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Development of tri-dexel based cutting simulator for cutter-workpiece engagement and cutting forces determination

Valentin Dambly[1], Hoai Nam Huynh[2], Édouard Rivière-Lorphèvre[3], Olivier Verlinden[1]

[1] *Department of Theoretical Mechanics, Dynamics and Vibrations, University of Mons (UMons), Place du parc 20, 7000 Mons, Belgium*
[2] *Department of Mechanical Engineering, University of British Columbia (UBC), Vancouver, BC V6T 1Z4, Canada*
[3] *Department of Machine Design and Production Engineering, University of Mons (UMons), Place du parc 20, 7000 Mons, Belgium*

valentin.dambly@umons.ac.be

Abstract

Robotic machining is a fast-growing technology in the field of mechanical manufacturing. Indeed, it is generally accepted that for the same working space, a fully equipped robotic machining cell can cost 30 to 50 % less than a conventional machine tool and enables agility to deal with complex workpieces. However, inaccuracies occur due to the robot's flexibility, inherent to its structure, while subjected to cutting forces. In order to improve the accuracy of robotic machining operations, it has been shown that compensation methods rely on faithful models of the operation. In the scope of model-based trajectory compensation, it is crucial to model the cutter-workpiece engagement (CWE) and the resulting forces along the tool while operating complex trajectories.

Numerous modelling methods of CWE features have been proposed since the breakthroughs in digital technologies. The constructive solid modelling emerges as the solution for volume intersection calculation, nevertheless with a view of coupling the computation of machining forces with the time-based dynamic simulation of cutting machine, a discrete computation of the CWE and forces is required. The two main discretized approaches discussed are the volume-based and the vector-based ones.

This article aims to present a module developed in C++ for test purposes that computes the machining forces and the update of the workpiece for 5-axis geometry. The proposed method is based on the modelling of workpiece using tri-direction network of dexels with scalable resolution and a disk modelled tool. The computation of chip thickness is carried out at each time step and is based on linear intersections between the cutting edges and the dexels network coupled with a quadratic interpolation in the tool space. The simulation results of 2.5D milling operations is compared with the validated 2.5D machining operations using in-house simulator DyStaMill.

Virtual machining, process simulation, 5-axis milling, workpiece modelling, tri-dexels

1. Introduction

The breakthroughs in digital technologies of the 1960s and the upcoming popularisation of software have pushed industries towards computer-aided design. Hence, the need to model machining parts in geometric point of view but also in a mechanical way for different machining operations generated a substantial amount of research [1]. The material removal simulations can be categorised based on the simulations purpose but also on the methods used to model the workpiece, the tool and their interaction [2]. Virtual machining englobes the simulation of micro-mechanics and macro-mechanics. Micro-mechanics simulations are designed for specific parts of the cutting process through a detailed analysis with, for example, finite element methods modelling the thermo-mechanical behaviour of the material. With a different scope, macro-mechanics simulations are used for a global understanding of a machining process, such as tool vibrations, process forces, machined surface indicators.

For every simulation of cutting operation, the cutter workpiece engagement (CWE) is a decisive parameter since it represents the area of the tool in action with workpiece, leading to the estimation of the uncut chip thickness and thus the computation of the machining forces. The management of the CWE, considering the vibration of the tool and therefore the cutting edges motion regarding to the workpiece, is a non-trivial problem and depends on the approaches chosen to model the workpiece and tool.

Recurrent workpiece modelling approaches can be divided in two main groups: the solid modelling methods and the discretised modelling methods.

Solid modelling regroups models considering the object as a whole entity with either its volume or its boundary surface. The spread volume modelling method is the constructive solid geometry (CSG) which considers parts as the result of a series of Boolean operations between primitive volumes [3]. Due to the computational efficiency of this method, it has been deeply investigated in the literature [4] and is met in CAM software at the planning level.

The volume can be represented with its surface. Within this scope, boundary surface approaches (B-rep) represent the part with parametric description of surfaces and curves. This scheme provides accurate rendering of parts and scalable complexity depending on the order of parametric functions selected. The resulting surface is composed of sewn patches such as triangles [5] or NURBS [6].

