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Prediction of cutting forces and surface quality in free form machining directly from CAM tool path

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Abstract

In the present work, a new approach for the modelling of milling is described. The cutting forces for complex operations in milling are calculated directly from the tool path provided by a Computer Assisted Manufacturing program. The main idea consists in using tool position points and tool-surface contact points coming from CAM data in order to calculate the local inclination angle of the generated surface and then the tool engagement in the workpiece material. By using an analytical model able to predict the cutting forces for the case of 3 axes milling for different tools, and by using a thermomechanical approach of cutting (Johnson-Cook constitutive law), the results are very encouraging. There remain some discrepancies in the amplitude of cutting forces which may be mainly caused by physical phenomena such as ploughing or vibration which are not taken into account in this model. The approach also enables to calculate a resultant surface (Z-map) in order to study the geometrical quality (form and roughness) of the machined workpiece.

Keywords: Cutting forces, Free form machining, CAM tool path, ball-end milling.

1. Introduction

One of the main orientations in industrial and academic works about machining is the development of an integrated system for the prediction of various phenomena occurring during cutting. The goal is to optimise the preparation of manufacturing processes and improve quality and productivity. The calculation of cutting forces takes a central place in modelling because this information is necessary to improve the behaviour of the tool during machining. More precisely, deflection of the cutter, which may be estimated thanks to the knowledge of these cutting forces, can be taken into account to reduce form defects and improve surface integrity. The prediction of cutting forces allows the enhancement of both cutting conditions and tool path, but it requires a precise knowledge of the cutting process.

Modelling of cutting can be based on three different and complementary main approaches:

- An analytical approach which attempts to describe and use the thermomechanical phenomena occurring during cutting.
- A mechanistic approach attempting to calculate the cutting forces in a simple and effective way by using reference measurements transposed to other situations.
- A numerical approach based usually on Finite Elements Modelling.

Because of the limitation of empirical methods in extrapolation and experimentation, and of FEM methods in computing time and complexity, it is essential to develop a predictive, robust and versatile method to simulate analytically the ball-end milling process. In this view, we present in this paper a global approach for the modelling of 3 axes milling with a ball-end cutter. This model permits to simulate most of operations necessary to obtain a prismatic or complex surface in 3 axes milling. Two methods can be used to calculate the local cutting forces: A mechanistic one (empirical cutting coefficients) and a thermomechanical one taking into account the behaviour of the machined material.

The first results obtained with the presented model are compared and validated with measurements obtained from specific wavelike surface tests conducted on a 42CrMo4 steel with a tungsten carbide ball-end mill. An introduction to surface finish prediction is also proposed in order to show the interest of the method for this second purpose.

2. Proposed Approach

The works presented in this paper are based on those done by Fontaine et al. [1-2] concerning the prediction of cutting forces in 3 axes ball-end milling of an inclined plane with different strategies. The main idea is here to consider a free form surface to be machined and to obtain the decomposition in segments from a CAM tool path generation in order to build locally a tilted plane of finite length which is in contact with the tool. The main point in the development of this idea is to propose a precise prediction of the cutting forces in ball-end milling and to extend the tool-material engagement model to the case of successive tilted planes. In this view, the first step is to describe properly global and local geometry of the cutter. Afterwards the CAM cutter location points can be used to determine the tool engagement.

2.1. Tool Geometry

The tool considered here is a ball-end mill, which is commonly used for sculptured surface machining, Figure 1. The associated geometric equations are available in previous works [1-3]. This method can take into account easily other tool geometries from a parametrical description [4-5].

