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A Lagrangian particle method for the treatment of impact and penetration problems

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Résumé: Un nouvel algorithme a été développé dans le logiciel de PLEXUS du système CASTEM pour traiter le contact solide/solide ou solide/fluide par une formulation Lagrangienne, en représentant un des corps (le plus friable) par un ensemble de "billes" dont la cohésion est assurée par une loi d'interaction entre les particules.

Abstract: A new algorithm was developed in the PLEXUS code of Castem system : this algorithm enables to treat solid/solid or solid/fluide contacts, using for one body a "marble cluster" the cohesion of which is ensured by an interaction law acting on the cluster particles.

1. INTRODUCTION

The Finite Element Method is a well suited tool to take into account the complexity of the geometries, the non linear behaviour laws, the contact modelling in the study of such problems. The Lagrangian algorithm is in its essence relatively simple and well suited for impact problems between solids. But it has drawbacks when the mesh is subject to large deformations and distortions. One or various remeshing are thus required during the computation. The Eulerian or Euler-Lagrange formulation helps avoid these large distortions but is more difficult to set up and presents difficulties when the boundary conditions are of lagrangian kind.

To solve these problems frequently encountered during collision between two structures, a new algorithm was developed in the PLEXUS code of Castem system : this algorithm enables to treat solid/solid or solid/fluid contacts, using for one body an updated lagrangian formulation, the other one being represented by a "marble cluster" the cohesion of which is ensured by an interaction law acting on the cluster particles. The motion of the different particles is no longer hindered by the mesh distortion : the marble connectivity is calculated throughout the computation according to the local state of the structure.

2. NUMERICAL MODEL

2.1 Cluster geometry

Given a volume, we try to fill it up with identical and equidistant marbles. At first glance the compact hexagonal network leads to the most compact filling up. We will keep this arrangement in the following :

the hexagonal area is :

$$S_0 = \frac{3\sqrt{3}}{2} \cdot D_0^2$$

the height of the element is :

$$H = 2\sqrt{\frac{6}{3}} D_0$$

the element volume is finally :

$$V_m = 3\sqrt{2} D_0^3$$

the number of marbles inside the element is :

$$n = 1 + \frac{1}{3} \times 6 + \frac{1}{2} \times (3 \times 2) = 6$$

$$\begin{array}{c} \frac{\sqrt{3}}{2} D_0 \\ \frac{\sqrt{3}}{3} D_0 \\ \frac{\sqrt{3}}{6} D_0 \end{array} \quad \begin{array}{c} \frac{\sqrt{3}}{2} D_0 \\ \frac{\sqrt{3}}{2} D_0 \end{array}$$

In their equilibrium state, the marbles make up a compact hexagonal network. Each node is then in contact with 12 neighbouring marbles. Each node of this network is associated to a single node element with 3 degrees of freedom the mass of which is :

$$M_0 = \frac{\rho_0 \cdot V_m}{n} = \frac{\sqrt{2}}{2} \rho_0 D_0^3$$

2.2 Behavior law

2.2.1 Determination of the volumic mass

The relative variation of the volume μ is :

$$\mu = \frac{\rho}{\rho_0} - 1 = \frac{V_0}{V} - 1$$

where ρ , V : density and specific volume at time t
 ρ_0 , V_0 : density and specific volume at time $t=0$

The density of material surrounding marble i is obtained in the following manner :

1) We define μ_1 as :

$$\mu_1 = \left[\frac{D_0}{D} \right]^3 - 1$$

where $\bar{D}$ is the mean distance between i and the neighbouring marbles.

2) To avoid two marbles getting too close without generating repulsive forces, we define a second variable:

$$\mu_2 = \frac{D_0}{D} - \delta$$

where $D = D_{ik}$ is the distance between marble i and a neighbouring one k
 δ depends on cluster geometry.

