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# Study of the X-FEM method possibilities for the simulation of machining

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**ABSTRACT:** This paper introduces an application of the eXtended Finite Element Method (X-FEM) to the case of machining simulation, which is still subjected to numerical limitations. The treatment of the contact problem at the tool/chip interface is presented, and highlights the interest of the coupling of X-FEM with the Level Set method. Validation results are detailed through typical examples. We then present the first simulations of chip formation, using a newtonian fluid law for the machined material, and extract the future improvements that the method is able to provide to cutting numerical simulation.

**Key words:** X-FEM, contact mechanics, machining, level sets

## 1 INTRODUCTION

Steels machining is a process which complexity makes subject to massive studies. The pioneer works of Merchant [1] started by mechanical analytical modellings that opened an issue to a variety of exhaustivity-rising studies, most shearing a common purpose: a quantification of the influences of the process parameters- often including the workpiece and the tool geometries and natures- on the sollicitations taking place during the cutting operation (strain, strain-rate, temperatures, friction). The purely analytical modellings rapidly showed their limits while faced to the strong couplings that govern the chip formation and flowing. Numerical approaches rapidly proved their necessity. These approaches can be split into three fundamental categories **a)** The classical lagrangian finite elements method, which has the major advantages of allowing a good representation of the constitutive laws and internal variables, but also a certain handiness and an excellent precision in the description of free surfaces. In the case of machining, these methods reveal yet the disadvantages of being faced to mesh distortions. They imply the use of ALE methods, and of remeshing techniques that are undeniably time and resources consuming. This limits the possibilities of cutting simulations on long distances. The second drawback of these methods is related to the treatment of strain localisations, specifically important in the case of machining numerical

simulation. **b)** The *non-classical* lagrangian finite elements, like the meshless [2,3] or NEM [4] methods. These robust methods allow to solve most of the problems related to meshes, but still show a certain difficulty for rather trivial operations, such as the surfaces description or the boundary conditions imposing. **c)** The eulerian approaches, among which X-FEM evolves [5]. In comparison with the previous ones, the main advantage of this method consists in maintaining the mesh, and taking profit from other techniques (the level sets [6] and the finite-element approximation enrichment using the partition of unity [7]) for surfaces representation. Thus, the facilities offered by calculations on elements are kept, but not their drawbacks, remeshings above all. Another important “skill” of the X-FEM method, due to its coupling with the Level Set technique, is the fluency it offers for contact treatment, as will be shown in this paper.

In spite of their qualities, all of these techniques still show common limitations for the problem of machining simulation. These limits are most related to the mesh rupture criteria, and the physical meaning of some presently used instructions (like *kill element* in the lagrangian methods). In fact, if no additional criteria are introduced, it is for example impossible to simulate chip fragmentation. While methods like damage including help to overcome this lack, they still show the withdrawal of a certain deficiency of experience justifications. Besides, an extra numerical technique is still needed to treat the strain localisation.

In the scope of this work, we present here an approach of contact which was implemented within the X-FEM/Level Set context. We extract the benefits of developments in such an eulerian framework, and discuss the possibilities of these developments in the direction of overcoming some of the major difficulties of machining simulation.

## 2 DEVELOPMENTS

### 2.1 Global problem

The situation to solve deals with an incompressible velocity-pressure ( $\mathbf{v}$ - $p$ ) formulation in a non-linear context. Figure 1 describes the geometry of the global problem, where ( $D$ ) is a meshed background, ( $\Omega$ ) is the volume of a body described by a level set function, and moving in ( $D$ ) with a prescribed velocity  $\mathbf{v}_d$  on a part ( $\Gamma_d$ ) of its border ( $\Gamma_v$ ), where velocities are imposed. The lower part ( $\Gamma_s$ ) of ( $\Gamma_v$ ) is imposed to be rolling, and the remaining part of the border of ( $\Omega$ ) is free.

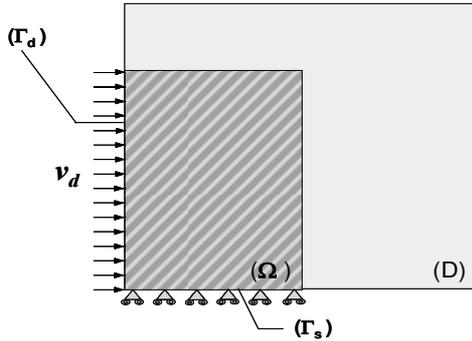


Fig.1: global problem representation

The system ( $S$ ) gives the variational formulation of this problem, in terms of  $\mathbf{v}$  and  $p$ :

