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Characterization of 3D surface topography in 5 axis milling

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Abstract

Within the context of 5-axis free-form machining, CAM software offers various modes of tool-path generation, depending on the geometry of the surface to be machined. Therefore, as the manufactured surface quality results from the choice of the machining strategy and machining parameters, the prediction of surface roughness in function of the machining conditions is an important issue in 5-axis machining. The objective of this paper is to propose a simulation model of material removal in 5-axis based on the N-buffer method and integrating the Inverse Kinematics Transformation. The tooth track is linked to the velocity giving the surface topography resulting from actual machining conditions. The model is assessed thanks to a series of sweeping over planes according to various tool axis orientations and cutting conditions. 3D surface topography analyses are performed through the new 3D roughness parameters proposed by recent standards.

Keywords: Surface topography, Surface Roughness parameters, Patterns, 5 axis milling

1. Introduction

In the field of free-form machining, CAM software offers various machining strategies depending on the geometry of the surface to be machined. The geometrical surface quality results from the choice of the machining strategy and corresponding parameters. Resulting machining time, productivity and geometrical quality directly depend on these parameters. In 5 axis machining, axis capacities as well as specific NC treatments affect tool trajectory execution, leading sometimes in changes in actual local federates. Moreover, as the tool axis orientation generally varies during machining the resulting pattern of the finished surface can be altered [1]. The prediction of the 3D surface topography in function of the machining conditions is an important issue in 5-axis machining. Process planning and tool path definition taking into account machining tool behaviour can only be correctly achieved if resulting surface patterns are well known and linked to the part functionality.

With the advances in 3D measuring system, in particular optical means, it is now possible to measure the 3D surface finish with a good precision [2]. The definition of new parameters to characterize 3D surface roughness becomes necessary. A standardized project [EUR 15178 EN] proposes the definition of 3D parameters as an extension of the well-known 2D parameters [3]. Only a few studies try to link the surface roughness to the surface requirements using 3D surface roughness parameters. For friction in servo hydraulic assemblies, negative Skewness and lower kurtosis values as well as the higher valley fluid retention index are found to have lower frictional characteristics [4]. The functionality of automotive cylinder bores is partially characterized by oil consumption and blow-by. In this specific case, it is more significant to consider Sq, Sk, Svk, Sds, Sbi to describe oil consumption and Sv, Svi for blow-by [5]. Concerning the fatigue limit, authors prefer to refer to Sq, Std and

Sal [6]. Due to the lack of information concerning the influence of the roughness parameter on the surface requirement, a description of the 3D pattern obtained after surface machining is essential to bring out the influence of machining parameters on the surface roughness, and to afterwards link surface roughness to functional requirements. In literature, few formalized studies exist which aim at linking the surface topography to the machining strategy parameters [7]. Two standpoints can be adopted: the experimental standpoint or the theoretical standpoint. Most of the experimental methods attempt to establish the link between the feedrates, the machining direction, the tool orientation and the 3D topographies from measurement of machined surfaces. Unfortunately, results are only qualitative; only a few of them clearly express the relationship between the machining strategy parameters and the surface topography [8], [9]. Adopting the theoretical standpoint, Kim describes the texture obtained in ball-end milling using numerical simulations including the influence of the feed rate only [10]. Bouzakis focuses on the motion of the cutting edge. The author highlights the influence of the tool orientation, the transversal step and the feed rate on the surface quality [11]. Toh supplements this work by defining the best direction to machine an inclined plane [12]. In a previous work, we propose to link the machining strategy in 3-axis ball-end milling to a 3D surface roughness parameter and to optimize the machining direction according to this parameter [13]. Kim proposed to simulate the 3D topography obtained in 5axis milling using a nose ball end. The envelope of the tool movement is modelled by successive tool positioning according to the feed per tooth.

In this paper, a theoretical approach is proposed to predict the 3D surface topography obtained in 5-axis milling with a nose-ball end cutter tool. The modelling of the cutting process is only geometric; phenomena of material pull out which take place during the cutting process are not taken into account. Unlike the method of Kim, the whole geometry of the tool is completely modelled, i.e. the cutting edge as well as the flank face. Hence, the study presented in this paper aims at formalizing the influence of the machining parameters on the 3D surface topography, with the objective of highlighting 3D standardized parameters that best characterize machined patterns.

