NEW TRENDS ON THE NUMERICAL MODELING OF FORMING PROCESSES

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ABSTRACT
In this work, we explore some recent numerical developments able to perform fast and accurate simulations of complex systems, as the ones encountered in forming processes. In particular, we will focus on the use of meshless techniques and a discussion on the perspectives introduced by multiscale modeling.

KEYWORDS Numerical modeling, Meshless methods, Forming Processes, Multiscale

1. INTRODUCTION
Numerical techniques for solving the complex models encountered in forming processes have experienced a remarkable progress in recent years. In convectional and non-conventional forming processes different difficulties are encountered from the modeling and its associated numerical treatment: (i) large thermomechanical transformation that usually involve large geometrical transformations; (ii) strong multi-physics coupling; (iii) localization in space and time with the consequent effect on the discrete resolution (in both space and time); (iv) multiscale behavior (that could be defined from the quantum level to the macroscopic one); (v) the large resulting discrete system, usually non-linear and that involves millions of degree of freedom; (vi) existence of evolving discontinuities; among many others. Obviously, today does not exist a technique able to alleviate all the just referred difficulties, but some progresses have been made for developing new strategies able to circumvent some of them, and that potentially could be integrated into the more experienced techniques in order to expand the domain of applicability of numerical simulation.

A novel technique that seems an appealing choice for treating this kind of models is the one known as Natural Element Method that will be revisited in the next section, before illustrating its application in the forming process framework. Further considerations in non-conventional machining are addressed in the last section.

2. NATURAL ELEMENT METHOD
The NEM [1] is a Galerkin procedure based on the natural neighbor interpolation scheme. This interpolation scheme is the key ingredient of the method here proposed. It relies on the concepts of Voronoi diagrams and Delaunay triangulations (see Figure 1), to build Galerkin trial and test functions. These are defined as the Natural Neighbor coordinates of the point under consideration, that is, with respect to Figure 2, the value in the point x of the shape function associated with the node 1 is:

$$\phi_i(x) = \frac{A_{abh c}}{A_{abc}}$$  \hspace{1cm} (1)

In addition, the NEM has other interesting properties such as linear consistency and smooth shape functions. These functions are dependent on the position and density of nodes, leading to standard FE constant strain triangle shape functions, bilinear shape functions or rational quartic functions in different situations (see Fig. 3 for a typical shape function). These properties permit an exact reproduction of linear displacement fields on the boundary of convex domains. In the non-convex case other possibilities exist [1,2].
3. SIMULATION PROCEDURE

This strategy allows to proceed with the same cloud of nodes from the beginning of the simulation to its end, because even if some Delaunay triangles become very distorted during the simulation, the solution accuracy does not depend significantly on the diagrams quality.

In this way remeshing are no more required, and consequently field projection between the old and new meshes avoided. It is well known that this remeshing procedure involves a non negligible amount of numerical diffusion.

The solution strategy is very simple. Let

$$\mathcal{J}(u(x,t)) = f(x,t)$$

be the model (system of partial differential equations) to be solved. One can proceed, as in the finite element framework, to consider the associated variational formulation

$$\int_{\Omega(t)} \Psi \left( \mathcal{J}(u) - f \right) d\Omega = 0, \forall \Psi$$

The initial domain is denoted by $\Omega_0$, in which we consider the Delaunay triangulation related to a cloud of $N$ nodes with known initial positions. The unknown field can be approximated in a standard way:

$$u = u_0 \phi_1(x) + \cdots + u_N \phi_N(x)$$
using the Sibson’s shape functions, and then introduced in the variational formulation (3) leading to a discrete linear system whose solution results in the nodal values. Then, using (4) the solution can be computed everywhere. Now, the domain is updated, by advancing all the nodes from their velocities:

\[ \mathbf{x}_i \leftarrow \mathbf{x}_i + \mathbf{v}_i \Delta t \]  

(5)

the Delaunay and Voronoi diagrams recomputed, and the solution related to the new time step computed. This procedure continues until the end of the process simulation.

All the internal variables, describing the thermo-mechanical history, are associated with the nodes and then their evolutions are computed at the nodal positions by performing a local calculation.

From the last analysis it seems natural that this strategy could be applied either in the solid or in the fluid mechanics frameworks. Moreover, its use simplifies significantly the solid-fluid coupling because both are defined in an updated Lagrangian framework. Its generalization to the 3D case is quite simple.

In figure 4 we depict some snapshots concerning the elastoviscoplastic deformation of a plate. This computation has been performed by using the same cloud of nodes during the entire transformation. In some cases, the accuracy of the solution needs for higher nodal densities in some regions, as is the case of models involving localization.