Using volumetric approaches for workpiece and tool modelling is efficient for tool-path validation and swept volume computation. Indeed, the CWE is computed with the Boolean difference between the workpiece and the tool envelope. At each time step, the immersion angle and its evolution along the operation are known [7].

Discretised modelling methods regroups methods considering discrete elements to model the workpiece. The elementary elements can be either points, leading to point-based methods [8], or line segments, leading to vector-based methods [9] or elementary volumes leading to volume-based methods [10]. Such methods are interesting since the discretisation enables tuneable resolution but introduce aliasing error [1].

Similarly to workpiece models, many approaches exist to model the tool. For the global determination of the removed volume, tool details are not required. The tool is then represented by its envelope in space [11]. The swept volume is computed as the intersection of this envelope with the workpiece. It is possible to determine the CWE with analytical models of the tool. The intersection of the envelope with the workpiece is computed analytically as arcs along the tool axis, the grouping of theses arcs consists in feasible contact area, useful for the CWE determination [12]. More generally, the established tool modelling approach presented by Altintas *et al.* is to represent it as a discretised slack of elementary disks [13]. Many advantages arise from this method such as the localisation of cutter edges, the scalability of discretisation and the possibility to compute the global machining forces as the sum of elementary contribution of each slice.

In the case of a dynamical simulation of machining operation, the cutting forces acting on the tool must be computed at each time-step. It is indeed necessary for the prediction of the machine tool response since the resulting deflections and vibrations impact the cutter position at the next time step. In order to compute the instantaneous cutting force, the tool edges must be modelled. In robotic machining, inaccuracies resulting either from vibrations or deflections occur while the robot is subjected to cutting forces, inherent to its flexibility inducing structure. In order to reproduce this behaviour, it is necessary to compute cutting forces at each time step. Hence, discretised methods are suitable choice for workpiece modelling in dynamical simulation. Schnoes *et al.* rather proposed a voxel-based method [14]. Further work in voxel technology is carried on by Jimin *et al.* where an alternative to high memory consumption caused by voxel is developed with rendering improvements [15].

The method proposed is a hybrid approach mixing the tri-dexel representation with a chip thickness determination via an analytical method.

First, a theoretical description of the dexel approach and tool modelling is proposed in Section 2. The Section 3 is devoted to the CWE determination method developed. Finally, a comparison between the results given by the tri-dexel simulator and the validated in-house simulator DyStaMill [16] is proposed in Section 4.

2. Tool-Workpiece modelling

As introduced, the modelling of the workpiece depends on the phenomenon the simulation aims to highlight. In the focus of time-domain simulation discretised methods enable direct computation of chip thickness with a control over the resolution of the workpiece and thus the accuracy of the machined surface.

2.1. Dexels modelling

Vector modelling consists in a discrete representation method of matter by means of a pattern of parallel line segments. As an example, the representation of a turbine with the tri-dexel approach is displayed in Fig. 1.

The dexels can be employed in different manners depending on the task. For 2.5D milling operations, stacked layers of 2D dexel grids can be considered [17]. However, for 5-axis operation, it is more suited to use tri-dexel approach in order to limit aliasing error along z axis. Methods for intersections computation with tri-dexels network has been developed considering interference with tool envelop [18].

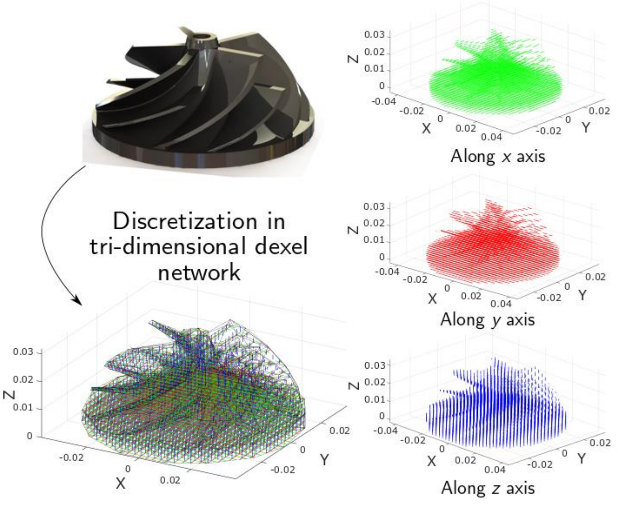

Figure 1. Discretization of turbine blade in a tri-dimensional dexel network.