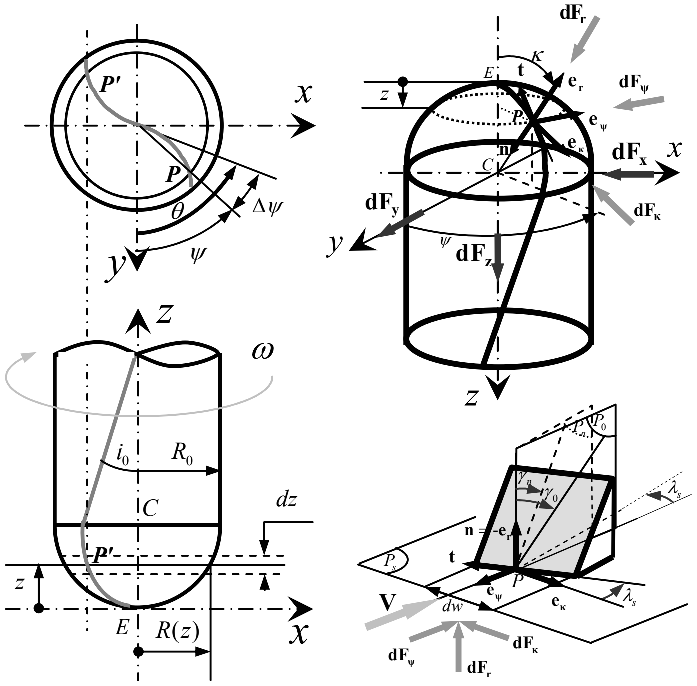

Figure 1: Global and local geometry of a ball-end mill

The current point *P* along a cutting edge referenced *j* is located from the local radius *R*(*z*), the location angles ψ_j and $\Delta\psi$, the rotation angle θ and the local helix angle *i*(*z*). The cutting edges engaged in the workpiece material are decomposed into a series of elementary edges starting from the axial increment d*z*. The local base vectors (e_r, e_κ, e_ψ) are introduced, associated to the spherical coordinates of point *P* (R_0, κ, ψ) respectively. The parameters defining the local geometry are: the inclination angle κ associated to vector e_r, the cutting edge inclination angle λ_S, the cutting angles γ_0 and γ_n and the elementary cutting width *dw*.

2.2. Geometry of machined surface and tool path

Without considering vibrations, the resultant surface geometry depends on tool geometry, tool path, tool inclination and on tool rotation. In a CAM software, tool envelope and inclination are taken into account to follow the surface to be machined and the tool path is defined through a decomposition which is function of the targeted tracking precision. Then Cutter Contact (CC) points and Cutter Location (CL) points are created, and the interpolation (path between two successive points) can be linear or more complex (polynomial, B-Spline). Therefore, by using CL points provided by a CAM application, coupled with information about local interpolation, inclination and angular position of the tool, a pertinent engagement in workpiece material can be define for all industrial applications. For the case of 3 axes milling and linear interpolation (typical configuration), CL points associated to the tool geometry and angular position are sufficient to consider accurately the position and engagement of cutting edges and then to calculate efficiently the cutting forces. In this case, the tool path is defined by a succession of tilted segments, and the cutting operation can be locally considered as the machining of a tilted plane. We consider in the following developments that each segment presents a local slope in the feed direction.

2.2. Feed along tool path

The characteristic local feed angles φ_x and φ_z are defined throughout the tool path according to the configuration presented in Figure 2 (a). They define the orientation of local feed vector **f** and local feed per tooth vector $\mathbf{f_t}$.

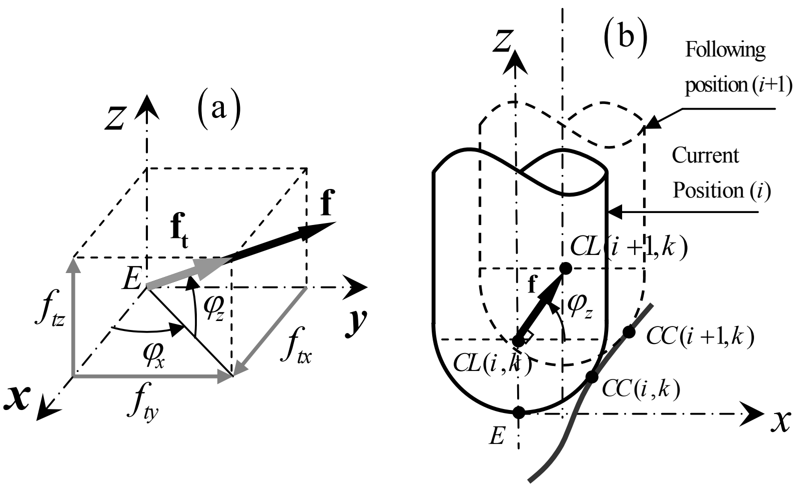

Figure 2: Local feed parameters: (a) Characteristic feed angles φ_x and φ_z, (b) Determination of local feed vector from CL points