The density of the i-marble is then :

$$\begin{aligned} \mu &= \max(\mu_1, \mu_2) \\ \Rightarrow \rho &= (\mu + 1) \rho_0 \end{aligned}$$

2.2.2 Pressure calculus

The normal stress along the segment joining 2 nodes is :

$$\sigma = s + p I$$

where s : stress deviator (in case of a perfect fluid, $s=0$)

p : hydrostatic pressure

Besides, the hydrostatic pressure is related to other parameters by an equation of state :

$$p = f(\rho, e, \dots)$$

where e is the specific energy

In the case of an acoustic behavior, we write the following equation of state :

$$p = \Delta \rho c^2 = (\rho - \rho_0) c^2$$

where c is the sound speed

When two marbles get more and more distant, the pressure becomes negative and generates attractive forces. In the case of a liquid, this pressure becomes equal to zero when it reaches a limit : it is the cavitation phenomenon. To take this effect into account, we balance the pressure by :

$$P' = \alpha P$$

where : $\alpha = 1$

when $D \leq \beta_1 D_0$

$$\alpha = \frac{D - \beta_2 D_0}{\beta_1 D_0 - \beta_2 D_0}$$

when $\beta_1 D_0 \leq D \leq \beta_2 D_0$

$$\alpha = 0$$

when $\beta_2 D_0 \leq D$

β_1 and β_2 depend on material properties.

2.3 Force calculus

The forces acting on the nodes are proportional to the normal stress σ ($\sigma = -pI$ for perfect fluids). The normal force acting on node i is : $F_n = -S p n$

The projection on OZ of the forces exerted by the 3 marbles j, k, m on marble i is :

$$3F \cos \theta = p A$$

with

$$\cos \theta = \frac{\sqrt{6}}{3}$$

A : contact area projected on XOY which corresponds to the hexagon circumscribed to the cercle C

$$A = \frac{\sqrt{3}}{2} D_p^2$$

For node j in interaction with node i studied, we calculate :

$$x_{ij}^k = x_j^k - x_i^k \quad k = 1, 3$$

$$D^2 = \sum_{k=1}^3 (x_{ij}^k)^2$$

where

$$D_p^2 = \frac{\bar{D}^3}{D}$$

hence

$$F_n = -\frac{\sqrt{2}}{4} D_p^2 \cdot P \cdot n$$

It was seen (in most cases) that :

$$\mu = \left[\frac{D_0}{D} \right]^3 - 1$$

$\Leftrightarrow$

$$\bar{D}^3 = D_0^3 / (1 + \mu)$$

We then take :

$$D_p^2 = \frac{\bar{D}^3}{D} = D_0^3 / D (1 + \mu)$$

we have finally :

$$F_n^i = -\frac{\sqrt{2}}{4} \frac{D_0^3}{D (1 + \mu)} \cdot P \cdot n$$

The strength F_n acts along the segment connecting both the nodes in interaction. For each node i of the marble cluster, we accumulate the interaction strengths generated by the marbles neighbouring the node.

We then get $a_k = x_{ji}^k / D$ which are the director cosinus of the segment connecting nodes i and j . Finally the force applied to node i resulting from the interaction between nodes i and j , and expressed in the global reference system is :

$$\begin{aligned} F_{1,j}^i &= a_1 F_n^i && \text{along } x \\ F_{2,j}^i &= a_2 F_n^i && \text{along } y \\ F_{3,j}^i &= a_3 F_n^i && \text{along } z \end{aligned}$$

The total force acting on node i and generated by all the marbles in interaction at time t with node i is :

$$\begin{aligned} F_1^i &= \sum_{j=1}^{nv} F_{1,j}^i \\ F_2^i &= \sum_{j=1}^{nv} F_{2,j}^i \\ F_3^i &= \sum_{j=1}^{nv} F_{3,j}^i \end{aligned}$$

nv being the number of marbles in interaction with i at time t .