The vector modelling method allows interesting compromises between efficiency and accuracy. It can be coupled with other methods with the aim of enriching the simulation. Typically, the dexels can be linked with other models. Denkena *et al.* developed a dexel model coupled with finite element model of the workpiece in order to simulate the workpiece elastoplastic response by co-simulation [19]. This coupled method links the advantages of dexels such as the quick computation of and the benefits of FEM with accurate computation of material behaviour.

2.2. Tool modelling

Modelling the tool is a key point is the simulation since the determination of the CWE is the interaction between the workpiece model and the tool model [13].

The chosen method for tool modelling is the slack of slices since it locates the cutting edges along the helical flutes and enables a straightforward computation of cutting forces by summing contribution of each slice, as illustrated in the Fig. 2.

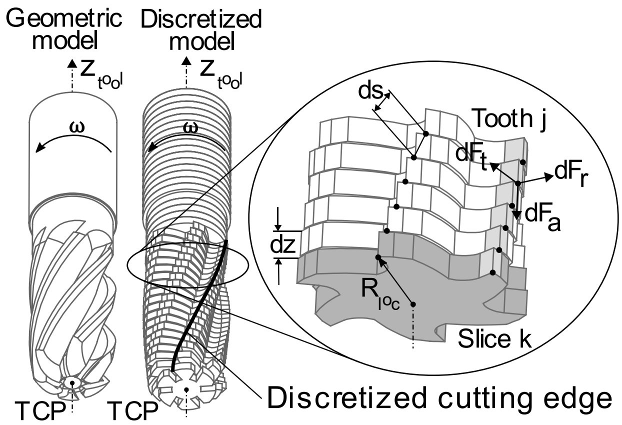

Figure 2. Discretized tool as slack of slices - adapted from [20]

3. Cutter-workpiece engagement

The determination of CWE proposed is the mix of two approaches: the interaction between a dexel workpiece and a sliced tool method with an analytical method for chip thickness determination.

3.1. Workpiece update

For discrete modelling methods, an increasing resolution leads to a higher accuracy at the expense of computation time. The grid resolution of the tri-dexel network depends on the angular increment of the tool, directly linked to the time-step. The selection of the time step for a dynamical simulation of a milling operation has been investigated [21].

As a compromise, the time-step is selected to ensure validity of force estimation while limiting the computation time. The minimum resolution (dr) criterion is deduced from the maximum allowed time-step as given in equation (1).

$$\sqrt{3}\, dr < dt\ \omega\ r_{tool} \qquad (1)$$

Time discretization of the tool motion is a linear interpolation between the tool position as shown in Fig. 3. The intersection between the linearly interpolated swept surface and the dexel network is computed as several line-plane intersections. The workpiece surface is updated based upon those intersections.

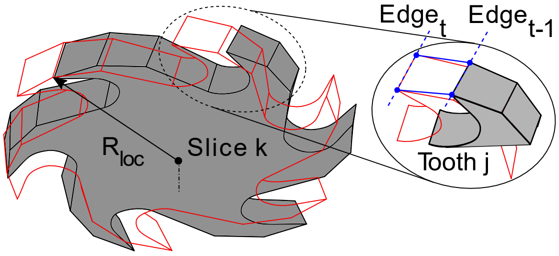

Figure 3. Linear interpolation between edges position.

