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Model for performance prediction in multi-axis machining

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Abstract: This paper deals with a predictive model of kinematical performances in 5-axis milling within the context of HSM. Capacities of each axis as well as some NC unit functions can be expressed as limiting constraints. The proposed model relies on each axis' displacement in the joint space of the machine-tool and predicts the most limiting axis for each trajectory segment. Thus, the calculation of the relative feed rate tool-surface can be performed highlighting zones for which the programmed feed rate is not reached and so, it constitutes an indicator for trajectory optimization. The efficiency of the model is illustrated through an example.
Keywords: High Speed Machining, multi-axis machining, inverse time, kinematical behavior

1. INTRODUCTION

Due to a specific cutting process at high velocities, High Speed Machining (HSM) allows decreasing machining time while increasing the surface quality of produced parts. Productivity is also improved by the use of multi-axis machining. Indeed, control of the tool orientation relatively to the surface reduces the number of part setups and increases the effectiveness of material removal.

However, within the HSM context, numerous parameters have to be managed during the programming and machining stages which constitutes a main difficulty of the process [Altintas, 2000]. Moreover, performances of the set "machine tool/NC unit" limit multi-axis machining profits. For instance, during machining the actual velocity is most generally lower than the expected one. Furthermore, velocity drops may appear [Dugas *et al*., 2002]. As a result, machined surface quality is affected and machining time is considerably increased.

From this analysis, we developed a predictive model of the kinematical behavior of the set "machine tool/NC unit". The objective is the prediction of trajectory portions for

which slowdowns may appear. In addition, actual machining time can be estimated. The originality of the model is the use of the inverse time (ISO 6983-1) which authorizes the coordination of as many axes as needed, whether translational or rotational. Constraints integrated in the model come from the trajectory (discontinuities, curvatures...), the NC parameters (cycle times, specific functions like "Look ahead") and the machine tool axis limits (maximum velocities, accelerations and jerks). This model enables predict each axis' velocity profile during the follow-up. The reconstruction of relative velocity tool-surface from axis velocities thus constitutes a good indicator of actual cutting conditions and machining time. Then, it is also possible to take into account these results to elaborate an optimal 5 axis machining strategy.

This paper deals with the structure of the predictive model. Constraints coming from trajectory, NC unit and machine tool axes are detailed and expressed using the inverse time in order to generate axis velocity profiles. Hence, the model efficiency is exposed by comparison between predictions of kinematical profiles and actual velocities measured during machining. The study relies on a five axis milling centre Mikron UCP 710 with an industrial NC Siemens 840D. More specifically, from the performances of the set machine tool/NC unit, trajectory portions for which modifications of cutting conditions arise can be highlighted. A specific attention is thus given on the micro-geometry of the machined surface.

2. LIMITS OF THE FOLLOW-UP DURING MACHINING

During machining, the actual follow-up of the trajectory does not exactly match the programmed one. These differences may originate from numerous sources along the process which transforms the NC file into tool displacements: trajectory adaptation by the NC, NC performances and axis limitations, motion control regulation, deformation of the mechanical structure, tool deflection, etc...

This paper more particularly focuses on the first stage of the processing: the tool-path preparation followed by the interpolation carried out by the NC unit (figure 1). Due to physical and numerical limits, adaptations of the calculated tool-path must be made during the follow-up, such as reducing the relative velocity tool-surface in function of each axis' performances or/and tool-path rounding according to given tolerances.

