT, joint configurations are first calculated. The machine tool architecture is supposed to be ideal. Once the trajectory described in the joint space, the next stage deals with evaluating the kinematical limits associated to axis and motor capacities, as well as NC specific functions. These limits act as constraints during trajectory processing.

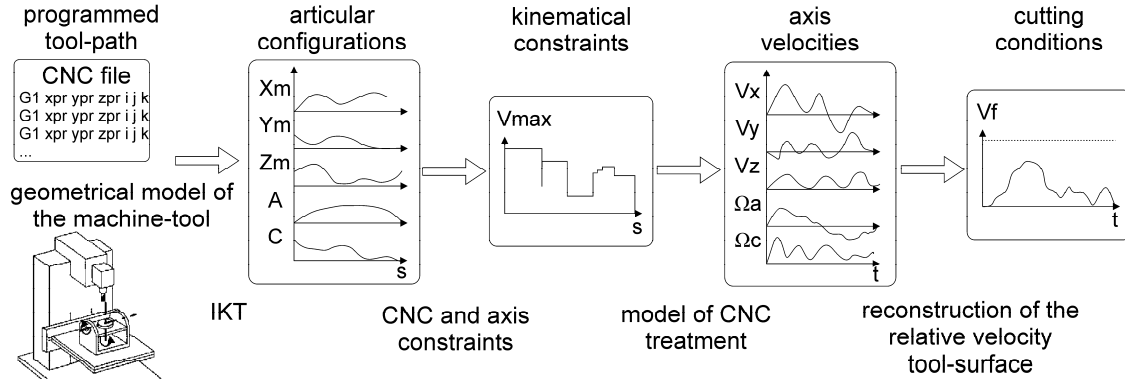


Figure 1; Structure of the predictive model.

Let us consider a trajectory segment, defined between two configurations. If the length of the segment is  $\Delta L$ , the elementary displacement for each axis  $i$  is  $\Delta P^i$ . Due to physical limits, kinematical characteristics must be adjusted to respect those limits when travelling along the segment. Therefore, axis velocity, acceleration and jerk must respect the following constraints:

$$\begin{cases} \hat{V}_{\max} = \min_{i=1..N} \left( \frac{V_{\max}^i}{\Delta P^i} \right); \hat{A}_{\max} = \min_{i=1..N} \left( \frac{A_{\max}^i}{\Delta P^i} \right); \hat{J}_{\max} = \min_{i=1..N} \left( \frac{J_{\max}^i}{\Delta P^i} \right) \\ \hat{V}_{NC} = \frac{1}{T_{\text{cycle time}}}; \hat{V}_{prog} = \frac{V_{prog}}{\Delta L} \end{cases} \quad (1)$$

Where  $V_{\max}^i$ ,  $A_{\max}^i$ ,  $J_{\max}^i$  are the maximal kinematical limits of each axis  $i$  (velocity, acceleration and jerk, respectively),  $T_{\text{cycle time}}$  is the CNC cycle time of interpolation, and  $V_f$ , is the programmed federate.

To facilitate the comparison of axis capacities, the previous constraints are expressed using the inverse time formalism. Considering the expression  $\hat{v}(t)$ ,  $\hat{a}(t)$ ,  $\hat{j}(t)$  for the velocity, acceleration, and jerk respectively, this yields to [Lavernhe *et al.*, 2007]:

$$\begin{cases} 0 \leq \hat{v}(t) \leq \min(\hat{V}_{\max}, \hat{V}_{prog}, \hat{V}_{NC}) \\ -\hat{A}_{\max} \leq \hat{a}(t) \leq \hat{A}_{\max} \\ -\hat{J}_{\max} \leq \hat{j}(t) \leq \hat{J}_{\max} \end{cases} \quad (2)$$