3.2. Chip thickness computation

Since the resulting cutting forces acting on the tool are computed as the sum of elementary forces determined at each slice, the chip thickness must be known for each tooth in every slice. It is computed as the distance between the edge position and the front surface. This front surface corresponds to the positions of the tool edges at previous time-steps. Since the velocity field of cutting edges is known, a quadratic approximation of the machined surface is conducted with Hermite interpolation between points of this front.

The edge position is obtained by computing the intersection between the line linking the slice centre (p_{kc}) and the tooth position (p_{kj}) with the front, as expressed in equation (2).

$$\{p_{kc} + \lambda\, p_{kj} \mid \lambda \in [0,1]\} \cap \{Hermite(front, \xi) \mid \xi \in [0,1]\} \qquad (2)$$

The front surface interpolated and its interaction with the tool edges is represented in Fig. 4.

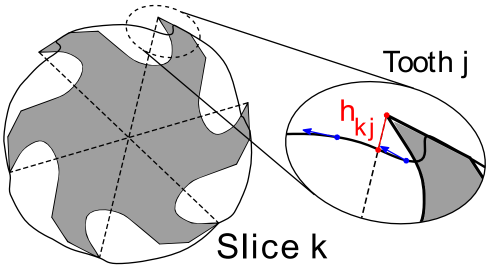

Figure 4. Chip thickness computation with surface front interpolated at each tool slice.

The determination of the cutting forces in the tool frame is carried on with the empirical Altintas model based on the chip thickness and the tool parameters such as helix angle as expressed in equation (3).

$$dF_i = K_{i,c}\, h\, dz + K_{i,e} \qquad (3)$$

Where subscript i states for tangential, radial and axial direction, $K_{i,c}$, $K_{i,e}$ correspond respectively to shear force and edge coefficients, h being the uncut chip thickness and dS, dz are represented in Fig. 2. This force computation model is implemented in a DyStaMill module [16]. The global force is retrieved from the tool frame by applying frame rotation.

4. Results

The milling simulation is carried on for flat-end mill. In order to compare with validated cases of the in-house simulator DyStaMill, the 2.5D case is studied. The validation of the dexel model is based on the comparison of the cutting forces and the machined surface. A first comparison is carried out for the simulation of a face milling operation on a Al6060 block. A second comparison is executed with experimental data for the face milling of Ti6Al4V. The parameters are given in the table 1.

Table 1. Simulation and experimental parameters

Validation Case	Numerical	Experimental
Material	Al6060	Ti6Al4V
Tool Parameters		
N° of edges	2	2
Shifted position	170°-190°	/
Identified run-out	/	0, -2.204 µm
Helix angles	30	20
Radius	5 mm	1 mm
Number of slices	20 slices	100 slices
Cutting Parameters		
Rotation speed (N)	22000 rpm	11940 rpm
Tooth feed (f)	0.05 mm/tooth	10 µm/tooth
Time step (dt)	5.45 10^{-5} s	10.05 10^{-5} s
Depth of cut a_p	2 mm	2 mm
Cutting thickness a_e	R/2	R/2

The machined surface of the Ti6Al4V block can be reconstituted from the tri-dexel network as shown in Fig. 5.

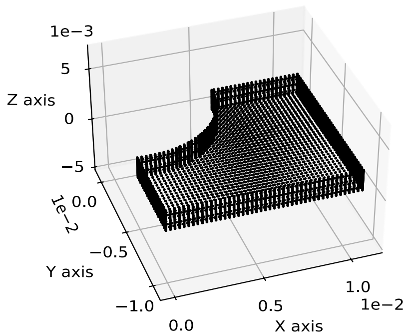

Figure 5. 3D view of the machined workpiece represented with the dexel nodes and its 2D projection in the XY plane.

The resulting forces in the tool frame for the simulation of Al6060 are given in Fig. 6. The magnitudes are equivalents with a maximum gap of 11%.

