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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 ways 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 with 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 areal surface roughness parameters proposed by recent standards.

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 surface quality results from the choice of the machining strategy and corresponding parameters (tool inclination, feed per tooth, cutting speed, radial depth of cut). Resulting machining time, productivity and geometrical surface quality directly depend on these parameters. In 5-axis machining, axis kinematical capacities as well as specific NC treatments alter tool trajectory execution, leading to changes in actual local feedrates. Moreover, as the tool axis orientation generally varies during machining, the resulting surface pattern can be affected [1]. The prediction of the 3D surface topography according to the machining conditions is an important issue in 5-axis machining to correctly achieve process planning and to link resulting surface patterns with part functionality.

1.1. Surface topography description

With the advances in 3D measuring systems, it is now possible to measure machined surface patterns with enough accuracy [2–4] although there is no standard traceability [5]. A draft standardized project [ISO 25178-2] developed by the ISO Technical Committee 213 working group 16, proposes the definition of areal parameters as an extension of the well-known profile parameters [6,7]. However, only a few studies try to link the surface roughness with surface requirements via areal surface roughness parameters. For friction in servo hydraulic assemblies, negative skewness and the lowest kurtosis values as well as the highest valley fluid retention index are found to have the lowest frictional characteristics [8]. 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 [9]. Concerning the fatigue limit, authors prefer to refer to *Sq*, *Std* and *Sal* [10]. Due to the lack of information concerning the influence of roughness parameters on surface requirement, a description of the 3D pattern obtained after surface machining is essential to bring out the influence of machining parameters on surface topography, and to afterwards link surface roughness with functional requirements.

1.2. Surface topography prediction

In the literature, few formalized studies exist which aim at linking the surface topography with the machining strategy parameters [11]. Two standpoints can be adopted: the experimental standpoint and the theoretical standpoint. Based on surface topography measurements, most of the experimental methods attempt to establish the link between the feedrates, the machining direction, the tool orientation and the 3D topographies. Unfortunately, results are only qualitative; only a few of them clearly express the relationship between the machining strategy parameters and the surface topography [12,13]. Adopting the theoretical standpoint, Kim described

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the texture obtained in ball-end milling from numerical simulations only accounting for the feedrate influence [14]. Bouzakis focused on the motion of the cutting edge. The author highlights the influence of the tool orientation, the transversal step and the feedrate on the machined surface quality [15]. Toh supplements this work by defining the best direction to machine an inclined plane [16]. In a previous work, we proposed to link the machining strategy in 3-axis ball-end milling with a 3D surface roughness parameter and to optimize the machining direction according to this parameter [17]. Kim proposed to simulate the 3D topography obtained in 5-axis milling using a filleted-ball-end tool. The envelope of the tool movement is modelled by successive tool positioning according to the feed per tooth.

Due to difficulties in measuring the surface topography for complex shapes, the need for models or simulations for predicting the machined 3D surface topography is real. However, if most literature works enhance the major role of the federate, the context of high speed machining is seldom considered. Actually, in multi-axis high speed machining the computation of the inverse kinematic transformation and the synchronization of the rotational axes with the translation ones impact the respect of the programmed feedrate which does not remain constant during machining. Therefore, it seems essential to integrate those local federate variations in a prediction model of 3D surface topography obtained in multi-axis high speed machining.

In this paper, a theoretical approach is proposed to predict the 3D surface topography obtained in 5-axis milling with a filleted-ball-end cutter tool integrating actual feedrate evolution.

Actual feedrate evolution is obtained thanks to a kinematical predictive model which accounts for the local variations of the velocity due to multi-axis high speed machining [18]. The modelling of the cutting process is only geometrical; material pull out is not consider here. The proposed model applies for complex surfaces for which the topography measurement is generally difficult. The topography prediction relies on the well-known N-buffer simulation method [19].

Based on simulations, the study finally aims at formalizing the influence of the machining parameters (feed per tooth, tool inclination, maximal scallop height allowed) on the 3D surface topography. For this purpose, the topography is characterized using the areal surface parameters. An attempt is made to propose links between areal surface parameters and the parameters of the machining strategy.

