CALCULATION OF FLUID-STRUCTURE INTERACTION FOR REACTOR SAFETY WITH THE CASSIOPEE CODE

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ABSTRACT

The cassiopee code is an eulerian-lagrangian coupled code for computations where the hydrodynamic is coupled with structural domains. It is completely explicit. The fluid zones may be computed either in lagrangian or in eulerian coordinates ; thin shells can be computed with their flexural behaviour ; elastic plastic zones must be calculated in a lagrangien way. This code is under development in Cadarache. Its purpose is to compute the hypothetical core disruptive accident of a LMFBR when lagrangian codes are not sufficient. This paper contains a description of the code and two examples of computations ; one of which has been compared with experimental results.

1 - INTRODUCTION

The computation of the dynamic response of the primary containment is a difficult problem for the safety analysis of fast breeder reactors. Several types of accidents could produce some mechanical work in the core. The kinetic energy of the fluids is then transmitted to the structural components through a plastic deformation. A great number of codes exists now or are under development for this problem. Lagrangian methods are not well suited for this purpose because of the many components which are in the primary vessel. Fluids and structures are moving together inside the reactor and there is a strong nonlinear interaction between them ; moreover some of the materials are moving with large distorsions such as the bubble which is located initially in the core position. Our code, CASSIOPEE, uses a two-dimensionnal axi-symmetric eulerian-lagrangian coupled method. In fact some parts of the domain are computed with lagrangian coordinates and the others with eulerian coordinates. However, all the parts that are elastic-plastic are computed in lagrangian coordinates while the fluids can be computed in either manner.

In this paper, partial differential equations and numerical methods are described. Special attention is focused upon aspects which are different of the other eulerian lagrangian coupled codes. Finally two examples of computation are exhibited.

2 - DESCRIPTION FO THE METHOD

2.1 Lagrangian Part

2.1/1 Differential equations

The partial differential equations we use are the Euler's equations for an inviscid fluid; they are written in cylindrical coordinates with axial symmetry

$$\frac{d\rho}{dt} + \rho\left\{\frac{1}{r}\,\frac{\partial ur}{\partial r} + \frac{\partial v}{\partial z}\right\} = 0$$

$$\rho\,\frac{du}{dt} + \frac{\partial p}{\partial r} = 0$$

$$\rho\,\frac{dv}{dt} + \frac{\partial p}{\partial z} = \rho\, g_z$$

$$\frac{dE}{dt} + p\,\frac{d}{dt}\,(1/\rho) = 0$$

ρ is the density and E the internal specific energy

2.1/2 Numerical Form

As in most lagrangian methods, meshes are quadrilaterals and speeds are defined at the nodes. When there is no rezoning the mass of each mesh is constant. For the momentum equations, masses are lumped ; the diagonalisation of the mass matrix is simple : the mass of each node is equal to one fourth of the sum of the mass of the surrounding meshes.

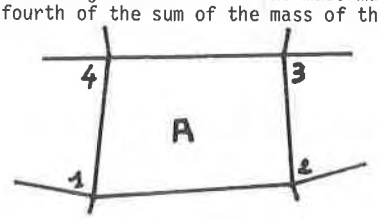

FIGURE 1 - A LAGRANGIAN MESH

The effect of the mesh A upon the point 1 is given by the following formulas :

$$m_1 \dot{u}_1 = - 2\pi \ R_1(Z_4 - Z_2) \ (P + Q)/2$$
$$m_1 \dot{v}_1 = + 2\pi \ (R_2 + R_4) \ (R_4 - R_2) \ (P + Q)/4$$

Q is the classical quadratic scalar pseudo viscosity ; in most cases it is taken equal to zero. With these formulas spherical symmetry is not exactly preserved as in Wilkins (1) but results are satisfactory.