The local feed vector **f** can be calculated step by step in considering the tool path decomposition, Figure 2 (b). Its components in the global frame are then obtained from the position of two successive points defined by the CAM data (cutter location points):

$$\begin{pmatrix} f_X = CL_X(i+1,k) - CL_X(i,k) \\ f_Y = CL_Y(i+1,k) - CL_Y(i,k) \\ f_Z = CL_Z(i+1,k) - CL_Z(i,k) \end{pmatrix}_{(X,Y,Z)} \tag{3}$$

where $CL_X(i,k)$, $CL_Y(i,k)$, $CL_Z(i,k)$ are the coordinates in the global reference frame (CAM program coordinate system X, Y, Z) for a CL point referenced (i) on a tool path referenced (k). The rank i+1 defines the following reference position.

The modulus of the local feed per tooth vector $\mathbf{f_t}$ can be deduced from the modulus of $\mathbf{f}$ by dividing it by the total number of teeth denoted N_t.

2.3. Tool engagement

The tool engagement in the part material for each reference position must be determined in order to know the quantity of material machined by each tooth. For each elementary edge resulting from the decomposition, it is necessary to check the position of the current point P which locates the cutting edge and to compare it with the form of the uncut surface attacked by the tooth. This surface can be delimited by three types of boundary conditions:

- the relative position of the workpiece uncut surfaces along the three axes and specifically along Z-axis (upper initial or pre-form surface),
- the previous tool path considered without any tool deflection and with perfect surface finish (path interval Δp defined in (X,Y) plane, Figure 3),
- and the path of the previous tooth (including tool run-out influence).

The description of the position of point P and the tests associated to these boundary conditions are detailed in previous works on modelling of free form surface milling [3]. The originality is here in considering the previous and following tool path by checking in the CAM data the position of the tool along these paths to the current position of point P. The CAM data is here mainly used to define the path interval Δp, the surface inclination transverse to the feed denoted $\varphi_{\Delta p}$ and the local radius of the tool in a previous or following position denoted R_p.

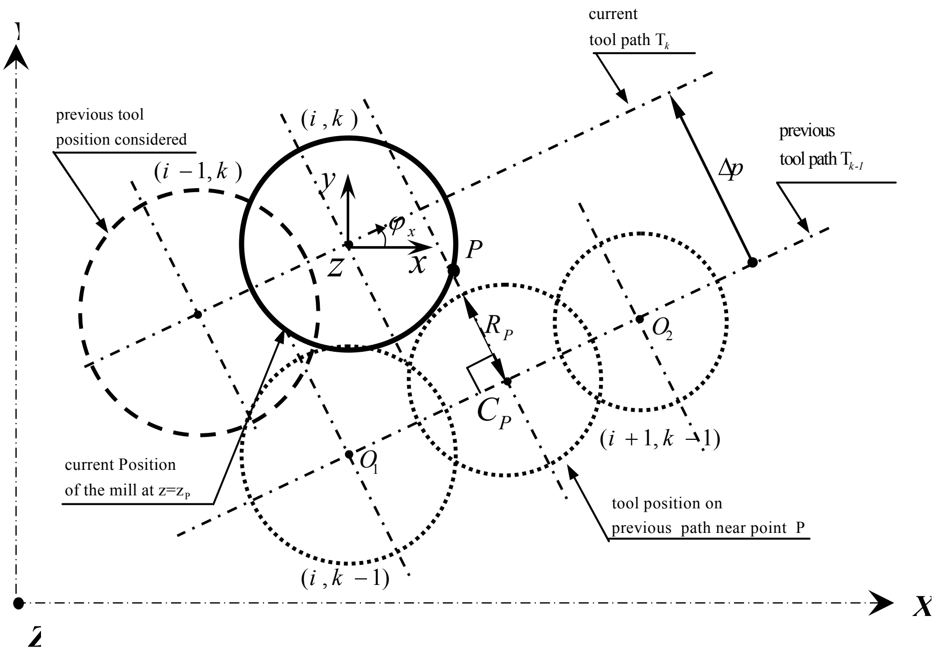

Figure 3: Comparison between point P on tooth j and previous tool path for a rectilinear trajectory in the (X,Y) plane Z=Z_P (here $\Delta p > 0$)

