PISCES 3DELK – A Coupled Euler/Lagrange Program for Computing Dynamic Fluid/Structure Interactions in Three Dimensions

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ABSTRACT

This paper describes the main features of PISCES 3DELK, a computer code that is used to solve complex three-dimensional fluid-structure interaction problems in reactor safety. These features include:

- an Eulerian finite difference scheme for calculating fluid flow and large distortions of solid media
- a Lagrange finite element scheme for calculating the response of thin structures
- coupling of the Euler and Lagrange schemes at fluid-structure interfaces

The code has been well validated and applied to a number of reactor safety analyses including blowdown in reactor primary vessels and components, and loadings on the secondary containment caused by a breach in the primary containment. Details of two analyses are presented in this paper.

The first analysis is of blowdown in a pressurized water reactor caused by a cold leg break (the HDR experiment). Results of the PISCES 3DELK calculation are compared with results obtained by the K-FIX code. Agreement between the two calculations is good.

The second analysis is of the depressurization caused by a feedwater pipe break in a steam generator of the CANDU reactor. Calculations have been performed which show that flexibility of internal components in the heat exchanger mitigate structural loadings.

1. Introduction

Todays high speed computers allow the practical application of three dimensional computer codes in safety studies related to reactor systems and components. Many of the problems encountered in this area not only require three-dimensional analysis, but also involve complex interactions between fluids and structures. PISCES 3DELK is a computer program developed by PISCES International to analyze this type of problem.

Main features of PISCES 3DELK include:

- an Eulerian finite difference scheme for calculating compressible fluid flow and large distortions of solid media.
- a Lagrangian finite element scheme for calculating the dynamic response of thin structures.
- coupling of the Eulerian and Lagrangian schemes for the effective solution of fluid-structure interactions.

These features are discussed in section 2.

Validation problems have been performed with PISCES 3DELK and reported elsewhere [1]. In addition to these problems, the program has been successfully applied to the following reactor safety analyses:

- blowdown in a pressurized water reactor caused by a cold leg break (HDR experiment).
- depressurization in a steam generator caused by a feedwater pipe break.
- loadings on the secondary containment of a pressurized water reactor caused by a breach in the primary containment [2].

Details on the first two of these analyses are presented in section 3.

2. Numerical Processors in PISCES 3DELK

A detailed description of the Euler and Lagrange processors in PISCES 3DELK is given elsewhere [3]. Only the main features of these processors will be presented here.

2.1 The Euler Processor

This processor employs an explicit finite difference scheme and is used primarily for the calculation of fluid flow. However, solution of the full stress tensor also permits the calculation of large deformations in solids.

The Eulerian mesh is formed by a three-dimensional grid of points, each point referenced by three indices I, J and K (see Figure 1). The hexagonal cells can be arbitrarily shaped to accomodate the complex geometries and structural interfaces present in reactor components.

The compressible, inviscid equations of motion for a liquid or solid are solved using these hexagonal cells as control volumes. For a solid, the stress tensor is decomposed into a hydrostatic pressure and deviatoric stress tensor. For a liquid, these stress deviators are zero.

An equation of state relates the pressure to density and specific internal energy, while the stress deviators are updated incrementally following elastic-plastic flow rules.

Standard equations of state allow the description of solids, liquids and gases, including combustible and porous materials. A two-phase thermal equilibrium equation of state for water is available and has been used extensively for reactor safety analyses.

Plasticity is computed using either a piecewise linear work hardening model and the von Mises yield condition or a Mohr-Coulomb work hardening model in which the yield stress is a function of pressure (suitable for modeling concrete).

Free surfaces and material interfaces are tracked using the Simple Line Interface Calculation (SLIC) developed by Noh and Woodward [4]. Within each cell, materials are assumed to have the same velocity and pressure. In cells containing more than one material, an iteration is performed in which the volume fractions of the materials are adjusted to obtain pressure equilibrium. The iteration ensures that void fractions are always zero except in cells which contain a free surface or spalled (cavitated) material.

Wall and prescribed flow boundaries can be applied to both external and internal cell faces of the Euler mesh. Also different Euler meshes may be joined together to form a network.

2.2 The Lagrange Processor

This processor employs an explicit finite element scheme and is used to model thin structural components such as the primary vessel, core barrel or deflector plate. Both nonlinearities in material and geometry are considered in the calculations.

The Lagrangian mesh is formed by a grid of points (nodes) following the structural surface, each point referenced by two indices J and K (see figure 2). Each of the quadrilateral regions is modeled by a pair of triangular plate elements.

The plate elements are analyzed in corotational coordinate systems as described by Belytschko, et al. [5,6,7], while global and nodal coordinate systems are used to solve the translational and rotational equations of motion, respectively.

In the corotational coordinate systems, the variations in rotation and strain are assumed to be small. This does not limit the formulation to small deformation, but requires that the number of elements be sufficiently large to satisfy the above assumptions. Thus, the translation and rotation of the corotational coordinates correspond to the rigid-body motion of the element. The displacement fields with respect to the corotational coordinate systems are the deformation displacements.

The deformation displacement fields are assumed to be linear in the plane and cubic normal to the plane of the element. Kirchhoff's assumptions, that normals to the midplane remain normal and straight, are imposed on the strain calculation.