The energy equation is computed only with variables defined at the center of the mesh. However in most of our computations shock waves are very weak and the differences between the Hugoniot curve and the adiabatic curve is very small ; Hence, very often, we don't use the energy equation, the specific internal energy is computed directly in function of the density which becomes the only thermodynamic independent variable.

2.1/3 Elastic-Plastic materials

Thick elastic-plastic materials can be computed by the lagrangian part of the code. In a previous version of the code the quadrangular meshes were used but some Hourglass instability was introduced and rapidly results used to become meaningless. Now, for that materials, each mesh is subdivided into two triangles, the elasto-plastic terms are computed separately on each triangle ; and it is the same thing for the effects of that terms on the nodes of the grid.

2.1/4 Rezoning

Though our code is an eulerian lagrangian coupled code we have put a rezoning routine for the lagrangian part ; it allows us to give a greater extension to the lagrangian domain. The code has two rezoning routines.

In the first one, the total number of lagrangian meshes is changed ; in fact nodes which are on some lines are suppressed and the meshes which were separated by that lines are merged.

The second one is a continuous rezoning routine based on the Ale method of Amsden (2). With this method the position of each internal node of the grid is modified in order to get a more regular grid. Each new position is an average of the old one and the positions of the four nearest neighbours. The coefficients of the average have been chosen to keep the jacobian of the transformation always positive. When the new grid has been computed, the speeds and the thermodynamical variables are modified to take into account the displacement of the grid. For each variable we choose a domain centered approximately at the point where the variable is defined and the fluxes accross the boundary of the domain are computed by a donor-cell method. Our method differs from the Ale method by the domain chosen for the momentum quantity.

FIGURE 2

DOMAINS FOR REZONING OF THE SPEEDS. ALE METHOD (LEFT) AND THIS WORK (RIGHT)

The boundaries of these domains are the dotted lines on figure 2. In our method the domain is bounded by segments joining points inside the meshes and the middles of the sides ; the points inside the meshes are chosen in order to keep the volume of a sub-mesh like AEPH approximately equal to a fourth of the volume of the mesh.

2.2 Thin Shells

Most of solid materials of the reactor are thin shells and often very thin shells. The first version of this code could compute the shells by the membrane approximation only. Now we have introduced the entire flexural behavior of the shells. As we want the same results as the previous version when the shells are very thin, we have written a particular method. In both cases, large rotations are acceptable because the strains are computed in terms of the current geometry. The hardening is isotropic and dependent on strain only.

2.2/1 Membrane approximation

In that approximation the strain tensor and the stress tensor are constant for each point of a shell mesh. The two values of the strain tensor are function of the speeds of the two ends of the element. Then the elasto-plasticity formulas give the stresses. We mention the formulas for the acceleration because they are not usual. In fact we use two different systems for the diagonalisation of the mass matrix of the shell.

In the first system the mass of a shell node is equal to the half sum of the masses of the shell meshes which are adjacent to that point. In the second system the mass of the node is equal to the mass of the solid contained between the two middles of the meshes adjacent to the node. In planar geometry the two systems give the same result. It is not the case in cylindrical geometry.

The first system is used for the effect of the pressure terms. A pressure applied against an element AB produces a force, this force is divided by half between the point A and B. This process, with the first system of lumped mass, is entirely consistent with the formulas used for the lagrangian domain.

The second system is used for the internal forces. For example, a tangential stress produces a tangential force in the direction of the element ; the sign of the force is different for the two ends of the element. The result of the division of this force by the mass of the node in the second system is the contribution of the tangential stress of the mesh to the acceleration of the node.

The spherical symmetry is sufficiently preserved by the method.

2.2/2 Shell approximation

The bending moments and the transverve stress must be computed to have the flexural behavior of the shell. We have chosen a method compatible with our method for the membranes. We do not use the convected coordinates of Belytschko (3). Nevertheless we suppose as in (3) that the deformation is linear versus the abscissa for tangential deformation and is a cubic for the transverse deformation ; hence the whole strain tensor can be computed as a function of the speeds of the nodes and of the speed of rotation of the shell at the nodes (we will explain later the computation of the speed of rotation).

