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Milled surface generation model for chip thickness detection in peripheral milling

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Abstract

Prediction of forces between tool and workpiece is essential in order to optimize machining and preserve process stability. In the last decades different predictive approaches have been developed: mainly mechanistic and numerical models. Mechanistic models could be applied to a wide range of cutter geometry and workpiece combination, even if a specific tuning, depending on material and application, is always needed. Numerical models could take in account many operative conditions than analytical ones, and allow predicting other parameters like stress, strain rate, temperature distribution, etc., but the computational time required is often unacceptable. The paper presents an innovative hybrid numerical-analytical approach for uncut chip cross-sectional area calculation in 2.5 axis end milling operations. The proposed model uses a mechanistic cutting force model to couple tool and workpiece finite element (FE) models: FE time domain simulations provide to predict effective paths of tool teeth relative to the workpiece, taking into account the dynamics of the entire system; while an appropriate algorithm, developed in Matlab®, allows to achieve a more realistic uncut chip area, from which it is possible to calculate the cutting forces. This approach provides an accurate representation of the machined surface. Simulation is compared with experimental results.

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Keywords: Uncut chip thickness; Milling Simulation; Milled surface prediction; Surface roughness; Vibration,

1. Introduction

Milling has assumed a central role among processes for material removal in manufacturing industries. In the last decades great effort has been spent for design more efficient machine tools or simulate machine tool’s capabilities. In particular simulation of the cutting process has become a key aspect in production optimization: accurate prediction of the machining process characteristics, such as the surface finish, cutting force and process stability are nowadays needed to improve milling performance [1, 2]. Chatter and vibration are the main factors that could seriously limit productivity of milling operations. Both are strongly related to the interaction between the dynamics of the tool and the workpiece, excited by the cutting forces due to the material removal process. Most of the previous researches in milling are focused on cutting force prediction using mechanistic approaches [2-5]. Mechanistic models could be proficiently applied to a wide range of cutter geometry and workpiece combination, even if a specific tuning, by means of experimental tests, is always needed [3]. The major drawback is that apart from ordinary cases, no reliable results can be acquired. Typical approach used for numerical modelling of cutting process is Finite Element Method (FEM). Originated from the need to solve complex elasticity and structural analysis problems in civil and aeronautical engineering, FEM is perhaps the most common numerical method, actually used in many areas of engineering: in the last decades FEM has become an effective and robust simulation tool even for many manufacturing process [6-8]. At the early stage Finite Element (FE) models were limited to the two-dimensional case of orthogonal cutting [9]. Recent advance in software and hardware technologies, and the effort dedicated to develop the Arbitrary Lagrangian

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Eulerian (ALE) formulation, have made possible to run three-dimensional simulation [7]. Currently available FE models could be potentially used to predict cutting forces, temperature distribution, tool wears rates, chip morphology and breakage, and residual stress; despite their capabilities, computational time is actually the main drawback. Furthermore the complexity of FE model increases significantly when the dynamic nature of cutting process is included in the simulation: vibration makes the use of mesh adaptation inevitable, because the position of the tool tip with respect to the chip changes periodically. The remeshing algorithm in this case has to deal with the unpredictable movement of the tool due to the self-excited vibrations. This is a formidable requirement and most present algorithms fail to deal with it successfully.

In this paper an innovative hybrid numerical-analytical approach for uncut chip cross-sectional area calculation in 2.5-axis end milling operations is presented. The basic idea that underlies the proposed approach is very simple: FEM is proficient to describe the dynamics of a mechanical system, but modelling the chip formation is excessively time consuming. On the other side mechanistic cutting force models are computationally efficient, but it is not easy to include in these models the dynamic response of the workpiece, since its dynamics continuously change due to mass removal. It seems actually clear that an efficient way to simulate a cutting process could be to consider an iterative method that uses mechanistic cutting force models to couple tool and workpiece FE models: FE time domain simulations provide to predict effective paths of tool teeth relative to the workpiece; while an appropriate algorithm allows achieving a more realistic uncut chip area, from which it is possible to calculate cutting forces. This approach allows taking into account the flexibility of both workpiece and tool in a very easy way, avoiding the need to consider material removal, which is the main responsible for the high computational effort required to simulate cutting process in a FE environment. In order to develop such system, a reliable algorithm able to calculate the instant chip thickness in the most general manner, has to be provided.

2. Undeformed chip thickness model

In the past many analytical and numerical approaches for determining the undeformed chip thickness were formulated. Early researchers considered circular paths for the cutting points, even if, as Martellotti [10] showed clearly, the path of milling cutter tooth is trochoidal. Further works on modelling the uncut chip thickness have been carried out in recent years to eliminate this simplification using analytical formulations [2,11], or time domain simulation [12].