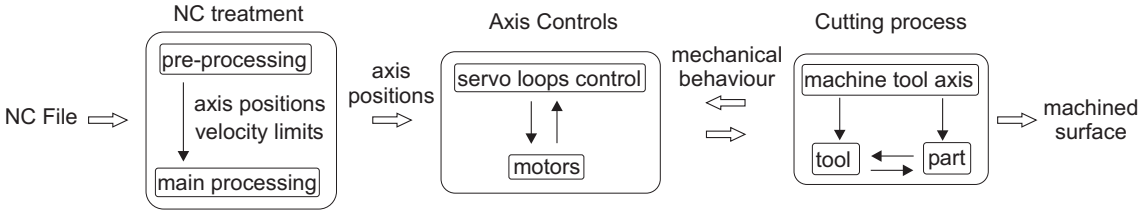


Figure 1; NC file treatment to machined surface

Within the context of multi-axis machining, whatever the architecture of the machine-tool, there is no direct correspondence between the part space and the joint

space of the machine tool. Indeed, the tool-path is computed in the local frame linked to the part. Then, tool positions and orientations are expressed in the joint frame of the machine tool by the Inverse Kinematics Transformation (IKT) in order to command axes. Hence, limits of the follow-up linked to the geometry of the trajectory and performances of axes as well as the capacities of the NC unit must be analyzed in the joint space.

2.1. Orders from NC file

Information contained into the NC file is the tool-path description in the part space and corresponding feed rates. Classically, the tool-path is defined as a set of tool positions (Xpr,Ypr,Zpr) and tool axis orientations (i,j,k). Corresponding axis configurations (Xm,Ym,Zm,A,C) are calculated thanks to IKT. This calculus may lead to several solutions for axis configurations [Jung *et al.*, 2002].

Supposing that the interpolation is linear in the joint space between two successive configurations, the trajectory followed by the tool on the surface is a curve (figure 2).

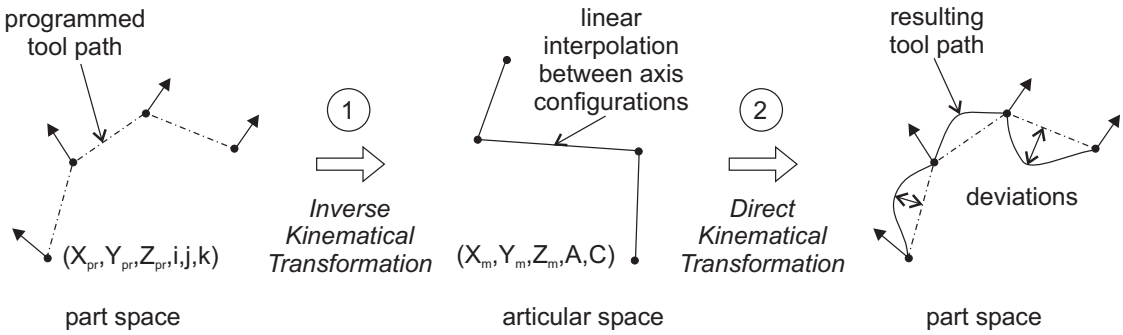


Figure 2; Influence of the linear interpolation in the joint space on the tool path.

As a result, the re-sampling of the tool path in the part space is necessary in order to control the deviations arising between the programmed tool path and the actual one. This step is performed in real-time by the NC unit with the constraint of respecting the Tolerance of Interpolation of the Trajectory (TIT).

Nevertheless, interpolation may cause rear gouging. A typical 5 axis case is the swapping from the range limit of a rotary axis to an achievable axis configuration. When swapping from one space of solutions to the other one, and despite the TIT value, undercuts appear [Tournier *et al.*, 2006]. These deviations can be avoided or minimized by modifying the part setup, by using and adapted post-processor or by computing tool repositioning [Anotaipaiboon *et al.*, 2006][Munlin *et al.*, 04].

In addition, axis velocities are thus computed from axis configurations (also called joint trajectory) taking into account the programmed feed rate. As the feed rate V_f is supposed to be constant between two successive positions P_1 and P_2, the velocity of each axis to cover the segment P_1P_2 is given by eq. (1), where L_{12} is the distance the tool must cover relatively to the part.

$$V_f{}^i = \frac{P_2{}^i - P_1{}^i}{\Delta T_{12}} = \frac{\left(P_2{}^i - P_1{}^i\right)}{L_{12}} \cdot V_f \quad (1)$$

Once the commands are expressed in the joint space, capacities of machine tool axes have to be analysed.