In fact we compute strain and stress at two points only, inside the element ; hence we obtain two values for each of the bending moments of the elements. The inertia momentum of the shell being neglected, we compute the transverse stress in function of the bending moments by the equation of static equilibrium as in CHANG (4)

$$\frac{\partial}{\partial s}\left[M_\phi r\right] - M_\theta \cos\phi - Qr = 0$$

where s is the curvilinear abscissa, M_ϕ and M_θ the bending moments, Q the transverse stress and ϕ the angle of the element with the r-direction.

The effects of the two tangential stresses on the acceleration of the two extremities of the element is taken into account in the same way as in the membrane approximation. The effect of the transverse stress is computed by formulas similar to that which are used for the pressure.

Finally, the angle of rotation of the shell at the nodes is computed by an iterative process :

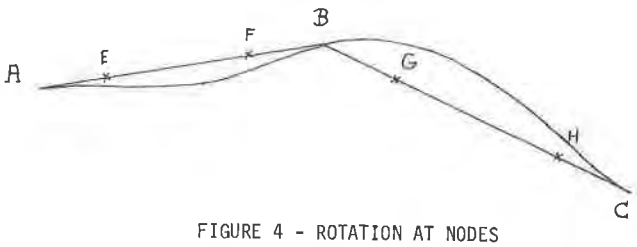

FIGURE 4 - ROTATION AT NODES

For the element AB and BC the bending moment M_ϕ has been computed at the points E, F, G and H. By linear extrapolation accross the points $^\phi$E and F a value for M_ϕ at B is obtained. Another value is obtained with the points G and H. The value of the rotation of the shell at the point B is then adjusted in such a way that the two values for M_ϕ at B are the same. A very small number of iterations is sufficient because our time-step $^\phi$is small.

2.3 Eulerian Part

2.3/1 Differences Equation

In the ICE method of Harlow and Amsden (5) as in most of eulerian method for incompressible fluids the speeds are defined at the middle of the mesh sides. Here speeds are defined at the corners of the mesh. That will allow us to introduce non rectangular meshes.

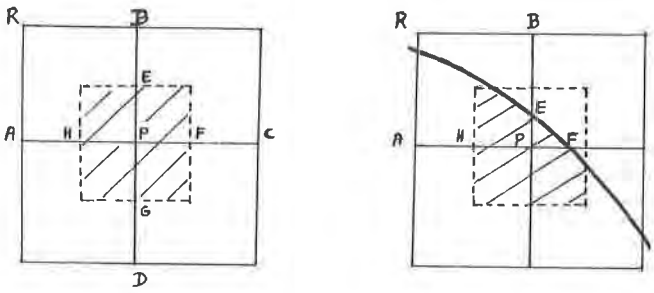

FIGURE 5 - EULERIAN MESH

The mass of the point P is the one contained in the hachure domain of figure 5. The acceleration at point P is computed with the pressure difference on the sides PE, PF, PG and PH. Transport terms use the donor-cell method with variable coefficients. Special care has to be taken for the transport terms when the lagrangian boundary cross the eulerian mesh. For example on figure 5 flux of mass from the mesh APER to the mesh on the right is computed accross the side PB or PE if there is a lagrangian boundary.

2.3/2 Boundaries

In most cases boundaries of the eulerian domain are lagrangian parts (thick domains or shells) and they are computed in lagrangian coordinates. However, voids and liquid can be computed by the eulerian part of the code. In that case some meshes are filled both with fluid and with void, and the pressure is an average of the pressure of the cavity and the pressure of the fluid. The boundary is a lagrangian line which is moving with the fluid. The speed of a particle put on that line is an average of the speeds of the nodes of the mesh which contains it. Some meshes can be small, the smallest are blended with the others.

After numerous numerical experiments we think that the eulerian meshes must be small to have a good conservation of energy.