A similar approach is used to investigate segment transitions. Indeed, geometrical discontinuities of the trajectory generate abrupt velocity and acceleration gaps during trajectory processing. Supposing that velocity gaps are processed with a constant acceleration, the maximal variation of velocity  $\Delta V_{\max}^i$  is linked to the maximal acceleration  $A_{\max}^i$  of the considered axis, and the tolerance of position  $e_{\max}^i$  set for trajectory follow-up:

$$\Delta V_{\max}^i = \sqrt{8 \cdot A_{\max}^i \cdot e_{\max}^i} \quad (3)$$

Then, taking into account these constraints, axis velocities are following evaluated considering a modelling of the CNC interpolator which integrates jerk limitation and look-ahead functions. The algorithm seeks for the jerk sequence that maximises the

velocity while respecting all the previous constraints. Axes are supposed to be perfectly coordinated along the trajectory: all axis parameters follow the same evolution in the inverse time formalism.

$$\begin{cases} \hat{j}(t) = \{-\hat{J}_{\max}, 0, \hat{J}_{\max}\} \\ \hat{a}(t) = \hat{a}_0 + \hat{j} \cdot \Delta t \\ \hat{v}(t) = \hat{v}_0 + \hat{a} \cdot \Delta t + \frac{1}{2} \hat{j} \cdot \Delta t^2 \end{cases} \quad (4)$$

Finally, velocity, acceleration and jerk of each axis are calculated by projection onto each elementary trajectory portion  $[ab]$  in the joint space:

$$v_{ab}^i(t) = \hat{v}(t) \cdot \Delta P_{ab}^i \quad (5)$$

The relative velocity tool/surface at the Cutter Location point ( $C_L$ ) is then reconstructed from axis velocities and data linked to the geometrical model of the machine-tool (for the considered machine-tool,  $S$  is located on the rotary axis A):

$$\vec{V}_{C_L \text{ tool / surface}} = \vec{V}_{C_L \text{ tool / machine}} - \vec{V}_{C_L \text{ table / machine}}, \begin{cases} \vec{V}_{C_L \text{ tool / machine}} = \vec{V}_{\text{axisX}} + \vec{V}_{\text{axisY}} + \vec{V}_{\text{axisZ}} \\ \vec{V}_{C_L \text{ table / machine}} = C_L S \wedge \vec{\Omega}_{\text{table / machine}} \end{cases} \quad (6)$$

## 2.2 Prediction of the surface topography

Material removal simulation is based on the well-known Nbuffer method presented in [Jerard *et al.*, 1989]. The input data are the tool postures and predicted feedrates issued of the previous section.

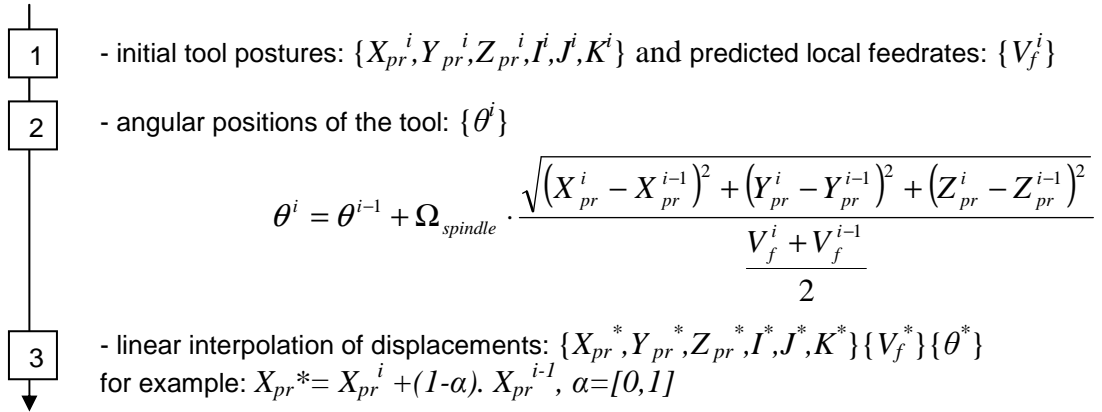


Figure 2; Tool path reconstruction.

To ensure tool-path continuity, a linear interpolation for feedrates  $\{V_f^i\}$  and tool postures  $\{X_{pr}^i, Y_{pr}^i, Z_{pr}^i, I^i, J^i, K^i\}$  is performed in the part frame (Figure 2). An interpolation in the joint space of the machine integrating the IKT is also carried out in order to take into account errors induced by 5-axis interpolation. For each sampling, the angular positions of the tool axis  $\{\theta^i\}$  are computed from local feedrate; the rotational velocity of the spindle  $\Omega_{\text{spindle}}$  is supposed to be constant and equal to the programmed one.