In order to use a mechanistic cutting force model to couple tool and workpiece FE models, a new numerical algorithm for the worked surface generation has been developed. The approach widely accepted in the calculation of cutting forces in milling process, consist in dividing the total cutting edges of a tool (with helical flutes, bull-nose, or ball-end mill) into a number of elemental cutting tools, treating each element as if it is independently involved in oblique cutting. Whatever mechanistic force model is used for the elemental force calculation, it is practically universally assumed that cutting forces are related to uncut chip area, defined as the surface of the chip normal to the direction of cutting velocity. As the tool is divided into disks of small thickness in axial direction, the surface that they cut is generated independently. This fact defines the main limitation of this method, because the tool feed motion requires being perpendicular to the tool axes. In this work a solution to overcome this problem is presented.

3. Milled surface generation model

The workpiece is divided into several sections orthogonal to the finished surface and parallel to the feed direction. The milled surface is then evaluated on each of these planes, considering a reference system attached to the workpiece with the origin on the nominal worked surface. This allows simulating the more general case, very common in five-axis milling operations, in which tool axes and feed direction are inclined by a varying angle; and at the same time makes it easy to construct a three-dimensional error map for general machining. At the present stage of the research the geometric description is limited to 2.5 dimensional modelling. Experimental comparison for a simple side milling operation is presented.

3.1. Workpiece geometry

In order to properly model the mass removal during the cutting process, the finished part geometry is meshed (Fig 1).

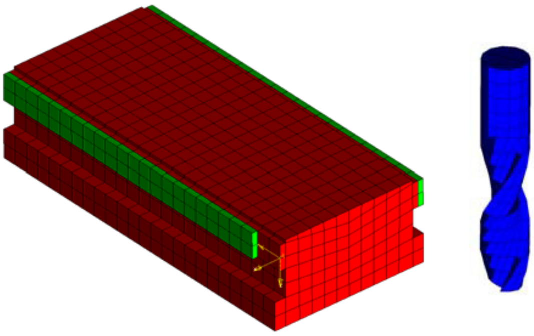

Fig. 1. Mesh of the nominal worked piece (red), of the stock (green), and of the tool (blue)

The elements that will be removed by the tool along the toolpath are then added to form the stock geometry: these elements could be easily detached during the machining simulation. A coarse mesh size could be used, avoiding excessive dimension ratio and warping.

3.2. Milling cutter geometry

Each cutting edge is considered as a set of points connected by straight lines. The milling tool coordinate system (o-xyz) is defined as: y coordinate is the reference for the angular position of the teeth, z is the tool axis direction, and x is perpendicular to both y and z. The geometry of the tool could be taken directly from the CAD model, enabling a coarse mesh for the FE model of the tool. This allows to model solid end mills with variable pitch, variable helix and variable rake angle for each cutting edge. Furthermore significant geometrical defaults (the run-out on flutes, for example) can be easily considered. Figure 2 shows a general cutting mill (a serrated end-mill). For the i-th tooth, the following relations could be used to describe the geometry of the cutting edge:

$$
\begin{aligned}
R_i &= R_i(z) \\
\varphi_i &= \varphi_i(z)
\end{aligned}
\qquad (1)
$$

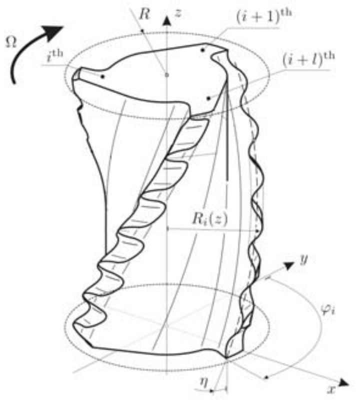

Fig. 2. General cutting geometry

This approach makes possible to obtain a complete three-dimensional geometric description of the cutting edges just knowing the position of the tool reference frame in the absolute computational reference system (the same used by the FE solver).