2.4 Assembly of domains

The connection between two domains is different when they are both lagrangian and when one of them is eulerian. Following the terminology of BELYTSCHKO (6) the coupling between the eulerian part and the lagrangian part is weak. The only information given by the eulerian domain is the pressure acting on the boundary and the lagrangian domain gives only the position of the boundary. That method is stable because the equations are explicit for the two domains with the same time-step and the Courant-Friedrichs and Levy criterium is satisfied on either side. There is always a slide-line between the lagrangian and the eulerian domain.

When two lagrangian domains are joined, two cases are possible : the two materials may be tied and the speeds are the same at the boundary, or there is a slide-line, for example between a shell and a lagrangian fluid zone. Slide-lines between lagrangian domains are of the master-slave type.

3 - TEST PROBLEMS

3.1 Response of a vessel to a growing bubble

We have computed the deformation of a small scale experiment. A thin vessel 0.7 m in diameter and 0.65 m in height is nearly filled with water. A low pressure explosive gives 50 kJ of mechanical energy (the Chapman Jouguet pressure is less than 4 kbar).

All the experiment has been computed in lagrangian coordinates because the deformations of the grid are small. A continuous rezoning has been used for the part of grid which is near the bubble and a slide line has been set between the fluid and the vertical shell.

The shell has been computed with the membrane approximation because its thickness is only 1.2 mm. Some configurations of the grid are drawn on fig. 6. The radial deformation is important first in front of the explosive and finally near the upper cover. As the shell displacements are noteasily seen, they are drawn on fig. 7 and 8 for the points which are in front of the explosive and for the bottom of the vessel. On fig. 9 the energies of water, shells and cover gas are put versus time. The agreement between the numerical and experimental results is good for the final deformation of the vessel. Crosses on figures are experimental results. (No pseudo-viscosity has been used for this computation).