$$(S) \begin{cases} \int_{\Omega} \boldsymbol{\sigma}^d : \mathbf{D}^d(\mathbf{v}^*) d\Omega - \int_{\Omega} \mathbf{p} \operatorname{div}(\mathbf{v}^*) d\Omega = \int_{\Omega} \mathbf{f} \cdot (\mathbf{v}^*) d\Omega ; \forall \mathbf{v}^* \in V_{ad}^0 \\ - \int_{\Omega} \mathbf{p}^* \operatorname{div}(\mathbf{v}) d\Omega = 0 ; \forall p^* \in P_{ad} \\ \boldsymbol{\sigma}^d = \mathbf{f}(\mathbf{D}^d(\mathbf{v})) \end{cases}$$

Where:  $\boldsymbol{\sigma}^d$  = deviatoric part of the Cauchy stress tensor,  $\mathbf{D}^d$  = deviatoric part of the strain-rate tensor,  $V_{ad}^0$  and  $P_{ad}$  are defined by:

$$V_{ad}^0 = \{ \mathbf{v} | \mathbf{v} \in (H^1(\Omega))^n, \mathbf{v} = 0 \text{ on } (\Gamma_v) \}$$

$$P_{ad} = \{ p | p \text{ is "regular"} \}$$

The Babuška-Brezzi incompressibility condition is fulfilled by the use of a finite element which is quadratic in terms of  $\mathbf{v}$  and linear in terms of  $p$  ( $P2/P1$  interpolation).

### 2.2 The contact problem

In order to perform a finite element simulation of a machining operation, a contact algorithm has to be implemented to treat the mechanical interaction between the moving piece and the cutting tool. This interaction is introduced in the previous system through an additional surface term:

$$(S') \begin{cases} \int_{\Omega} \boldsymbol{\sigma}^d : \mathbf{D}^d(\mathbf{v}^*) d\Omega - \int_{\Omega} \mathbf{p} \operatorname{div}(\mathbf{v}^*) d\Omega = \int_{\Omega} \mathbf{f} \cdot (\mathbf{v}^*) d\Omega + \int_{\Gamma_c} \mathbf{T}(\mathbf{v}) \cdot \mathbf{v}^* dS ; \forall \mathbf{v}^* \in V_{ad}^0 \\ - \int_{\Omega} \mathbf{p}^* \operatorname{div}(\mathbf{v}) d\Omega = 0 ; \forall p^* \in P_{ad} \\ \boldsymbol{\sigma}^d = \mathbf{f}(\mathbf{D}^d(\mathbf{v})) \end{cases}$$

In ( $S'$ ),  $\mathbf{T}$  is the contact stress and ( $\Gamma_c$ ) is the piece border where a contact may occur. A penalisation method is used for the contact treatment. In such a framework,  $\mathbf{T}$  is given by relation (1).

$$\mathbf{T} = -\chi \delta \mathbf{n} \quad (1)$$

where  $\chi$  is an arbitrary penalisation factor, which value has to be well chosen.  $\mathbf{n}$  is the outward normal unit vector to the piece, evaluated in the old configuration (at the previous time-step), and  $\delta$  is the algebraic depth of penetration of the piece in the tool.  $\delta$  is positive when a numerical penetration actually takes place (figure 2).  $\mathbf{T}$  is equivalent to an elastic force proportional to  $\delta$ .

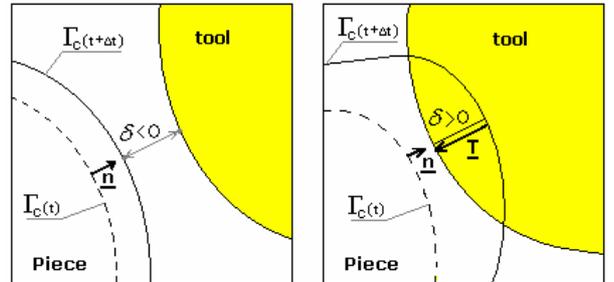


Fig.2: The contact penalisation

In the X-FEM context, the penalisation method is based on the Level Set technique. The evaluation of  $\delta$  is simply performed by evaluating the level set associated to the tool on the Gauss-points located on the piece border (2). This technique offers a major advantage: the search for the elements in the front border is no longer necessary, and so for the surfaces' normals calculation. These normals are simply given by the level sets functions derivation (3). In relation (3), due to the closure of the piece and tool when a contact happens, we approximate  $\mathbf{n}$  by the opposite vector to the tool's outward unit normal ( $\mathbf{n}_{tool}$ ). This approximation is besides expected to prevent from numerical inconsistencies.