In particular, the comparison between the distance PC_P and the local radius R_p (defined in Figure 3) can be done by checking the position of the tool defined by the CAM system around the position of current point P. This procedure is efficient but can be time consumer. Nevertheless, the method can be reinforced storing the points P considered and using them to construct a resultant surface by keeping the lower points distributed on a regular grid (Z-map surface). The tests of tool engagement in regard of the previous tool paths are then enhanced and the resultant surface quality can be analysed too.

2.4. Calculation of local and global cutting forces

For each elementary cutting edge considered as engaged in the workpiece material, the local cutting forces can be estimated from a classical cutting force model. This model can be for example mechanistic (use of empirical cutting coefficients) or thermo-mechanical (use of material and friction parameters) and the purpose is to determine the elementary forces dF_r, dF_κ and dF_ψ from local geometry (cutting angle γ, edge inclination angle λ_s, elementary cutting width dw, undeformed chip thickness t_0), (see Appendix B). The elementary force components dF_r, dF_κ and dF_ψ are projected on the local coordinate system linked to the tool. Elementary values of cutting forces dF_x, dF_y and dF_z are then obtained and they can be summed up for each considered angular position of the tool (rotation increment $d\theta$) in order to present the global cutting forces F_X, F_Y and F_Z acting on the tool. The corresponding relations are available in previous works [1-3].

In order to simplify and accelerate the cutting forces estimation for a long and realistic tool path, the calculation is done at each CL point considered for a tool rotation of $2\pi/N_t$. To optimise the calculation time, the results obtain on a CL point can be reproduced along the distance between the considered point $CL(i,k)$ and its follower $CL(i+1,k)$. The cutter rotation is then locally propagated and the rotation angle between two successive CL points can be easily determined from the local interpolation segment, the feed per tooth f_t and the local feed angle φ_z. The total rotation of the tool between two successive CL points is denoted $\Delta\theta(i)$ can be calculated at each step from:

$$\Delta\theta(i) = \frac{2\pi}{N_t}\left(\frac{\left|CL_X(i+1,k) - CL_X(i,k)\right|}{f_t \cos\varphi_z}\right) \tag{19}$$

The cutter rotation around its axis is located by the reference angle θ and it corresponds to the summation of the parameters $\Delta\theta(i)$ all along the tool path considered.

3. Results and Experimental validation

3.1. Machining of an inclined plane

The cutting forces presented in this section were measured with a Kistler dynanometer (9265B) and stored with a PC equipped with specific acquisition software and hardware. All signals were checked in terms of stability and repeatability. The local forces are here calculated using a thermomechanical approach of oblique cutting [6-7], which uses a Johnson & Cook constitutive law and a friction coefficient depending on local feed and cutting speed.

The tests were here conducted for two strategies: up-ramping and down-ramping [4-5]. The machined material is a 42CrMo4 steel and the tool is an uncoated tungsten carbide ball-end mill with the following characteristics: D_0 = 12 mm; N_t = 2 teeth; Constant helix pitch with a nominal helix angle i_0 = 25°; and orthogonal rake angle α_0 = 8°.