2.2. Limits linked to machine tool axis

All trajectory long, each axis is solicited differently. Solicitations depend on the geometry of the joint trajectory and its discontinuities. Due to the variety of machine tool structures, the sole study of the trajectory does not allow to directly determine trajectory portions for which axis will slow-down during follow-up.

During the displacement along segments, the follow-up of the trajectory is limited by the less powerful axis. Indeed, particularly on serial architectures, axis capacities are different. Therefore, for each elementary segment of the trajectory, the follow-up is limited by the maximum kinematical capacities (velocity, acceleration and jerk). When rotary and translational axes are solicited, it is difficult to determine the limiting axis. As the nature of movements is different, axis capacities cannot be compared directly. To overcome this difficulty, we propose to express axis kinematical capacities using the inverse time method.

Discontinuities of the joint trajectory appear on block transitions. Tangency discontinuities are the most critical ones for trajectory follow-up. Passing exactly through these discontinuities with a non null feed rate would require infinite accelerations on each axis which is physically not possible. Rounding tolerances are thus introduced to improve the follow-up, while controlling the geometrical deviation to the trajectory (figure 3).

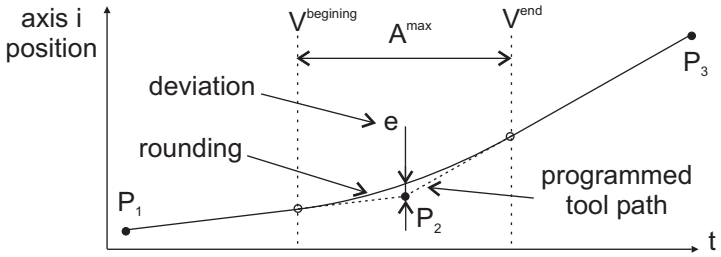


Figure 3; Rounding tangency discontinuity.

Equation (2) presents the relation between deviation and kinematical capacities, supposing that the tangency discontinuity is passed with the maximal acceleration. Hence, the velocity (V^i) is reduced to satisfy at the same time the maximal deviation and the maximal acceleration (A^i_{max}) allowed for each axis.

$$e^i_{max} = \frac{\left(V^i_{end} - V^i_{begining}\right)^2}{A^i_{max}} \quad (2)$$

2.3. Limits linked to the NC unit

Especially in High Speed Machining (HSM) context, NC unit performances may limit the follow-up. Between two tool positions, the NC unit needs at least one interpolation cycle time to compute axis commands. So the programmed feed rate may be lowered to satisfy this cycle time:

$$V_{max}^{NC} = \frac{L_{12}}{T_{cycle\ time}} \tag{3}$$

All the considerations previously exposed are supporting the predictive model of the kinematical behavior for the set "machine tool/NC unit".

3. PREDICTIVE MODEL OF KINEMATICAL BEHAVIOR

The main objective is to evaluate the actual velocity of each axis during multi-axis machining. The evolution of the velocity all trajectory long must highlight the location of trajectory portions for which feed rate will strongly slow-down. The analysis can be used to optimize the step of tool-path computation by the CAM software. Moreover, the predictive model allows the reconstruction of the relative velocity tool-surface. It is then possible to evaluate the impact of kinematical performances on productivity and on geometrical quality of the machined surface.

The formalism used can be considered as an extension of the programming method called inverse time (ISO 6983-1). It consists in expressing a kinematical characteristic (position, velocity, acceleration...) through its inverse time form. Therefore, with such formalism it is possible to compare kinematical performances of the translational and the rotational axes. For the considered trajectory, the model directly reveals which axis is the limiting one, with respect to the following characteristics: maximum velocity, maximum acceleration and maximum jerk. Such analysis may then be carried out whatever the articulated mechanical structure or the number of axes. It also takes into account the influence of the interpolation cycle time.