$$\delta(\mathbf{x}^{t+\Delta t}) = -I_{S_{tool}}(\mathbf{x}^t + \mathbf{v}^{t+\Delta t} \Delta t) \quad (2)$$

$$\mathbf{n}_{tool} = \nabla I_{S_{tool}}(\mathbf{x}^t + \mathbf{v}^{t+\Delta t} \Delta t) \quad (3)$$

A Newton-Raphson iteration scheme is needed to linearize the problem. The contact algorithm loops on the piece-border points and iterates the resolution until all penetrations come to a negative value ( $\leq 0$ ). The piece motion, which is traduced into a domain transport by level sets propagation, is then possible at convergence. This motion is fulfilled by a separate algorithm that operates in 3 steps [6]:

- Extension of the known velocity from the border of the moving body (iso-zero of the level set) to the whole domain ;
- Propagation of the level set with respect to this velocity field ;
- Reinitialisation of the level set so to conserve a function of a signed distance.

### 3 VALIDATION TESTS AND RESULTS

#### 3.1 Homogeneous test

The first validation test (Signorini problem) consisted in putting into contact a moving body and a rigid obstacle. This is actually a simple compression test. Excellent solutions are obtained even with coarse meshes.

#### 3.2 Squeeze-test

The moving material is a thin sample subjected to a shearing compression with the rigid obstacle (Figure 3).  $v_y$  is fixed to 0 on  $(\Gamma_d)$ . The validation is made on one time step, starting from a quasi-contact situation. Figure 4-a shows the results in terms of velocity. When the contact is established, the velocity solution is checked to be parabolic in an horizontal section of the moving body (figure 4-b).

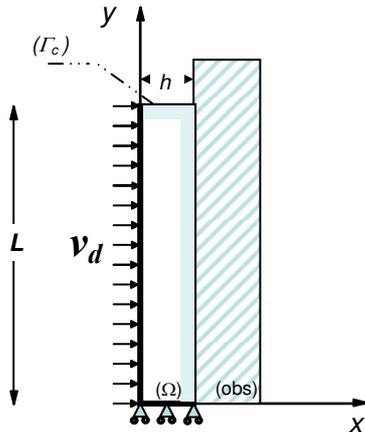


Fig.3: The squeeze-test

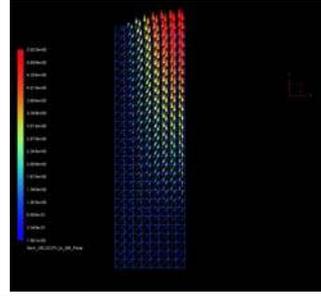


Fig.4.a. Velocity field for the squeeze-flow problem

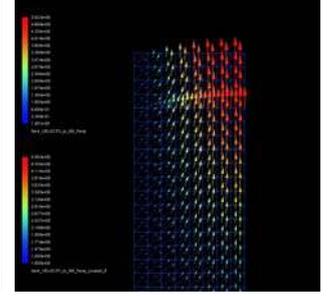


Fig.4.b. Velocity field in a section of the moving body

The analytical solution in terms of pressure is given by the Hele-Shaw solution. If  $y$  is the coordinate in the vertical direction then:

$$P_a = 12\mu V_d(L^2 - y^2)/h^3 \quad (4)$$

We verify the good concordance of the analytical and calculated solutions on the contact border of the moving body (figure 5).

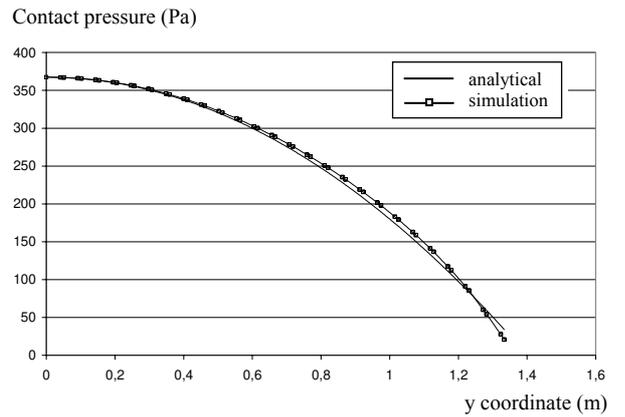


Fig.5. Analytical and calculated pressure comparison

#### 3.3 Drop crush

Becoming quite simple to solve since the previous calculations are verified, the test of a drop entering into contact with a smooth surface is the first test including both the algorithm of level sets propagation and of contact treatment. Although the solution is strongly conditioned by a good adjustment of the penalty factor, perfectly realistic profiles are obtained for this problem (figures 6-7-8, where the imposed velocity is  $v_d = v_{dx} = 0.4m/s$ ).