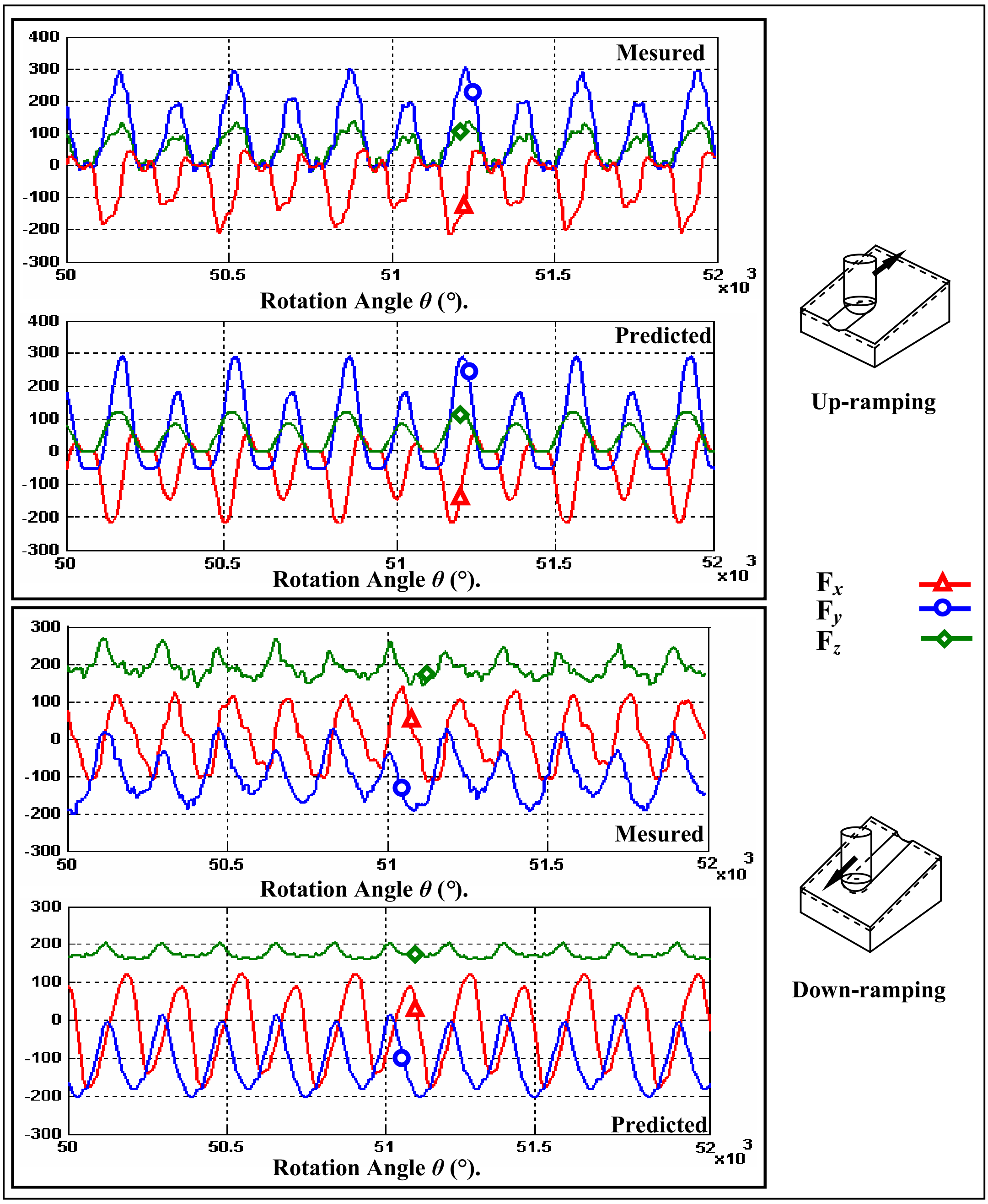

Figure 4: Measured [5] and predicted cutting forces (F_x, F_y, F_z)
Ω = 5000 rpm, f_t = 0.05 mm/tooth, Δp = 12 mm, e = 0.01 mm, ψ_e = 80°, and δ =15°.

The Figure 4 shows very good correlations between calculated cutting forces curves and measured ones. Amplitudes and shapes are well reproduced for the two strategies, as well as the influence of tool run-out. Nevertheless, it can be noticed a clear discrepancy for the cutting forces along Z-axis in down-ramping configuration and this can be explained by the fact that the tool end works in this case. In this region of the tool, non shearing phenomena appear (mainly ploughing) and they are not taken into account in the model used for the cutting forces calculation.