The filleted-end tool is considered as a rigid body, and is approximated by a local meshing. Indeed, only active cutting edges are considered. Each cutting edge is locally assimilated to a surface of revolution ( $\gamma \sim 0.5^\circ$ ). To ensure a correct approximation of the tool surface, the meshing is performed with a chord error equal to  $0.1 \mu\text{m}$  (Figure 3).

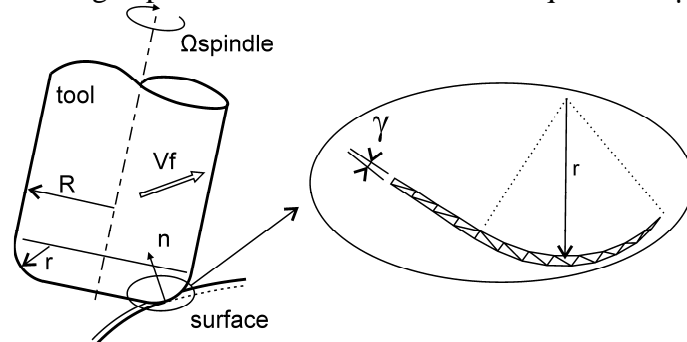


Figure 3; Cutting edge modelling of a filleted end tool.

On the other hand, the surface is represented by a set of points and corresponding normal lines. Finally, the simulation of the machined surface is obtained by computing the intersections between the normal lines and the tool for each configuration  $\{X_{pr}^*, Y_{pr}^*, Z_{pr}^*, I^*, J^*, K^*, \theta^*\}$ .

### 3 MODEL ASSESSMENT

As the simulation model consists of two independent steps, each step is assessed independently. The model for actual trajectory prediction was assessed in a previous work for the CNC machine tool Mikron UCP 710 of our laboratory [Lavernhe *et al.*, 2006]. To show the efficiency of the model, an application is now proposed for a different CNC machine tool with different kinematical characteristics. Validation of the model for surface finish prediction is proposed through various examples, for which some of machining parameters are modified. For instance, the influence of the federate as well as the influence of the tool axis orientation is investigated.

#### 3.1 Assessment of the kinematical model

As the model is supposed to be generic whatever the CNC machine tool, an application is proposed in the present work for another 5-axis machine tool, a Huron KX8 five equipped with a CNC Siemens 840D. The machine structure is of type RRTTT, with an angle of  $45^\circ$  between the two rotational axes. Main limit values of the kinematical characteristics are reported in table I. The cycle time is  $T_{\text{cycle}} = 3 \text{ ms}$ .

| Axis  | X  | Y  | Z   | A   | C   |
|---|----|----|-----|-----|-----|
| $V_{\text{max}}$ m/min & tr/min                           | 50 | 50 | 50  | 50  | 50  |
| $A_{\text{max}}$ m/sec <sup>2</sup> & tr/sec <sup>2</sup> | 5  | 5  | 5   | 3   | 3   |
| $J_{\text{max}}$ m/sec <sup>3</sup> & tr/sec <sup>3</sup> | 40 | 80 | 100 | 100 | 100 |

Table I; Axis kinematical characteristics.

The test part is a hyperbolic paraboloid with a double curvature (figure 10). Trajectories are defined according to the surface rules, with a tool inclination of  $1^\circ$ . Although, the

locus of the contact points is a straight line, the surface curvature involves a combined movement of all the 5 axes.

The programmed feed rate is set to 5m/min. Axis velocity profiles calculated using the predictive model are reported in figure 4 as well as values collected by the CNC machine tool encoders. For both the simulation and the measure, the relative tool/surface velocity is built according to equation 6. Results are presented in figure 5.