The following stage is the axis coordination which can be carried out using inverse time. Trajectory follow up is hence performed according to available kinematical capacities.

3.1. Time inverse method

Let us consider the movement of the axis i from the position P_1 to the position P_2. The axis displacement from one position to the other is:

$$\Delta P_{12}^{i} = P_2^{i} - P_1^{i} \tag{4}$$

By assuming that the interpolation is linear in the joint space, the current position of the axis between the two positions is expressed as follows:

$$p_{12}^{i} = \Delta P_{12}^{i} \cdot \alpha_i \quad \alpha_i \in [0, 1] \tag{5}$$

Thus, the expression of the current position of the axis in the inverse time form is:

$$\hat{p}_{12}^{\,i} = \frac{p_{12}^{\,i}}{\Delta P_{12}^{\,i}} = \alpha_i \tag{6}$$

The velocity of the axis is thus obtained by differentiation of equation 6:

$$v_{12}^{\,i} = \frac{dp_{12}^{\,i}}{dt} = \Delta P_{12}^{i} \frac{d\alpha_i}{dt} \tag{7}$$

And, the expression of the velocity is given by the inverse time which is necessary to go from configuration 1 to configuration 2:

$$\hat{v}_{12}^{\,i} = \frac{d\alpha_i}{dt} = \frac{v_{12}^{\,i}}{\Delta P_{12}^{i}} = \frac{1}{\Delta T_{12}} \tag{8}$$

Finally, we can express in the same manner acceleration and Jerk:

$$\begin{aligned} \hat{a}_{12}^{\,i} &= \frac{d^2\alpha_i}{dt^2} = \frac{a_{12}^{\,i}}{\Delta P_{12}^{i}} \\ \hat{j}_{12}^{\,i} &= \frac{d^3\alpha_i}{dt^3} = \frac{j_{12}^{\,i}}{\Delta P_{12}^{i}} \end{aligned} \tag{9}$$

Displacements of the axes are coordinated with respect to the joint trajectory. This coordination is implicit in inverse time since each axis displacement is reduced to a unit displacement. This involves for joint trajectory segments:

$$\begin{cases} \hat{v}_{12}^{\,i} = \hat{v}_{12} \\ \hat{a}_{12}^{\,i} = \hat{a}_{12} \quad \forall \text{ axis } i \\ \hat{j}_{12}^{\,i} = \hat{j}_{12} \end{cases} \tag{10}$$

For each displacement, there is a limiting axis with respect to each kinematical characteristic, velocity, acceleration and jerk. According to these limits, we determine the maximum kinematical characteristics to respect along the segments:

$$\hat{V}_{max}^{\,axis} = \min\left(\frac{V_{max}^{i}}{\Delta P_{12}^{i}}\right) \quad ; \quad \hat{A}_{max}^{\,axis} = \min\left(\frac{A_{max}^{i}}{\Delta P_{12}^{i}}\right) \quad ; \quad \hat{J}_{max}^{\,axis} = \min\left(\frac{J_{max}^{i}}{\Delta P_{12}^{i}}\right) \tag{11}$$

This gives the following constraints:

$$\begin{cases} 0 \le \hat{v}_{12} \le \min\left(\hat{V}_{max}^{f}, \hat{V}_{max}^{NC}, \hat{V}_{max}^{axis}\right) \\ \hat{a}_{12} \le \hat{A}_{max}^{axis} \\ \hat{j}_{12} \le \hat{J}_{max}^{axis} \end{cases} \tag{12}$$

3.2. Prediction of the velocity profiles

This step consists in determining the evolution of the position, the velocity and the acceleration of each axis in function of the time by integrating constraints previously calculated. For that purpose, the principle is the calculation of these kinematical profiles through the inverse time form, and then to project them along the trajectory.