2. 3D Surface topography in 5 axis machining

The material removal simulation is based on the well-known Nbuffer method. The main difficulty is the integration of effects linked to 5-axis machining within a context of high velocities. Indeed, the use of two additional rotational axes leads to two main difficulties during trajectory execution: the computation of the Inverse Kinematical Transformation in real time to define setpoints corresponding to tool postures, and the synchronization of the rotational axis with the translational ones [14]. Moreover, due to kinematical axis capacities, axis velocities may vary leading to feedrate fluctuations which can alter the 3D pattern. In the proposed approach, the prediction of 3D surface topography takes advantage of a model of velocity prediction developed in a previous work [14] which gives a good estimation of the local feedrate of the tool-teeth.

The method of material removal simulation is presented in figure 2. From the CAM trajectory, a set of tool postures is defined in the part coordinate system, and then expressed via the IKT in the machine coordinate system. Including axis limits, local feedrates can be predicted. Based on a linear interpolation, the time interval separating two postures is calculated, allowing the calculation of the angular positions of the tool axis $\{\alpha^i\}$:

$$\theta^i = \theta^{i-1} + \Omega_{spindle} \cdot \frac{\sqrt{(X_p^i - X_p^{i-1})^2 + (Y_p^i - Y_p^{i-1})^2 + (Z_p^i - Z_p^{i-1})^2}}{V_f^i + V_f^{i-1}} \cdot 2$$

In this equation, the rotational velocity of the spindle $\Omega_{spindle}$ is supposed to be constant and equal to the programmed one. The elementary trajectory (between two postures) is thus sampled (postures and angular positions) according a given sampling parameter leading to $\{X_p^i, Y_p^i, Z_p^i, I^i, J^i, K^i, \alpha^i\}$. For its part, the tool is supposed to rigid, and is approximated by a local meshing. Only active cutting edges are considered. To ensure a correct approximation of the tool surface, the meshing is performed with a chord error equal to 0.1 μm .

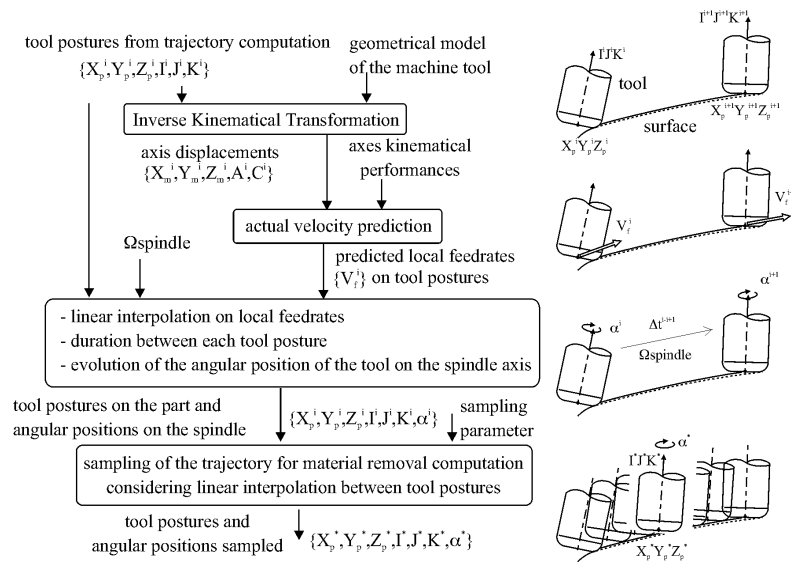


Fig. 2: Local trajectory calculation in 5-axes

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 $\{X_p^*, Y_p^*, Z_p^*, I^*, J^*, K^*, \alpha^*\}$.