2. 3D surface topography in 5-axis machining

Material removal simulation relies on the well-known N-buffer method [19]. The main difficulty is the integration of the effects linked to 5-axis machining within a context of high velocities. Indeed, the use of the two additional rotational axes leads to two main difficulties during trajectory execution: the computation of the Inverse Kinematical Transformation in real time to define set points corresponding to tool postures, and the synchronization of the rotational axes with the translational ones [18]. Moreover, due to kinematical axis limits, axis velocities may vary leading to feedrate fluctuations which can alter the 3D pattern. In the proposed approach, the prediction of the surface topography takes advantage of a model of velocity prediction developed in a previous work which gives a good estimation of the local feedrate of the tool-teeth [18].

To illustrate this purpose, do consider the example of the surface presented in Fig. 1. The surface, a hyperbolic paraboloïd with a double curvature, is machined along its rules with a filleted-end tool (R = 5 mm, r = 1.5 mm), considering a tool inclination of 1° (tilt angle = 1°, see Fig. 4). During machining, the surface curvature involves a combined movement of all the 5-axes. The programmed feedrate is set to 5 m/min. Using the predictive velocity model, the calculation of the feedrate all trajectory long is carried out [1]. Fig. 2 presents the evolution of the local feedrate for the machining of the trajectory at the middle of the surface (red arrow in Fig. 1). Simulated values as well as measured ones are reported.

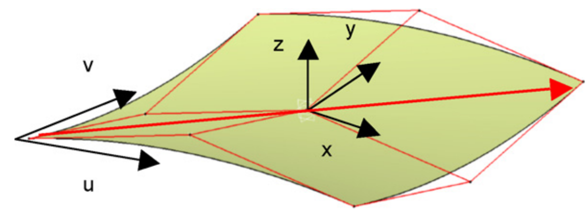

Fig. 1. Hyperbolic paraboloïd.

As it can be observed, whether for the simulation as for the measurement, the programmed feedrate is only reached at the beginning and at the end of the trajectory; velocity is strongly decreased at the middle of the trajectory. However, some differences between simulated and measured values are noticeable: although the velocity decreasing is correctly predicted by simulation, deceleration is faster and occurs later. Nevertheless, simulation gives a good estimate of the feedrate, and thus of the local feed per tooth. Therefore, as actual cutting conditions can be known, a more precise simulation of the 3D surface topography is now possible.

The simulation requires the modelling of the surface, the modelling of the tool geometry and the definition of the actual tool trajectory [1]. The surface is sampled by a grid of points defined in a (XY) plane. A line, parallel the local surface normal, is associated to each point of the grid, thus defining a line-net. This line-net is truncated by the cutter tool according to the actual tool trajectory, and the remaining part of the line-net defines the 3D topography of the machined surface.

For its part, the tool is supposed to be rigid and measured by optical means. The complete tool geometry is approximated by a local meshing, i.e. the cutting edge as well as the tool flank face. 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.

Concerning the tool trajectory, the proposed method integrates actual local feedrates calculated using the prediction model (Fig. 3). More generally, the tool trajectory is defined in the part coordinate system (PCS) by a set of tool postures. Considering the velocity

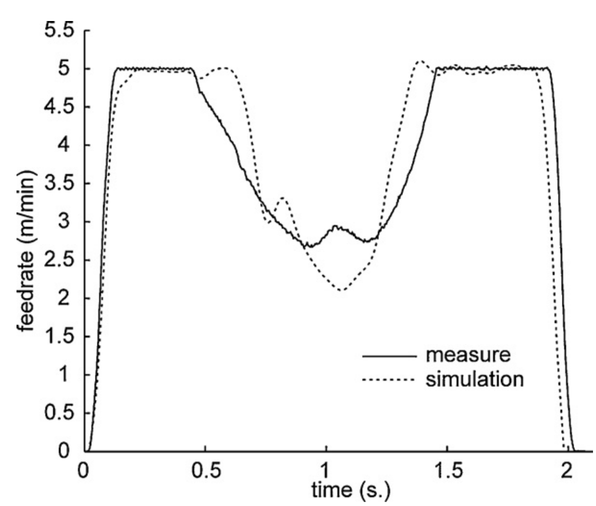

Fig. 2. Simulated and measured feedrates.