3.2. Machining of tilted wavelike surface

Dedicated tests were carried out with a two teeth tungsten carbide ball-end mill. They deal with finishing operations of an inclined wavelike form surface (1 mm offset : normal depth of cut d_n = 1 mm). The workpiece material is also a 42Mo4 steel and it is machined on a 3 axes CNC milling machine. The acquisition system was similar than in previous tests with this time a 9272A Kistler

Dynamometer. In this case, the local forces are calculated using an empirical approach of cutting (cutting coefficients K_r, K_κ, K_ψ) associated respectively to the three local cutting forces dF_r, dF_κ and dF_ψ, and without using secondary coefficients to reproduce the influence of non shearing phenomena.

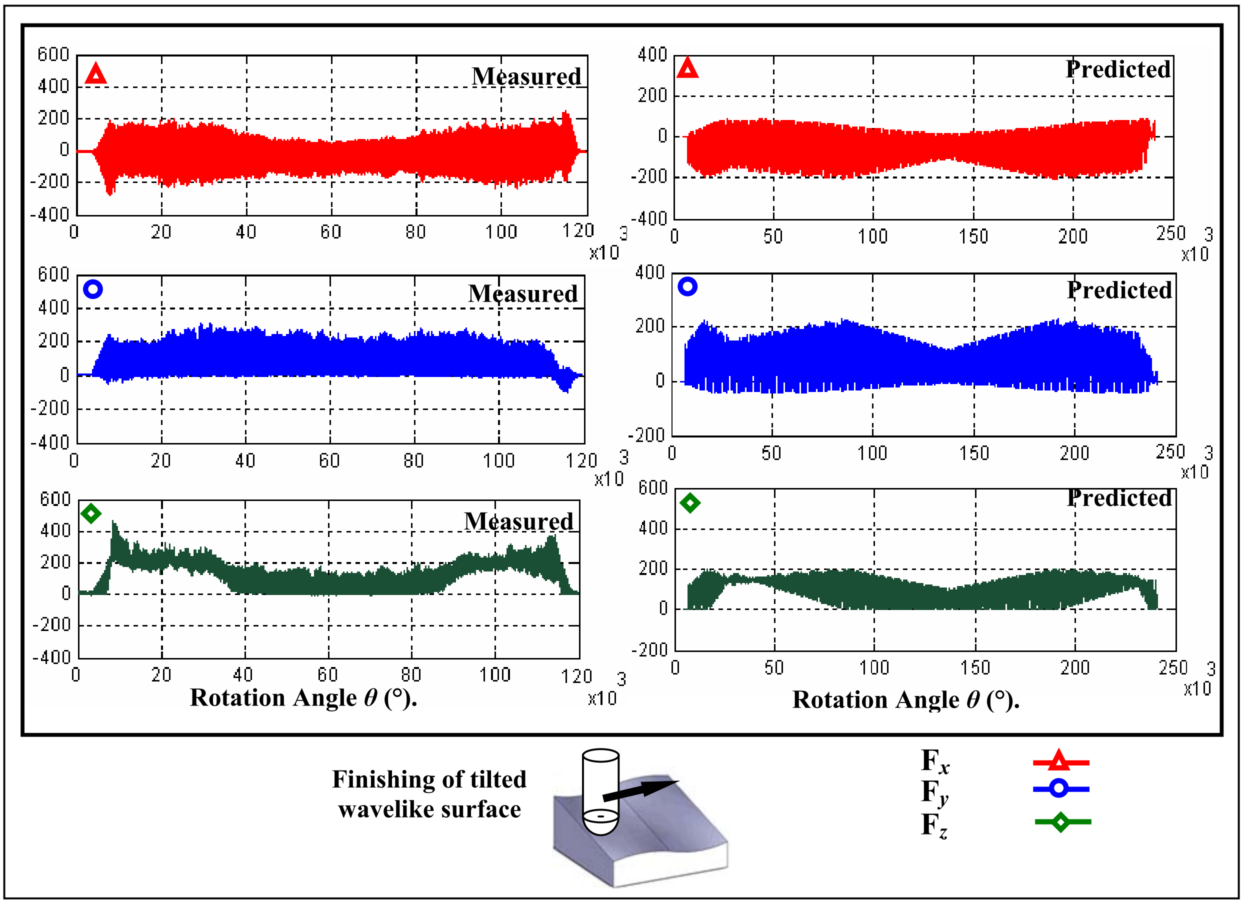

Figure 5: Measured and predicted cutting forces (F_x, F_y, F_z) for one pass finishing of a sculptured surface (mechanistic approach): $K_r = 2100$ N/mm^2, $K_\kappa = 500$ N/mm^2, $K_\psi = 1700$ N/mm^2 $\Omega = 3980$ rev/min, $f_t = 0.1$ mm/tooth, $d_n = 1$ mm, $\Delta p = 1$ mm, $e = 0.015$ mm, $\psi_e = 10°$.