In order to assess the model detailed a series of experiments is carried out (figure 3). These experiments aim at comparing various 3D surface topographies obtained by simulations to actual measured ones. A series of plane sweepings is performed for which three parameters are variable: the tool axis orientation, the feedrate and the maximal scallop height allowed (Table II). Actual machining is performed on a 5-axis HSM using a filleted-end milling tool ($R=5\text{mm}$, $r_c=1.5\text{mm}$) with a unique tooth in order to control the tooth geometry which contributes to the final imprint. The tool orientation is defined according to the tilt angle (θ_t) and the angle screw (θ_n).

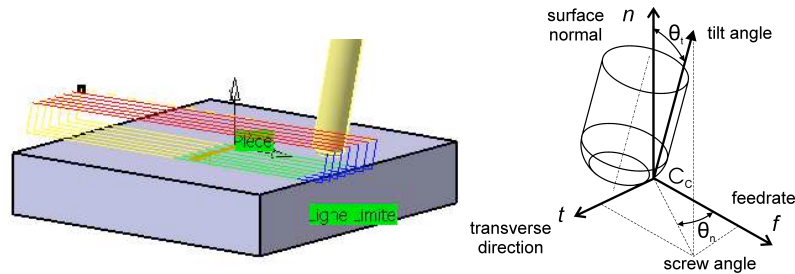


Figure 3; Definition of the experimentation.

| Screw angle (°) | | | Tilt angle (°) | | Scallop height (mm) | | Feedrate (m/min) | |
|-----------------|----|----|----------------|----|---------------------|-------|------------------|---|
| 0 | 20 | 40 | 1 | 10 | 0,005 | 0,001 | 2 | 4 |

Table I; Experimentation parameters.

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. To lighten the paper, only a few cases are reported in table II. Nevertheless, for all the cases of the experimentation, simulated patterns as well as defect magnitudes match the measured one (Table II and figure 4).

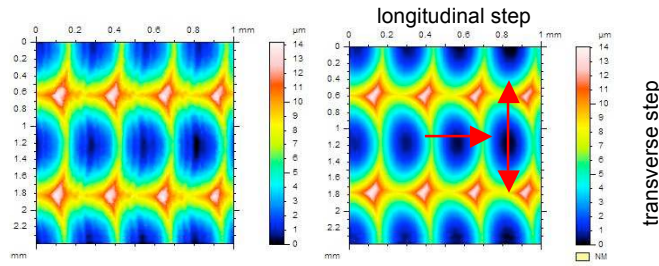


Figure 4; Measured and simulated pattern (Screw 0°, tilt 10°, scallop height 0.01mm, feed rate 4 m/min)

The small differences that can be observed between simulated and measured data may come from the real tool geometry and/or the cutting process. However, the proposed model is efficient to predict 3D surface topography in 5-axis machining. Therefore, the analysis of machining parameters influencing surface topography is conducted through simulations.

| Screw (°) | Tilt (°) | Scallop height (mm) | Feedrate (m/min) | St ($\overline{\mu\text{m}}$) | | Sa ($\overline{\mu\text{m}}$) | | Trans. step (mm) | | Long. step (mm) | |
|-----------|----------|---------------------|------------------|---------------------------------|------|---------------------------------|------|------------------|------|-----------------|-------|
| 0 | 1 | 0,005 | 2 | 6.99 | 5.58 | 1.27 | 1.21 | 2.76 | 2.63 | 0.13 | 0.133 |
| 0 | 1 | 0,005 | 4 | 9.17 | 9.24 | 1.46 | 1.66 | 2.71 | 2.62 | 0.269 | 0.266 |
| 0 | 10 | 0,01 | 4 | 14.1 | 15.7 | 2.47 | 2.56 | 1.21 | 1.18 | 0.267 | 0.266 |
| 20 | 10 | 0,01 | 4 | 6.54 | 5.63 | 0.96 | 1.05 | 0.46 | 0.43 | 0.264 | 0.266 |

Table II; Comparison between measured and simulated patterns.

3. 3D surface topography parameters

As expected, the feed rate is an essential parameter, as it actually conditions the 3D pattern (Figure 5, cases 1 and 2). Modifications of local feed rate during machining may affect the 3D surface finish.