3.3. Material removal model

The machined surface is fully defined by the motion between workpiece and the cutting edges. In order to provide an accurate description of the machined surface topography the stock volume is partitioned into several computational planes orthogonal to the nominal worked surface and parallel to the feed direction. For each plane, the surface is represented by a finite set of vertices $\{S_i\}$, each defined by their Cartesian coordinates in the workpiece reference system (O-XY). The coordinates are stored in a dynamic array that is initialized with the stock geometry, and continuously updated at every time step, during the cutting simulation. For each computational section the proper cutting edge position is calculated at each integration step: first an appropriate transformation matrix is used to obtain the mathematical representation of the cutting edge in the local system frame (the one attached to the workpiece), and then the intersection between the cutting edge (points P_j), the tool axis (points A_j), and the considered plane is obtained (Fig 3). In order to identify the intersection points between the cutting edge and the surface profile, a linear interpolation between two steps could be used, but the error could become significant if a great time step integration regarding the cutting velocity is used. This is important mainly for high-speed machining (HSM). In order to maintain good accuracy in geometrical computation, a quadratic interpolation of the cutting edge trajectory was adopted according to the model proposed by Peigné et al. [12]. The interpolating curve C (the red curve in Fig 3) is built to fit the current position of the cutting edge, and the two previous positions.

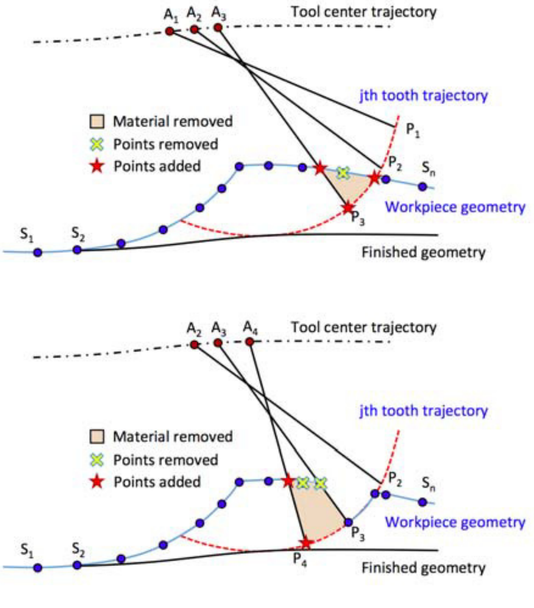

Fig. 3. Material removal and machined surface generation model

The number of new created points is automatically chosen, according to the curvature of the interpolating curve. In order to model the material removal process at each time step, the surface points included in the volume scanned by the tooth rake faces must be removed from the surface description array, and the new points, describing the milled profile, created according to the following process:

- The intersection points between the surface profile and the cutting edge trajectory are identified (in a general case could be more than one)
- The intersection points between the surface profile and the straight line going from the cutting edge to the tool centre are identified (even in this case could be more than one)
- The points that belong between the previous mentioned intersection points are removed, and the updated surface profile is obtained

4. Accuracy of the proposed model

Two geometrical errors have to be distinguished: the cutting edge trajectory interpolation error, which could be controlled with the quadratic interpolation of the cutting edge trajectory; and the surface linear interpolation error, which is related to the time step used. For the proposed approach two different time steps have been considered: the first one is related to the FE analysis; the latter to the mathematical modelling of material removal. For FE simulations in the time domain, the time step size roughly corresponds to the transient time of an acoustic wave through an element, using the shortest characteristic distance. In other words it depends on the material and mesh size. For the evaluation of the surface topography, and the instantaneous uncut chip area, a different time step size could be used instead: being just a geometrical approach, the uncut chip thickness algorithm is unconditionally stable. The correct time step size depends on the required accuracy, and the main aim of the simulation: for the evaluation of the cutting forces, a larger time step size could be used while for surface topography prediction the correct value have to be calculated taking into account the feed for tooth.

4.1. Machined surface topography

Surface topography is the result of the material removal process due to relative motion between tool and part. It is quantified by the vertical deviations of a real surface from its ideal shape. Surface roughness is generally used to determine and evaluate the quality of a product. So an approach able to predict the final roughness is preferred. The total height of the roughness in milling (h) is related to the feed per tooth (f_z), the cutting radius (R), and the teeth number (z). Considering a rigid tool and a rigid workpiece system, maximum feed mark height can be calculated as shown in Equation 2:

$$h = \frac{f_z^2}{8 \cdot \left(R \pm \frac{f_z \cdot z}{\pi} \right)} \qquad (2)$$

Positive sign in the denominator is for up milling and negative sign is for down milling. This equation assumes equal tooth pitch around the cutter and no run-out. In order to allow the evaluation of the feed mark height, the time step size has to be smaller then the ratio between the feed per tooth and the maximum peripheral cutting velocity. This value is set as the time interval between outputs for the displacement of the reference nodes for tool and workpiece, calculated by FE analysis.

5. Experimental measurements

A raster metal removal operation along the machine tool Y-axis was carried out using a Mori Seiki NMV1500 DCG 5-axis vertical milling machine centre. Workpiece surface was flattened once clamped on the dynamometer, so it can be considered totally flat (Fig 4). The shape was chosen in order to reduce its flexibility.