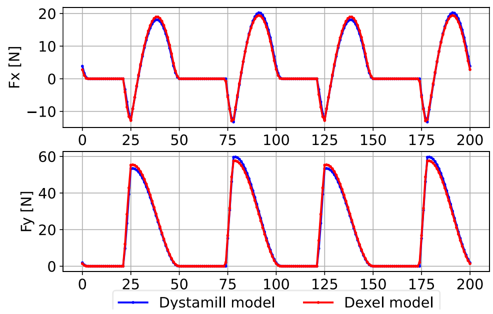

Figure 6. Comparison of the machining forces over 200 iterations for the simulation validation in Al6060.

The comparison with experimental data is given in Fig. 7. As an illustration of the 3D usage, the face milling of a block and the cutting of a corner is proposed in Fig. 8.

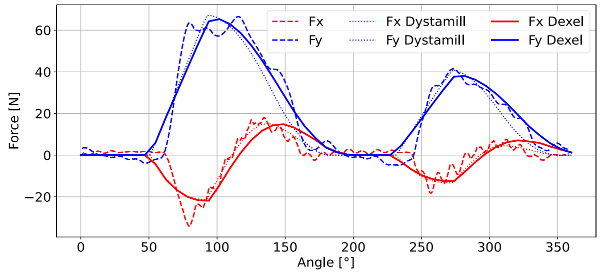

Figure 7. Comparison of the machining forces over a revolution between Dystamill, dexel module and experimental data. Measurements were collected with a Kistler dynamometer and filtered under 2kHz.

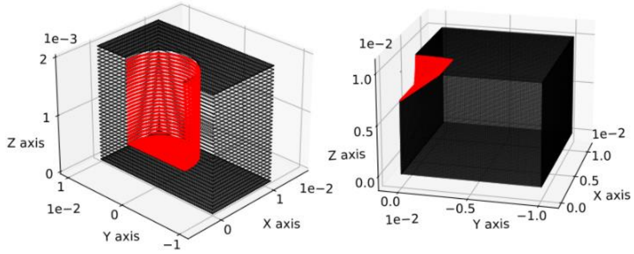

Figure 8. Face Milling simulation and corner milling of an Al6060 block. Machined dexels nodes are in red.

5. Summary

This paper provides a review of workpiece modelling methods in virtual machining. In the focus of time-based simulation, where dynamical behaviour of cutting machines is considered, a coupled dexel-analytical method is proposed for instantaneous machining forces and machined surface computation. The results are compared with validated in-house simulator DyStaMill for 2.5D operations where the maximum error gap reaches 11% and with experimental data collected from the face milling of Ti6Al4V workpiece.

6. Conclusion

The proposed method allows to combine discretized methods advantages with the time efficiency of analytical methods. The goal of this simulator is to serve as an estimator of the cutting forces for 5-axis milling operations and the modelling of resulting machined part. The simulator is presented as a C++ module taking position and velocity of the tool centre point as input and giving instantaneous machining forces as outputs. It can be coupled with dynamical model of cutting machine.

7. Future Work

An extension of the module's is planned where the interpolation between tool position is carried out with quadratic surface patch. The aim is to compare the computational efficiency of the intersection module between a linear surface and a quadratic surface. Moreover, the computation time is directly function of the resolution *$O(n^2)$*, which may cause issues for detailed simulations. Yet, it can be reduced by considering a preselection of the dexels. Instead of browsing the whole network for intersections, the tool envelope at the following time step can be used to test dexels likely to be cut. Finally, modelling and testing 5-axis operations are to be carried out.

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References

[1] Altintas Y, Kersting P, Biermann D, Budak E, Denkena B and Lazoglu I, 2014, Virtual process systems for part machining operations, *CIRP Annals - Manufacturing Technology*, **63**.

[2] Denkena B, Grove T and Pape O, 2019, Optimization of complex cutting tools using a multi-dexel based material removal simulation, *Procedia CIRP,* **82**, pp 379-82.

[3] Surmann T and Enk D, 2007, Simulation of milling tool vibration trajectories along changing engagement conditions, *Int. Jour. Mach. Tools & Manuf.,* **47**, pp 1442-48.