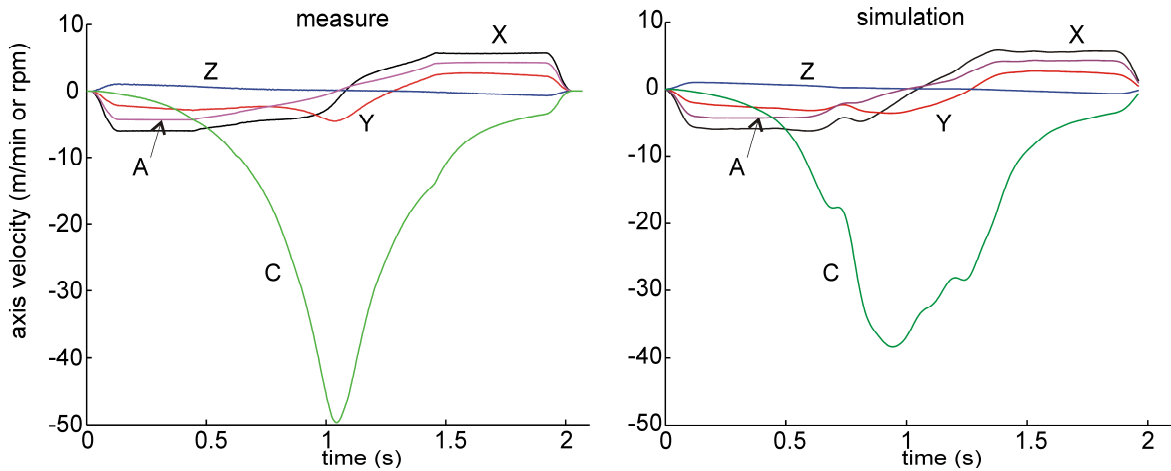


Figure 4; Axis velocity profiles.

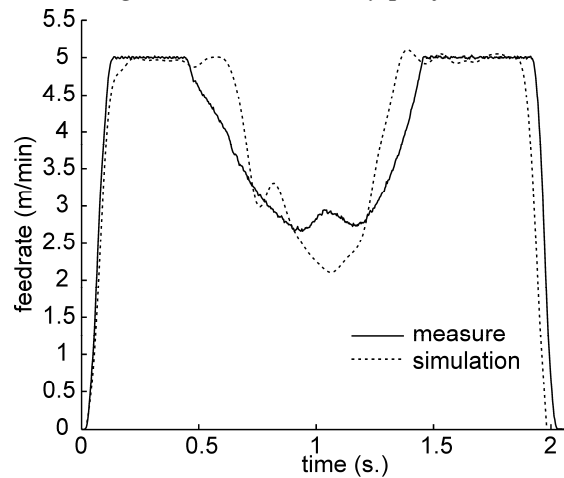


Figure 5; Simulated and measured feed rates.

Velocity evolutions are similar: the programmed feed rate is reached at the beginning and at the end of the trajectory; velocity strongly decreased at middle of the trajectory. However, some differences are noticeable: although the velocity decreasing is correctly predicted by simulation, deceleration is faster and then occurs later. In the same way, after the middle of the trajectory, predicted acceleration is faster and the programmed feed rate is reached earlier. Some adjustments of “look ahead” functions are required to improve simulations. Nevertheless, the simulation gives a good estimate of the feed rate and then of the tooth velocity. Therefore, actual cutting conditions are known which allows a more precise simulation of the 3D micro-geometry of the surface. Indeed, the tooth feed rate is an influent parameter on the surface finish.

### 3.2 Assessment of the 3D micro-geometry prediction model

In order to assess the model detailed in §2.2, a series of experiments are carried out (figure 6). These experiments aim to compare various 3D surface finish obtained by simulations to actual ones.

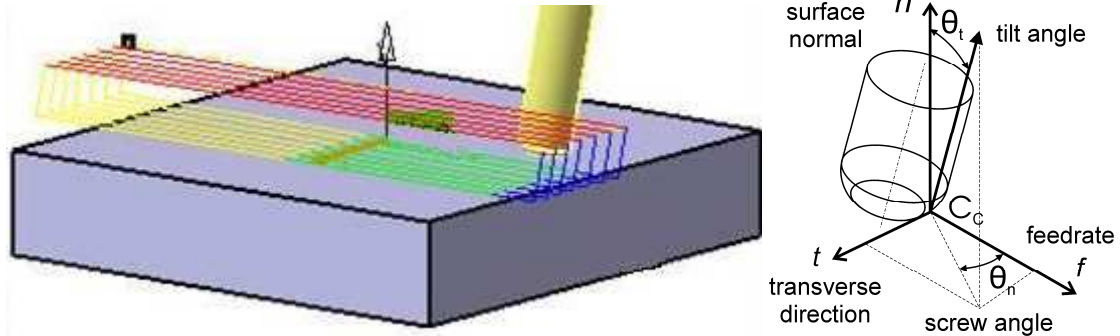


Figure 6; Definition of the experimentation.