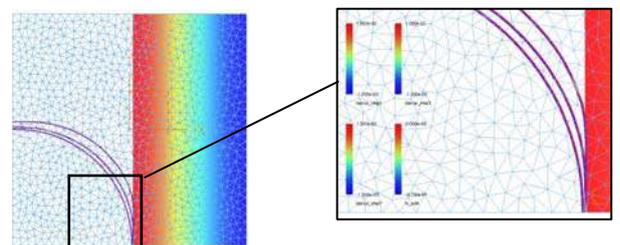


Fig. 6: Drop border deformation on the contact interface

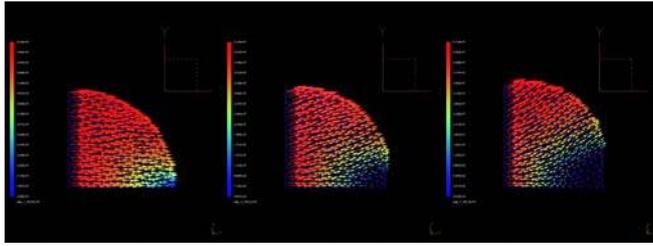


Fig. 7 : Velocity field evolution for the crushing drop test (from left to right: time  $t = 0.01$  s;  $t = 0.03$  s;  $t = 0.07$  s)

### 3.4 Machining test

The machining operation includes a moving piece and a tool. We proceed to a simplified modelling of the machining operation: The tool is modelled by a stationary rigid body, and the piece by a Newtonian fluid which moves towards the tool with a prescribed velocity, imposed far from the contact surface. The piece and the tool are initially in contact. Satisfying results are obtained for this Newtonian flow. We note that even when adjusting the viscosity and the penalty factor (figure 8), no similarity can be obtained with the real behaviour of the machined material (*i.e.* a steel workpiece, ordinarily modelled by laws such as the Johnson-Cook plasticity model as in [8,9]). The shearing can be observed to produce a strain rate and a pressure elevation at the tool tip (figure 9), but no localisation could be induced in the band where the velocity direction changes under contact effects. At this stage and with the used constitutive law, only qualitative validations can be performed. Large improvements can now be obtained through the implementation of a machined steel adapted constitutive law.

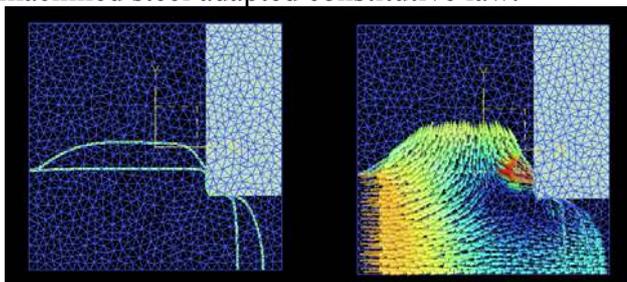


Fig. 8: Deformed material ( $t = 0.01$  s and  $t = 0.39$  s) and velocity field ( $t = 0.39$  s) for the newtonian fluid ( $v_d=1$  m/s)

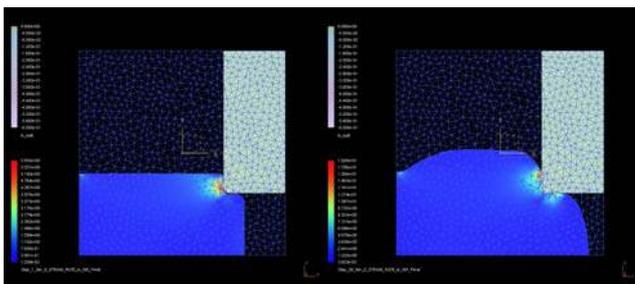


Fig. 9 – Strain-rate evolution during the machining operation ( $t = 0.01$  s and  $t = 0.39$  s)

## 4 CONCLUSION

We presented here an original implementation of the contact treatment based on the coupling of X-FEM with the Level Set method. This approach was proved to simplify the simulation of a chip removing operation. Up to now, this is the main advantage obtained in this research context. Other improvements are needed to overcome some drawbacks of the use of X-FEM, which are the disadvantages of the Eulerian approaches in general: they are related to the use of constitutive laws for metals which imply the transport of internal variables. Nevertheless, the coupling of X-FEM with the finite element approximation enrichment should allow to apprehend the deformation localisation from the cut material constitutive law, without losing the quality of the FEM solution, this constitutes a challenging result for this research axis.

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