The results presented on Figure 5 are very satisfactory even for a simplified calculation (cutting forces calculated only at each CL point and propagated on following interpolation interval). In this case, only discrepancies at the entrance and exit of the workpiece are significant. The discrepancy in the amplitude of cutting force Fz is due to the fact that secondary cutting coefficients were not used in this calculation.

3.3. Theoretical surface geometry after machining (Z-map)

Each point P considered in the tool engagement determination is then recorded and this data is treated to obtain a 3D picture of the theoretical machined surface, Figure 6. The pertinence and precision of the obtained geometry depend on the calculation increments dz and $d\theta$ used in the decomposition of the tool envelope and its rotation respectively. The step of the used grid is also very influent and a value of this step inferior to the feed per tooth must be used in order to reproduce the roughness in feed direction. The transverse direction (sweeping direction) roughness is easier to obtain because the path interval Δp is usually higher than the feed per tooth. The first results obtained correspond to a rigid tool case and the global geometrical characteristics of the machined surface are reproduced (form, transverse picks and valleys, theoretical roughness), but in order to compare them accurately with real machined surfaces, the flexibility of the tool and tool-holder as to be taken into account.

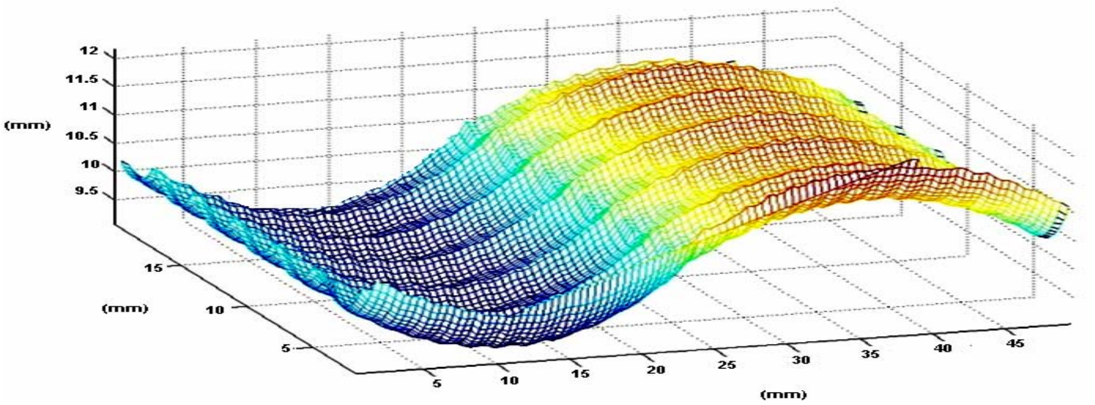

Figure 6: Presentation of Z-map surface deducted from the model for a wavelike surface

4. Conclusions and prospects

This article presents a geometrical model which uses the tool localisation points (CL) coming from a CAM application to calculate the tool path and engagement in workpiece material. The local cutting forces are obtained with a mechanistic model or with a thermomechanical model for both roughing and finishing operations in 3 axes milling of sculptured surfaces. The tests performed concern ball-end milling operation in a 42CrMo4 steel but this model can be used for other machined material, cutting tools and cutting conditions. The good results obtained are significant and open the way of synergy between analytical tools and CAD/CAM tools. The validation of a 3-axes milling model lead to the extension of this method to multi-axes milling of complex surfaces as well as to the prediction of real tool's behaviour during machining and even resultant surface quality.

This modelling approach is useful to gain an understanding of the cutting phenomena and to simulate the machining process in order to enhance surface integrity, tool life, stability and productivity by optimising cutting conditions, tool path and even tool geometry.

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