[4] Boz Y, Erdim H and Lazoglu I, 2015, A comparison of solid model and three-orthogonal dexelfield methods for cutter-workpiece engagement calculations in three- and five-axis virtual milling, *Inter. Jour. Adv. Manuf. Tech.,* **81**.

[5] Gong X and Feng H-Y, 2015, Cutter-Workpiece Engagement Determination for General Milling Using Triangle Mesh Modeling, *Jour. Comp. Des. & Eng.,* **3**.

[6] Lazoglu I, Boz Y and Erdim H, 2011, Five-axis milling mechanics for complex free form surfaces, *CIRP Annals - Manuf. Tech.,* **60**, pp 117-20.

[7] Weinert K, Du S, Damm P and Stautner M, 2004, Swept volume generation for the simulation of machining processes, *Int. Jour. of Machine Tools and Manufacture,* **44,** pp 617-28.

[8] Ambati R, Pan X, Yuan H and Zhang X, 2012, Application of material point methods for cutting process simulations, *Comp. Mat. Sci.,* **57**.

[9] Inui M and Umezu N, 2012, Cutter Engagement Feature Extraction by Using Dexel Representation Solid Model, *Key Engineering Materials,* Vols. **523-24**, pp. 420-32.

[10] Nishida I, Okumura R, Sato R and Shirase K, 2018, Cutting Force and Finish Surface Simulation of End Milling Operation in Consideration of Static Tool Deflection by Using Voxel Model, *Procedia CIRP,* **77**, pp. 574-77.

[11] Aras E and Feng H-Y, 2011, Vector model-based workpiece update in multi-axis milling by moving surface of revolution, *Int. Jour. Adv. Manuf. Tech.,* **52**, pp. 913-27.

[12] Xi X, Cai Y, Gao Y and Gao C, 2020, An analytical method to calculate cutter-workpiece engagement based on arc-surface intersection method, *Int. Jour. Adv. Manuf. Tech.,* **107**.

[13] Engin S and Altintas Y, 2001, Mechanics and dynamics of general milling cutters Part I: Helical end mills, *Int. Jour. Mach. Tools & Manuf.,* **41**, pp. 2195-12.

[14] Schnoes F and Zaeh M F, 2019, Model-based Planning of Machining Operations for Industrial Robots, *Procedia CIRP,* **82**, pp. 497-02.

[15] Joy J and Feng H-Y, 2017, Frame-sliced voxel representation: An accurate and memory-efficient modeling method for workpiece geometry in machining simulation, *Comp.-Aided Design,* vol. **88**.

[16] Huynh H N, Rivière-Lorphèvre E, Ducobu F, Ozcan A and Verlinden O, 2018, Dystamill: a framework dedicated to the dynamic simulation of milling operations for stability assessment, *Int. Jour. Adv. Manuf. Tech.,* **98**, pp. 2109–26.

[17] Luo S, Dong Z and Jun M, 2017, Chip volume and cutting force calculations in 5-axis CNC machining of free-form surfaces using flat-end mills, *Int. Jour. Adv. Manuf. Tech.,* **90**.

[18] Theegarten J M, Plakhotnik D, Stautner M, Kilic Z, Berckmann E and Murtezaoglu Y, 2019, Discrete Cutter-Workpiece Engagement for Five-Axis Milling Using Tri-Dexel Model, in *Virt. Mach. Proc. Tech.*

[19] Denkena B, Maass P, Schmidt A, Niederwestberg D, Vehmeyer J, Niebuhr C and Gralla P, 2018, Thermomechanical Deformation of Complex Workpieces in Milling and Drilling Processes, Springer, pp. 219-50.

[20] Huynh H N, 2019, Robotic machining: Development and validation of a numerical model of robotic milling to optimise the cutting parameters, Phd Thesis.

[21] Riviere-Lorphèvre E, Huynh H N and Verlinden O, 2018, Influence of the time step selection on dynamic simulation of milling operation, *Int. Jour. Adv. Manuf. Tech.,* **95**, pp. 1-16.