For this purpose, a series of plane sweepings with a ball end-mill tool are performed according to variable parameters: various orientations of the tool axis various feed rates and various maximal scallop heights allowed (Table II). Actual machining is performed on a 5-axis HSM using a filleted-end milling tool ( $R=5\text{mm}$ ,  $rc=1.5\text{mm}$ ) with a unique tooth in order to control the geometry of the tooth witch contributes to the final imprint.

| Test | Screw( $^\circ$ ) | Tilt ( $^\circ$ ) | Scallop height (mm) | Feedrate ( m/min) |
|------|-------------------|-------------------|---------------------|-------------------|
| 1    | 0                 | 1                 | 0,005               | 2                 |
| 2    | 0                 | 1                 | 0,005               | 4                 |
| 3    | 0                 | 10                | 0,01                | 4                 |
| 4    | 20                | 10                | 0,01                | 4                 |

Table II; Parameters of the experimentation.

The machined surfaces are measured using an optical instrument (Wyko NT1100 - <http://www.veeco.com/>). To characterize the obtained pattern, 3D parameters define in the report [EUR 15178 EN] are used. For all cases, patterns as well as defect amplitudes issued from simulation match the measured ones (figure 7, 8 and Table III).

| Test | $St$ ( $\mu\text{m}$ ) |      | $Sa$ ( $\mu\text{m}$ ) |      | Trans. step (mm) |      | Long. step (mm) |       | Orientation ( $^\circ$ ) |       |
|------|------------------------|------|------------------------|------|------------------|------|-----------------|-------|--------------------------|-------|
| 1    | 6.99                   | 5.58 | 1.27                   | 1.21 | 2.76             | 2.63 | 0.13            | 0.133 | 90                       | 90    |
| 2    | 9.17                   | 9.24 | 1.46                   | 1.66 | 2.71             | 2.62 | 0.269           | 0.266 | 90                       | 90    |
| 3    | 14.1                   | 15.7 | 2.47                   | 2.56 | 1.21             | 1.18 | 0.267           | 0.266 | 90.1                     | 90    |
| 4    | 6.54                   | 5.63 | 0.96                   | 1.05 | 0.46             | 0.43 | 0.264           | 0.266 | 71.38                    | 69.34 |

Table III; Comparison between measured and simulated patterns.

Therefore, the model proposed to predict 3D surface topography is efficient. Small deviations between simulated and measured data may come from the actual tool geometry or/and the cutting process. Nevertheless, the analysis of influent parameters on the surface topography can be conducted through simulations.



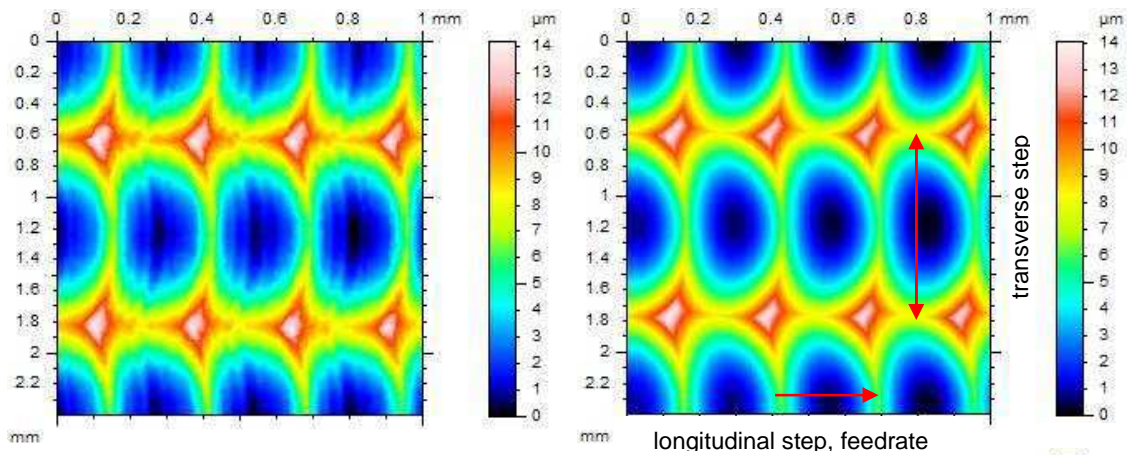


Figure 7; Measured and simulated pattern for case number 3.