At this stage, we must take into account some parameters and functions of the NC unit. First, we choose the piloting mode of the axes by constant jerk, i.e., trapezoidal profile of acceleration. Henceforth, this piloting mode is the most popular for high-speed machines. Then, the calculation of sampled trajectory profiles is carried out according to the frequency of the controls of the position loop. Thus, we can thereafter send these position-instructions into a modeling of controls in order to estimate the variations of follow-up of the trajectory (position and velocity). The last step of the velocity prediction concerns the integration of the dynamical anticipation, also called "look ahead" which allows anticipating the constraints to be respected during the trajectory follow-up.

4. MODEL VALIDATION

4.1. Test part definition

For the method validation, the tool-path is calculated using home algorithms based on a surface representation of the trajectories. With the tool-path surface representation, we directly specify the envelope surface of the CL points (Cutter Location points). The selected surface is a hyperbolic paraboloid (one unique Bézier patch) (figure 4).

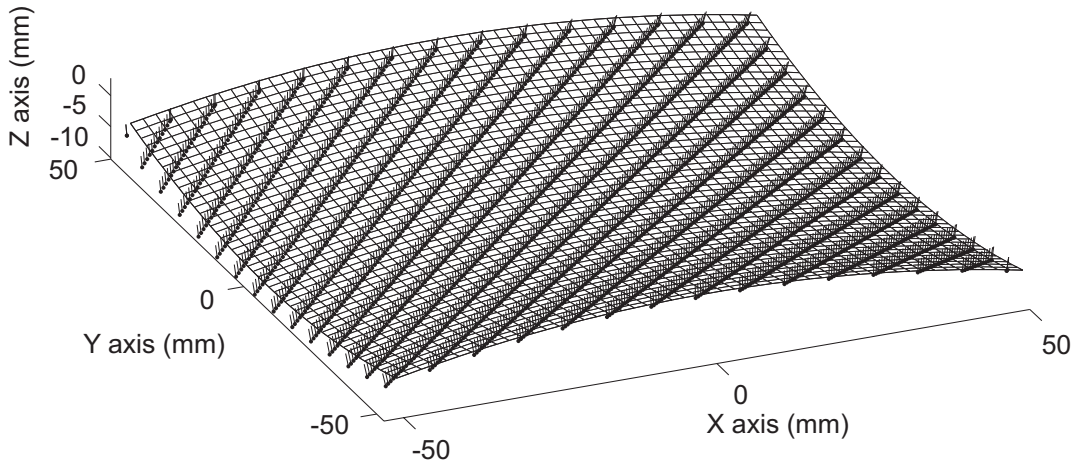


Figure 4; Calculated tool-path

The machining strategy used is one-way parallel planes, for which planes are oriented by 45° relatively to the surface so that trajectories correspond to the surface rules. Thus, the trajectory of a point in the part space is a straight line as the tool axis is oriented with a constant angle of inclination of 5°. The programmed feed rate is 5 m/min.

The IKT is carried out in real-time by the NC unit. The authorized variations by axis are of 0.02mm for the translational axes and 0.05° for the rotational ones. The part set-up within the machine-tool workspace is such that the programming frame

corresponds to the machine frame. It is important to notice that for this example, all the axes of the machine are solicited during machining.

4.2. Comparison of predicted and measured velocities

In this section, we concentrate on a trajectory corresponding to one pass located near the centre of the surface. Simulations using the previously exposed model are illustrated in figure 5. It can be observed that, due to the velocity limits along the blocks, the programmed feed rate can never be reached. Indeed, the programmed feed rate is greater than the maximum velocity with respect to the cycle time of interpolation all pass long. Trajectory segments are thus too short to reach the programmed feed rate. Moreover, close to the middle of the trajectory, the C angle is strongly solicited. Indeed, we can see that the maximum performances of the C axis are under other axis limits. We can conclude that C is the limiting axis.