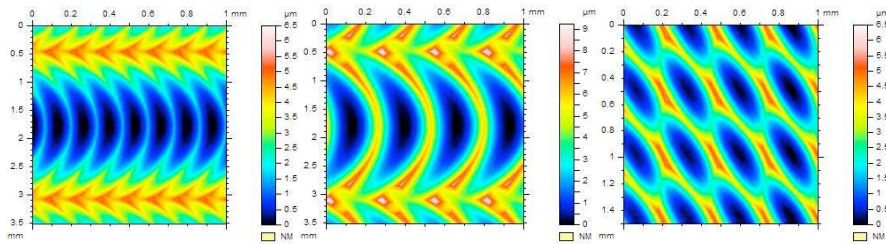


Figure 5; Simulated patterns (from left to right, screw 0,0,20; tilt 1;1,10, Scallop height 0.005,0.005,0.01; feedrate 2,4,4)

Usually, the maximum scallop height allowed is one of the most used parameters in CAM software to define the 3D surface topography. As shown in figure 5 (case 4), a non null screw angle provides a pattern for which the notion of cusp has no more significance. Hence, the influence of the tool axis orientation is significant in 5-axis machining and the description of surface patterns must account for this parameter. According to previous work which try to link 3D surface roughness parameters to the part functionality [4,5,6], the study proposed is reduced to the more significant parameters for fatigue and friction applications. These parameters are classified in function of their family: Amplitude parameters S_q , S_v , S_{sk} , S_{ku} ; Spatial parameters S_{al} , S_{ds} , S_{td} . Results relative to our experimentation are given in table III. Concerning S_{td} , the screw angle seems the more relevant influent parameter. This is consistent with pattern observations. In fact the marks left by the tooth are oriented according to this angle. Due to the modification of the effective cutting diameter, the screw angle has also a significant effect on S_{al} , S_{td} , S_t and S_v . On the opposite, its effect is quite negligible on kurtosis or skewness values. The tilt angle is the most significant parameter for S_q , with a little effect on S_{al} . However, it does not influence the texture

direction Std. Results emphasise that feedrate is more influent than the maximum scallop height on the studied 3D parameters. Particularly for the distribution of peaks (Sds), the feed rate is the most significant parameter.

| Parameter | | | Mean | Screw | Tilt | Scallop height | Feedrate |
|-----------|--|-----|--------|--------|---------|----------------|----------|
| Amplitude | Height of the surface | St | 4,79 | -2,34 | 0,56 | -0,82 | 1,27 |
| | Arithmetic deviation of the surface | Sa | 0,92 | -0,45 | 0,19 | 0,1 | 0,16 |
| | Root-Mean-Square Deviation of the Surface | Sq | 1,10 | -0,32 | -0,57 | 0,12 | 0,24 |
| | Kurtosis of Topography Height Distribution | Sku | 2,33 | 0,01 | -0,04 | -0,17 | 0,06 |
| | Skewness of Topography Height Distribution | Ssk | 0,47 | 0,00 | -0,07 | -0,05 | -0,02 |
| Volume | Valley Void Volume of the Surface | Sv | 1,71 | -0,81 | 0,25 | -0,28 | 0,47 |
| Spatial | Density of Summits of the Surface | Sds | 606,38 | 132,87 | -115,13 | -31,68 | -153,50 |
| | The Fastest Decay Autocorrelation Length | Sal | 0,15 | -0,12 | -0,07 | -0,03 | -0,04 |
| | Texture Direction of the Surface | Std | -21,80 | -13,33 | 0,03 | -0,44 | -0,70 |

Table III: Mean values of the effects

Nonetheless, previous observations must be modulated as influences of the machining strategy parameters are close to each other. In addition, interactions between parameters have not been studied in this work. Indeed, the scallop height, the screw and the tilt angles are linked by the transversal step calculation. This actually binds respective influences.

4. Conclusion

The final objective of our work is to propose a method of machining strategy choice based on the machined surface function. For this purpose an algorithm to simulate the pattern obtained in 5-axis milling is proposed and assessed. From simulated patterns it is possible to evaluate functional 3D surface roughness parameters and to link them to machining strategy parameters. Simulations bring out that depending on the surface function one of the machining parameter is determinant on the surface quality. The proposed study should be completed by the study of relative links between the machining strategy parameters.

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