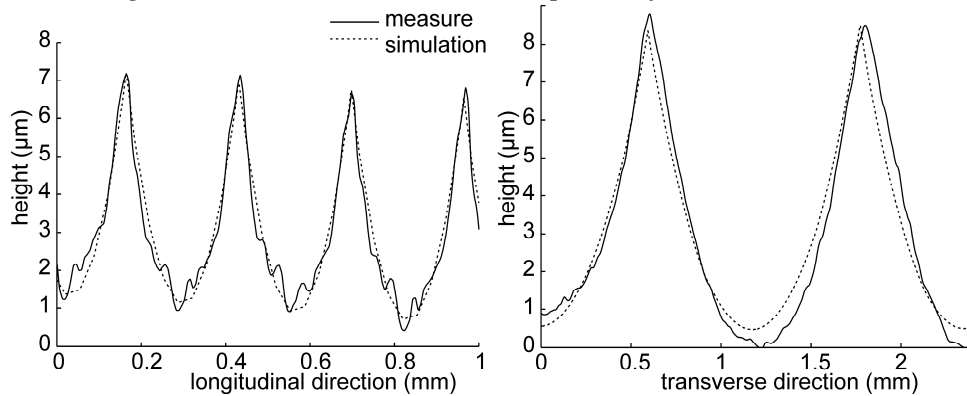


Figure 8; Simulated and measured profiles (case 3).

These experiments also highlight the influent parameters. Indeed, as it is expected, the feed rate is an essential parameter, as it actually conditions the 3D pattern (Figure 9, cases 1 and 2). Therefore, modifications of feed rate during machining may affect the 3D surface finish.

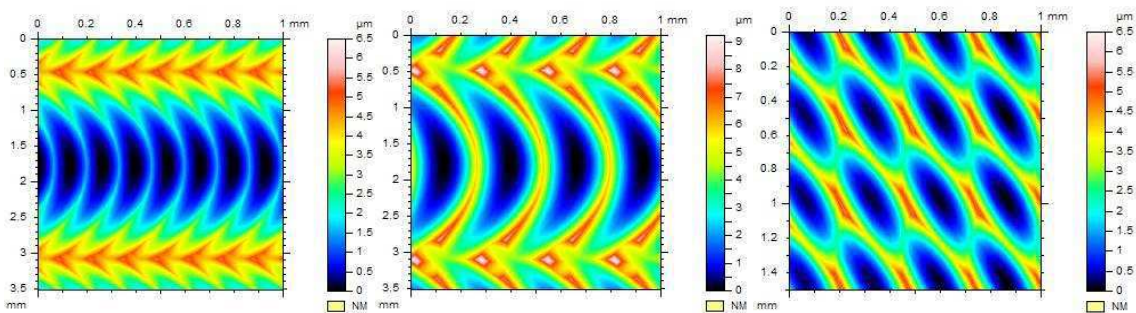


Figure 9; Simulated patterns (from left to right, case 1, case 2, case 4).

Moreover, usually the maximum scallop height allowed is one of the parameters the most used in CAM software to define the 3D surface topography. As shown in figure 9 (case 4), a non null screw angle provides a pattern for which the notion of cusp only has no more significance. The description of surface patterns obtained with 5-axis must include cutting conditions as well as tool orientation.

#### 4 APPLICATION

The model of NC simulation and surface finish is applied to the paraboloid. The programmed feedrate is set to 5m/min in the NC file; studied tool-path is set in red (figure 10). Axis tool angles are tilt=1°, screw=0°; the distance between each tool-path is set to 5mm.