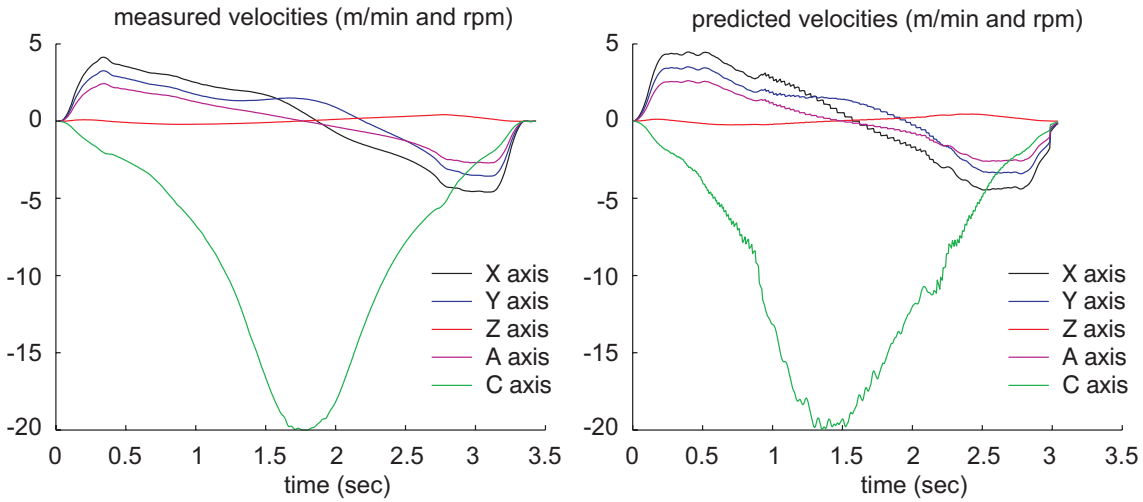


Figure 5; Comparison between measured and predicted axis velocities

Figure 5 also brings out two zones for which the passage of discontinuities between segments limits follow-up. These discontinuities are located near the middle of the trajectory. Note that the small undulations at the beginning and at the end of the pass are due to dynamic anticipation. If one strongly increases the number of anticipated blocks, the two velocity limits can be reached.