Figure 5 depicts the appearance of an adiabatic shear band after impact, by assuming again an elastoviscoplastic constitutive equation in the context of an explicit dynamics, and by using an appropriate automatic procedure to adapt the nodal density.

Other specificity of the proposed numerical technique is its ability to label the nodes, that is, if we have two materials that are mixing we could label the nodes belonging at the initial time to the first one by assigning a color (red for example) being the others labeled with the blue color. As we can proceed with the same cloud of nodes in the entire time interval, each node keeps its color allowing to quantify the mixing at the end of the simulation. Figure 6 and 7 shows the initial and final snapshots related to the numerical simulation of the friction stir welding process of two plates, whose initial nodes are labeled with the red and blue colors. We can observe that a nice material mixing is obtained in the interface neighborhood as the welding process (pin rotation) progress.

**Fig. 4. Large elastoviscoplastic transformation**

**Fig. 5. Adiabatic shear band**
This simulations were carried out by assuming a viscoplastic law. Other appealing property of this technique is its ability to capture free interfaces (in particular the alpha-NEM version widely described in [1]). Thus, the combination of an the alpha shape constructor and the natural neighbor interpolation allows to define a robust technique for simulating free surface problems as usually encountered in fluid mechanics. Some welding processes need supply an amount of material that usually consists in a drop that impacts a solid or a liquid phase. Figure 8 depicts the impact of a drop on a solid and rigid surface.

This technique has been successfully applied in the simulation of laser coating processes, arising, for instance, in superconductor texturing processes or ceramic tiles processing, illustrated in Fig. 9.
The resulting Stefan problem (thermal model including change of phase) can be accurately solved by using the natural element method as described in [3]. The evolution of the temperature field when the heat source is moving with uniform velocity on the plate surface is illustrated in Fig. 10.

The melted zones at two different times are depicted in figure 11 and compared in figure 12 with the experimental results.

4. MICRO AND NONOMETRIC MODELING

Fine descriptions of the structure and mechanics of materials at the micro, nano and subnanometric scales involve numerous computational challenges.

Accurate descriptions of such materials need for a multiscale approach and the definition of pertinent bridges between these different scales.

The finest description concerns the atomic level where quantum mechanics leads to molecular dynamics simulations. Even if the resolution of the Schrödinger equation could lead to the establishment of accurate interatomic potentials, that could be used in molecular dynamics simulations, the curse of dimensionality that this equation induces represents even today a computational challenge.

The large number of atoms to be included in MD simulations, the extremely small time step imposed by the numerical stability and the approximated (at best only quantum inspired) interaction potentials, are the main drawbacks related to its use.
The next description scale introduces some simplifications leading to a coarse grained molecular dynamics, the DPD (dissipative particle dynamics) being one of such approaches. In that approach atoms are substituted by aggregates (or clusters) of atoms that interact from a variety of “empirical” interaction potentials.

Coarser descriptions focus on some entities by substituting the other entities by their effects usually modeled by random distributions.

This is the scale of Brownian dynamics simulations where the Langevin equation is a prototype.

Other descriptions come back to the continuous medium.

In those approaches the physical entities are substituted by a distribution defined in the physical space, in time and in the conformation coordinates: e.g. velocities in the case of models related to systems composed by charged non-charged particles (Boltzmann or Vlasof-Poisson-Boltzmann equations, the last one modeling quantum relativistic plasma); or the molecular conformation in the case of macromolecular systems (multi-bead-springs or multi-bead-rods models) leading to the Fokker-Planck formalism.

This approach, despite its mathematical simplicity, introduces a density function that is defined in a multidimensional space, and then the associated partial differential equations must be solved in a multidimensional domain.

To circumvent the curse of dimensionality that these high-dimensional partial differential equations induce, stochastic techniques have been applied intensively in the last decade. Some improvements have been proposed, the Brownian Configurations Fields being one of such approaches.

Recently some incipient techniques based on sparse grids or those based on separated representations have allowed solving models defined in highly multidimensional spaces [4].

The coarsest scale in the description of such material is the one related to the macroscopic flow. Micro-macro Lagrangian/Eulerian approaches have been intensively applied. Today meshless approaches, as the one described in the first part of this work, are opening interesting possibilities because its natural Lagrangian character that makes possible simulate flows using the same cloud of nodes that are advected with the material velocity.

The key point in that multiscale approaches is the definition of appropriate bridges between these scales. In the case of macromolecular systems, where the inertia effects can be (and are) usually neglected, the bridge is simple (Kremer’s rule). For other systems the establishment of such bridges is at present an open problem.

REFERENCES


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