2.4 Contact forces

The calculus of the contact forces is identical to the one for the sliding 3D surfaces (see [7]). We assume that the master element and marble impact is equivalent to an elastic shock of 2 points. The gravity centre A of the penetrated face nodes is of mass m_T and has a velocity V_T .

$$m_T = \sum_{i=1}^{nbn} m_i$$

$$V_T = \left(\sum_{i=1}^{nbn} m_i V_i \right) / m_T$$

where nbn is the number of nodes of the face of the master element.

The marble (point B) is of mass m_0 and has a velocity V_0 . The gravity centre velocity V_G of both the 2 points A and B is :

$$V_G = \frac{m_0 V_0 + m_T V_T}{m_0 + m_T}$$

In a reference system connected to the gravity centre for each point, the velocity changes sign after the shock : one can thus write :

$$V'_j - V_G = - (V_j - V_G)$$

The impulse Q transferred to the slave node is :

$$Q = \sum_{i=1}^{nbn} q_i$$

$$\text{with} \quad q_i = (V_i - V'_i) m_i = \frac{\Delta t_1 + \Delta t_2}{2} \cdot \frac{Fa}{nbn}$$

Δt_1 : time step of the current cycle

Δt_2 : time step of the next cycle

$$\text{hence} \quad Q = \sum_{i=1}^{nbn} 2m_i (V_i - V_G) = \frac{\Delta t_1 + \Delta t_2}{2} \cdot Fa$$

$$F_a = \frac{4}{\Delta t_1 + \Delta t_2} \cdot (m_T (V_T - V_G))$$

The calculated force F_a is then projected along the normal n to the element face, and added to the exterior force of the corresponding node.

$$\text{For the slave node (marble)} \quad F_B = - (F_a \cdot n) \cdot n$$

$$\text{For each node of the penetrated face} \quad F_A = (F_a \cdot n) \cdot n / nbn$$

3. EXAMPLES

Various behaviours have been implemented in the PLEXUS software for the marble elements :

- acoustic fluid material
- PUFF material (hydrodynamic behaviour for high velocity phenomena)
- linear elastic material

A few examples are treated here using these new elements.

3.1 Bending of beam (mixed mesh)

This example illustrates the possibility to connect a zone modelled by marbles to another one modelled using classical finite elements.

A beam is modelled by a mixed mesh made up of 1134 marble elements and 2112 6-node prismatic elements (see figure 1).

This beam is fixed at one end, and subject to a vertical impulsive load at the other end.

3.2 Impact of water jet on a plate

This example clearly shows the assets of marble modelling. The aim is to study the behaviour of a plate subject to a water jet at a high velocity (140 m/s). The computation would be impossible in Lagrangian, as the mesh would undergo to large distortions. The Euler-Lagrange approach would require too many elements : we needed to model all the zone the fluid could occupy at any time of the simulation.

In this case, the plate is modelled using classical shell elements (1600 shells), while the fluid is modelled by 2720 marble elements. The computation is performed in 10000 time steps, and requires 4500 CPU seconds on an IBM RS6000/590. Figure 2 shows the deformed states at various time steps.

3.3 Perforation of a plate

This time, the plate is represented by marble elements, while the projectile is modelled with classical finite elements. The marble modelling allows an easy simulation of the perforation phenomenon (see figure 3).

4. CONCLUSION

In case of very important deformations, classical Lagrangian description becomes insufficient if the body blows up into fragments. The connectivity being fixed, certain body movements are not allowed. The model presented here and implemented in PLEXUS code seems well suited to treat such problems.

The encouraging results, obtained with simple behavior laws (acoustic fluids, elastic material, interaction law between marbles programmable by user) allow us to envisage the introduction of more complex behaviour laws : steel with plasticity, concrete model, composites ...

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Figure 1 Bending of Beam

Figure 2 Oblique impact of fluid jet on a plate ($V = 141$ m/s)

Figure 3 Perforation of a plate ($V = 1600$ m/s)