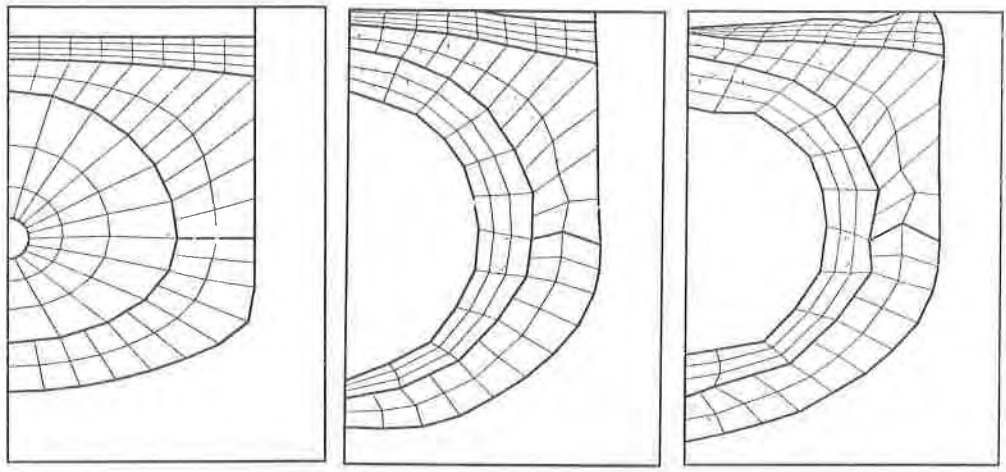

FIGURE 6 - VESSEL CONFIGURATION AT VARIOUS TIME

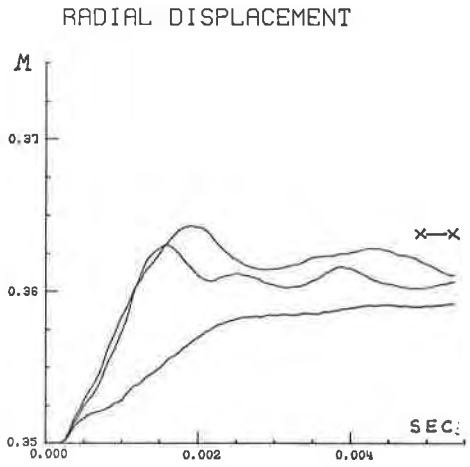

FIGURE 7

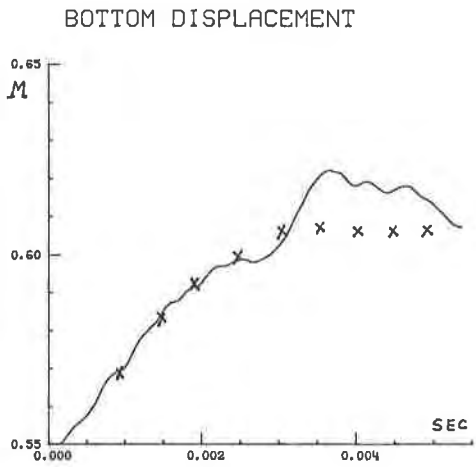

FIGURE 8

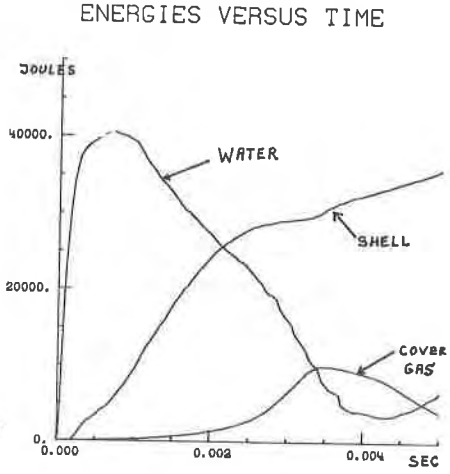

FIGURE 9

3.2 Vessel with internal structures

We have no small scale experiment for that computation. The expanding bubble is set at the place of the core. The core support structure is computed as a thick shell. Fig. 10 represents the reactor configuration at different times. To illustrate the response of the structures, the displacement of the bottom of the vessel is given on fig. 11 and the radial displacement near the top on fig. 12. For the thick shell representing the core support structure, energy history and rise are drawn on fig. 13, 14. It is easily seen that the deformation of that shell is not entirely plastic : two oscillations occur during the rise of the shell.