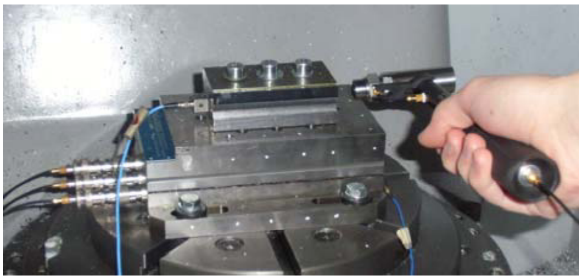

Fig. 4. Experimental modal analysis of the workpiece

A three-component Kistler dynamometer type 9254 A was used for measure the cutting and feed force components. An Osawa G2CS2 □10x10x25x75 end-mill with 10mm of diameter and 2 cutting edges with regular pitch and helix angle was used in up milling of the worked surface. The cutting and tool parameters are listed in Table 1.

Table 1. Cutting ad tool parameters

Milling parameters		Tool parameters	
Revolving speed (rpm)	2500	Diameter (mm)	10
Feed per tooth (mm)	0.1	Teeth number	2
Cutting speed (m/min)	1310	Helix angle	30°
Axial depth of cut (mm)	9.0	Material	Carbide
Radial depth of cut (mm)	1.0		

Axial and radial depth of cut were chosen according to the parameters suggested by the tool provider, to ensure a stable cut without chatter presence, and kept constant during the experiments. Feed rate (f) was also calculated in order to keep the feed per tooth (f_z) recommended by the cutting tool provider. The tool was clamped in HSK E-32 ER 16x60 toolholder with a mechanical chuck, and run-out was experimentally evaluated (2.4μm). In order to verify the hypothesis of rigid cutting process, an experimental modal impact test of both the workpiece before finishing, and the tooltip of the tool has been performed (Fig 4 - 5).

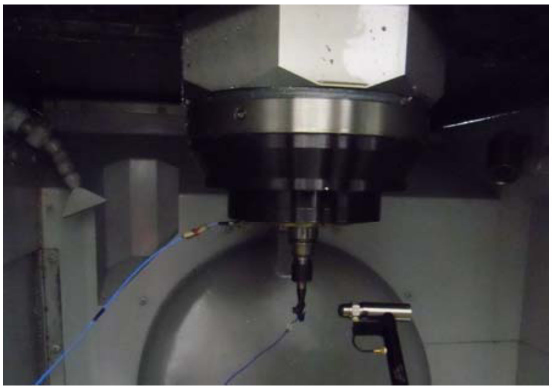

Fig. 5. Experimental modal analysis of the tool

In the experimental modal testing, a Brüel & Kjaer Type 8202 impulse hammer, LMS Scadas III frontend, LMS Testlab 11A software, and a PCB 352C22 accelerometer (0.4 g) have been used. The frequency response functions obtained (FRFs) are shown in Fig 6.

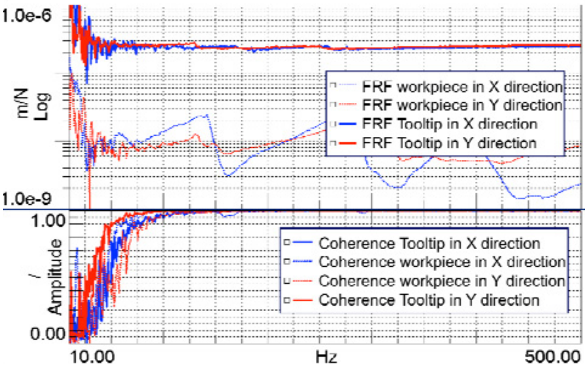

Fig. 6. Tooltip (thick line) and workpiece (light line) measured FRFs in X (blue line) and Y (red line) direction, and relative coherences

The time histories of measured cutting forces are shown in Fig 7, together with their spectrum (Fig 8). For the spectrum diagram the vertical grid lines correspond to the tool passing frequency (83.33 Hz) harmonics.