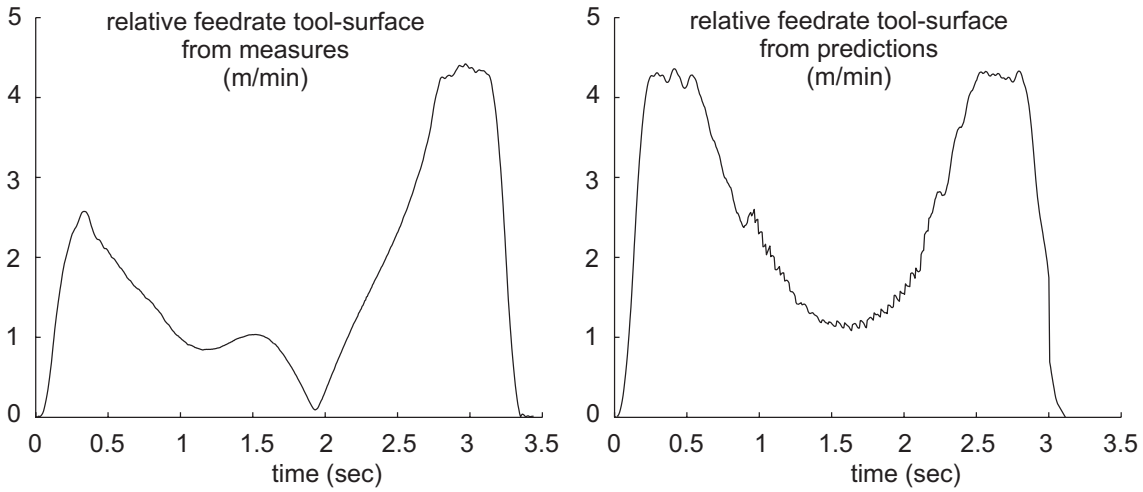


Figure 6; Comparison between measured and predicted relative feed rate

Figure 6 presents the comparison between relative tool-surface velocity measured during the program execution and the simulated one. The general shape of the predicted and the measured velocities corresponds. Nevertheless, there are differences on the values, in particular for the first half of the trajectory: actual velocities are lower than those predicted. The actual behavior is surprising. Indeed, as the joint trajectory is quite symmetrical, the same characteristic should be observed for velocity profiles. This is clearly observed for the predicted profile but not for the actual velocity profile for which slowdown is strongly marked with apparently no notable reason. Indeed, it seems that the treatment by the NC unit is not uniform throughout the trajectory. Therefore, the prediction of velocity is here only valid for the second part of the pass. Despite, the model allows a correct machining time estimation for the considered pass.

4.3. Influence on geometrical quality

As it can be observed in figure 7, the machined part does not present significant marks. Nevertheless, at the vicinity of the middle of the pass (zone 1) the surface finish is slightly altered: regularity of the tooth track which can be seen for other passes (zone 2) no longer exists.

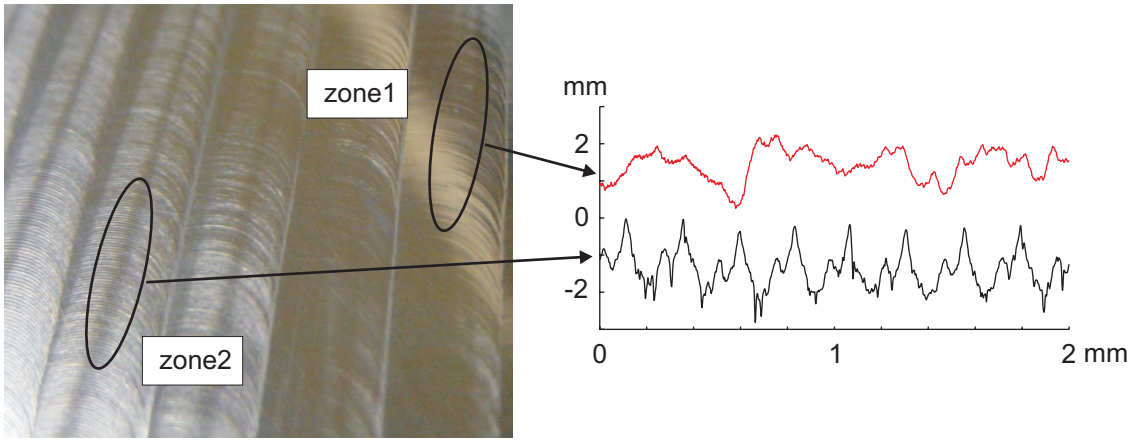


Figure 7; Comparison of the tooth track according zones

However, for the present case the decreasing of the relative velocity tool-surface is not significant enough to produce a strong alteration of cutting conditions.

5. CONCLUSION

In this paper, we have presented a predictive model that evaluates axis velocities from a NC file integrated NC and axis capacities. Thanks to its specific formalism, the model can be applied whatever the machine tool architecture and the axis number. The formalism used is an extension of the inverse time method and consists in expressing each kinematical characteristic of position, velocity, and acceleration through its inverse time form. For a given trajectory such formalism allows the comparison of kinematical performances of translational and rotary axes and provides the most limiting axis with regard the trajectory follow-up. Through an example, we showed that predicted velocity profiles match the measured ones. Zones for which velocity decreases are detected by reconstruction of the relative velocity tool-surface. Modifications of cutting conditions on these zones are thus highlighted by a visual analysis of the geometry. Nevertheless, the complexity and the specificity of industrial NC units in multi-axis machining make difficult a very sharp modeling of the kinematical behavior. However, the model is a good indicator of the actual follow-up.

These works are currently being integrated in a surface based model for the description of the tool trajectories [Lartigue *et al.*, 2004]. The objective is to optimize the follow-up by a modification of the machining strategy and more particularly the tool axis orientation.

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