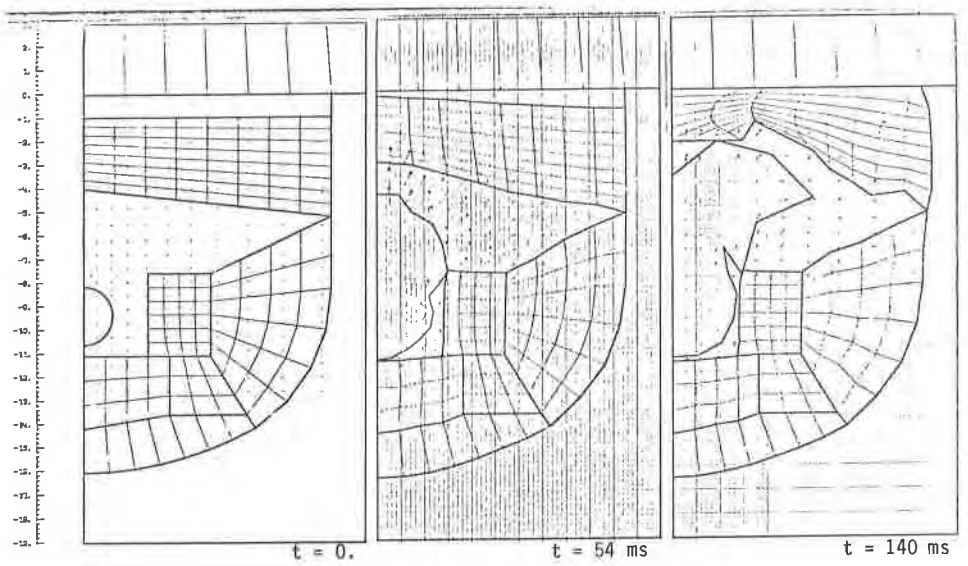

FIGURE 10 - REACTOR CONFIGURATIONS AT VARIOUS TIME

HEIGHT OF BOTTOM OF VESSEL

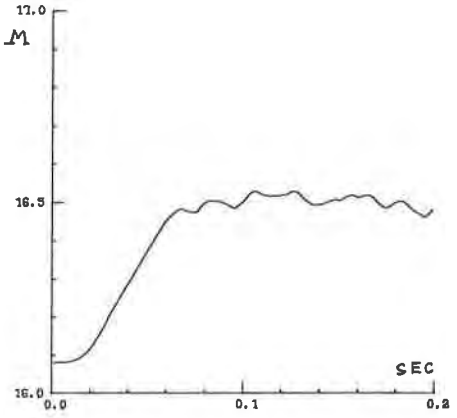

FIGURE 11

RADIAL DISPLACEMENT

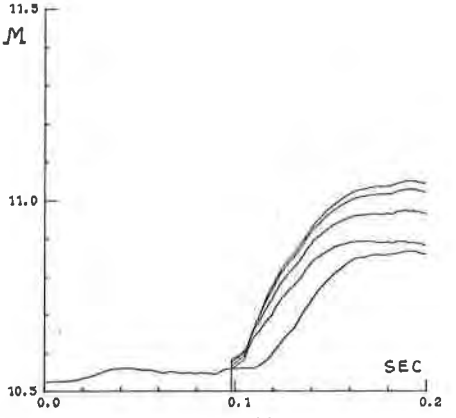

FIGURE 12

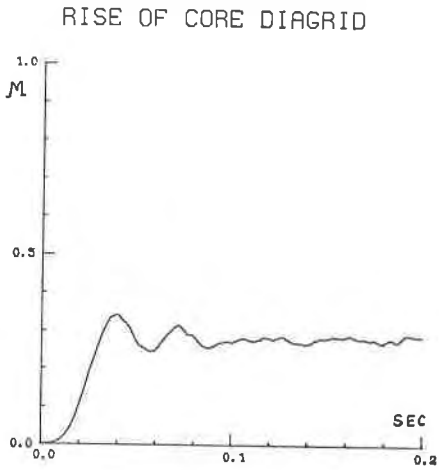

FIGURE 13

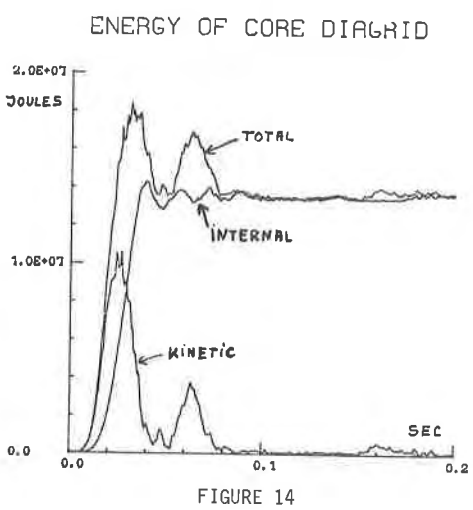

FIGURE 14

4 - CONCLUSION

The CASSIOPEE code is an eulerian lagrangian coupled code capable of forecasting the response of vessels submitted to a fluid-structure interaction, even for the complicated configurations found in a fast breeder reactor. The complete flexural behaviour of the shells can be taken into account and the code is flexible enough to allow the use of more accurate lagrangian coordinates for the major part of the domain. The code has been written for LMFBR safety studies but is not strictly submitted to this purpose.

Small scale experiment results have shown a satisfactory agreement with the CASSIOPEE calculations.

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