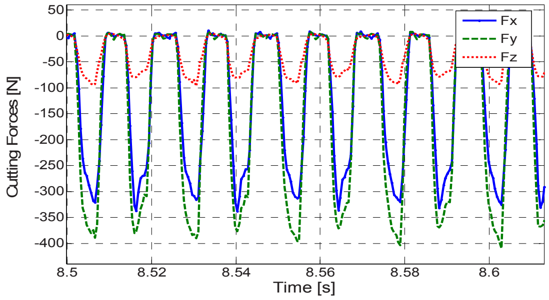

Fig. 7. Measured cutting forces in X (blu) and Y (red) direction

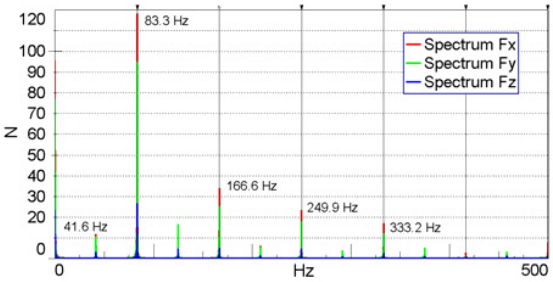

Fig. 8. Spectrum of the measured forces

As clearly appears from Fig 6, while the workpiece could be considered rigidly clamped to the rotary table, the tool tip flexibility (0.25 μm/N) should be considered for the estimation of the worked surface roughness, because the displacement of the tool during the cutting process is not negligible. Thus a reliable experimental-numerical comparison on the finished surface topography could not be presented, because the cutting model has not been implemented yet. Surface roughness was measured with a Mahr-Perthen PRK Surface profilometer. Evaluation length was 15mm and nominally 2μm stylus tip was used at a speed of 2m/s and with 0.75mN static stylus force. The measured surface crest height was 3.7μm.

6. Simulation results

Based on the proposed model for the milling process geometry, simulation studies have been conducted considering the same cutting parameters of the experimental measurements, and different time steps. First simulations with both workpiece and tool perfectly rigid have been performed: the numerical results have shown that the proposed algorithm is able to correctly predict the maximum feed mark height, if a sufficient number of points per feed per tooth is considered. The difference with the analytical value (2.496μm) is lower then 2%. The chip thickness is quite insensitive to the time step choice instead. In order to provide a qualitative validation of the proposed approach, a simulation with an imposed vibration has been considered. The amplitude of the vibration has been evaluated considering the measured flexibility of the tool (Fig 6) and the spectrum of the measured cutting force (Fig 8). For sake of simplicity, only the tooth passing frequency (83.33 Hz) has been considered. The resulting uncut chip area vs. time is presented in Fig 9.

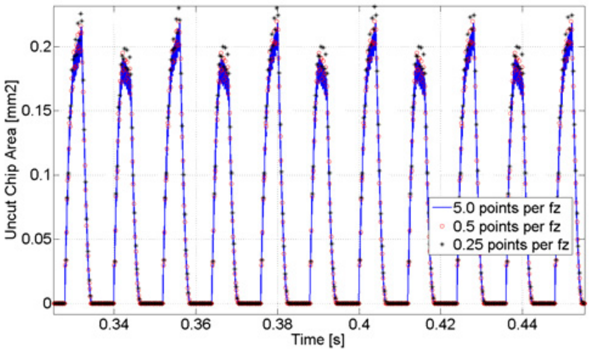

Fig. 9. Predicted uncut chip area values vs. time with different simulation time steps

Even the simulated surface roughness presents a shape that is not too much dissimilar to the experimental profile (Fig 10).

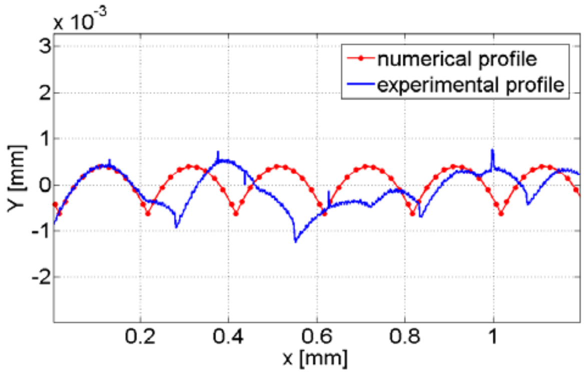

Fig. 10. Predicted vs. experimental roughness profile

The simulation takes about 100s to reproduce 1s of the milling process on a 2.5 GHz Intel Core Quad CPUQ9300, using a single core, considering a discretization of 0.5 mm in the axial depth of cut.

7. Conclusion

The paper proposes an overall structure for a novel simulation approach of a general milling process, able to take into account the flexibility of both workpiece and tool. To reach this target, the cutting process module, which is the core of this "virtual machine tool", should be able to estimate the cutting force and the machined surface error under widespread cutting conditions. A general milled surface generation model for chip thickness detection has been developed. The question whether numerical models are useful for evaluating cutting forces and milled surfaces geometry, depends naturally on the context. Sometimes a model returning a qualitatively correct answer is sufficient. However, in the later design stages, quantitative correct results are required. The proposed approach is potentially able to match both these requirements, just setting a proper accuracy. Despite a more in deep experimental validation should be performed, the proposed approach seems to be really promising.

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