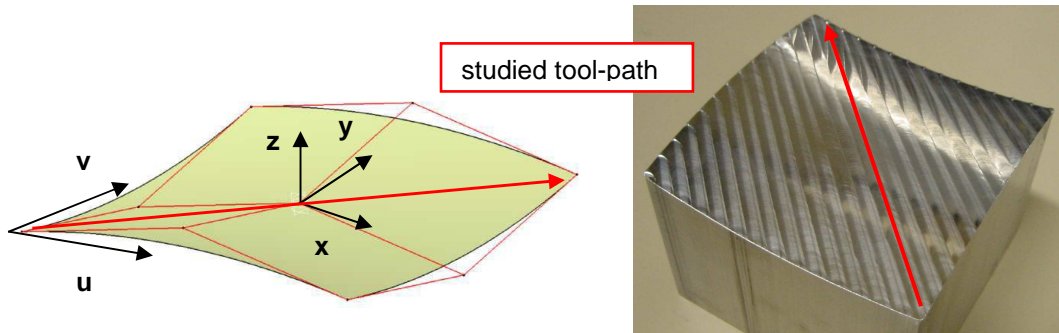


Figure 10; Surface definition and machined part.

From predicted velocities (figure 5), the 3D micro-geometry is simulated. Figure 11 highlights the influence of the actual velocity during machining; the simulation is located at the middle of the tool-path. The longitudinal step is clearly decreased, whereas scallop height is quite similar; topography is not completely different in this case. We can also remark that cause of the curvature, the line of scallop is not centred between two successive tool-paths, topography seems to be translated to the right.

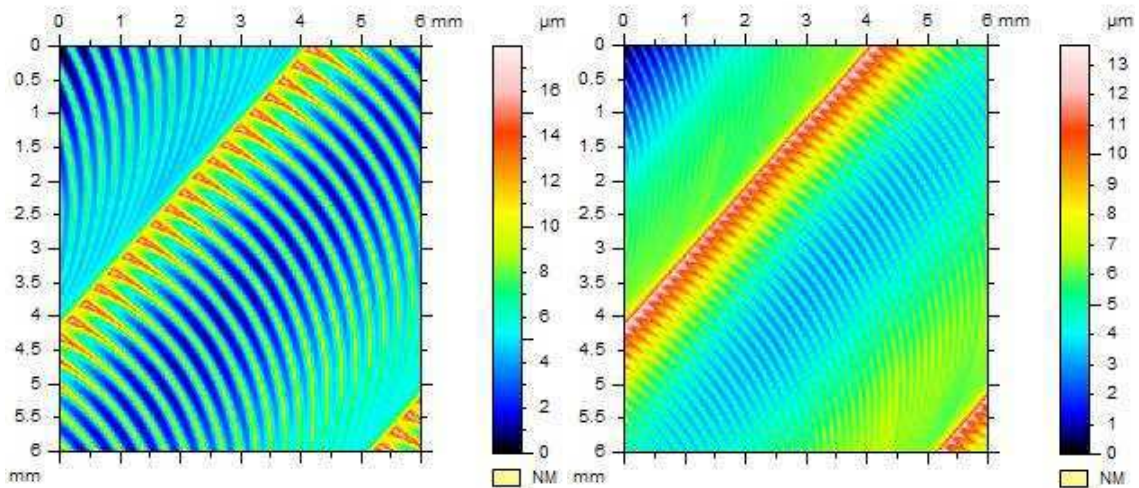


Figure 11; Simulated topographies for the paraboloid with programmed (5m/min, left) and predicted or actual feedrate tool/surface (2.5m/min, right).

## 5 CONCLUSION

A model for predicting axis velocities during machining is proposed with the objective to integrate actual velocity so calculated into the simulation of 3D machined surface topography. From the CNC file, and for a given CNC machine tool, axis velocities are simulated taking into account axis capacities as well as CNC HSM specific functions. The relative velocity tool/surface is then reconstructed and used as an input data for a surface finish simulation based on the N-buffer method. Comparisons between simulations and measurements of 3D surface topography for various influent parameters assess the proposed model. Therefore, as micro-geometry measurement of a complex surface is still a major issue, the model developed gives a solution. The analysis of influent parameters on surface topography through simulations should provide a very useful theoretical model linking feed rate, tool orientation, and other cutting conditions to the surface roughness.

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