A piecewise linear strain hardening model and the von Mises yield condition are used to compute the elastic-plastic behavior of the material. Stresses are computed by first assuming an elastic increment. If the new effective stress exceeds the yield surface, the total strain rate is subdivided into elastic and plastic rates. The elastic and plastic stress rates are separately obtained by using an elastic or plastic stress-strain matrix [8] for updating the new stresses. The yield surface is updated due to strain hardening.

Membrane forces and bending moments are obtained numerically by performing volume integrals using the new stresses. Transverse forces are determined from element-equilibrium equations. The forces and moments determined in the corotational coordinates are transferred to the respective global and nodal coordinate systems to compute the translational and rotational degrees of freedom.

The equations of motion are integrated explicitly in time with a central difference scheme. The time step is estimated from linear analysis. An energy balance check is also performed to ensure the stability.

2.3 Euler-Lagrange Coupling

The interaction between an Euler and a Lagrange mesh is computed using a "weak" coupling scheme.

Each time step, the Euler mesh (fluid) provides a pressure loading to the Lagrange mesh (structure). The structure is moved by this loading and in return acts as a wall boundary to the fluid, allowing the fluid to move freely in the tangential direction but restricting the flow normal to the interface.

To facilitate this coupling at the interface, a one-to-one correspondence is maintained between the Euler mesh points and the Lagrange nodes. Each mesh point that initially coincides with a structural node moves with that node and the volumes of Euler cells adjacent to the interface are adjusted accordingly. Each of these cells provide a normal force to the structure which is equal to the cell pressure multiplied by the projected area of the fluid on the structure. This normal force is distributed equally to the four associated structural nodes.

Cell-centered Euler velocities simplify the computation of flow around sharp corners. Since no adjustment of the normal velocity component is needed, cell centered velocities also help to ensure momentum conservation.

Stability criteria for the explicit time integrations used in PISCES 3DELK dictate a maximum computational time step that allows a weak coupling scheme as described above to be used with confidence. However, the time step required for structural components is usually less than that required for the fluid. To maintain computational efficiency in these cases, a subcycling scheme has been included which allows the computation of multiple Lagrange time steps for each Euler time step.

3. Application of PISCES 3DELK to Reactor Safety Analysis

Two examples of fluid-structure interaction calculations are presented here. Another paper in this conference [9] discusses the analysis of a full-scale HDR blowdown experiment which studies the dynamic response of the core barrel in a reactor vessel. A number of validation problems which compare PISCES 3DELK results with theoretical or experimental data are reported elsewhere [1].

3.1 Simplified HDR Calculation

A simplified HDR blowdown analysis [10] has been performed with PISCES 3DELK for comparison with a K-FIX calculation of the same problem [11].

K-FIX [12] is a LASL code that uses a somewhat different method of calculation than PISCES 3DELK. A finite difference method is used to solve both fluid and structural equations. An implicit integration scheme is used for the fluid, while an explicit scheme is used for the structure.

The geometry of the reactor vessel is sketched in Figure 3.a. The broken cold leg of the single loop is simulated by a pressure boundary applied at location B (see also Figure 3.a).

Figure 3.b shows the Eulerian mesh used for the calculation. A plane of symmetry passes vertically through the center line of the cold leg, thus only one half of the vessel is modeled in the calculation.

The core barrel is modeled by a Lagrangian mesh. The top of the core barrel is clamped onto the vessel. A massive ring is attached to the bottom to represent the mass of internal structures inside the core barrel.

A non-uniform mesh for both the fluid and the structure is used to give detailed information in the vicinity of the cold leg and vessel interface.

The profiles of the radial deflection of the core barrel in a plane closest to the pipe break at four different times are shown in Figure 4. The bending of the core barrel is caused by the differential pressures across the core barrel. The flexibility of the core barrel significantly reduces the speed of the decompression wave which propagates in the annular downcomer region (from 993 m/s to approximately 400 m/s).

Figure 4 also shows the K-FIX results for comparison. Although the radial deflections calculated by PISCES 3DELK are slightly different from the K-FIX results, the bending shapes and the wave propagation speed are approximately the same. Thus, even though the two codes employ a different method of calculation and a different mesh and time step were used in the two models, the results show good qualitative agreement.

A simplified HDR calculation without the massive ring at the bottom of the core barrel has also been successfully calculated and compared with the K-FIX results [3].

3.2 Blowdown in the Heat Exchanger of a CANDU Reactor

PISCES 3DELK has been used to determine the effect that flexible internal components have on blowdown in the heat exchanger of a CANDU reactor caused by a break in a feedwater pipe.

Internally, a vertical central divider plate separates the heat exchanger into two regions. On both sides of this divider plate horizontal baffle plates are spaced vertically at regular intervals. The region modeled in the present calculations is shown in Figure 5. This is the area horizontally between the feedwater nozzle and the divider plate and vertically between the lower thermal plate and the second baffle plate. There is a gap between the first baffle plate and the divider plate through which flow can occur (see Location B, Figure 5).

Two calculations were performed in which the first baffle plate was considered to be first rigid and then flexible. The Euler mesh used for these calculations is shown in Figure 6. It uses half symmetry about a vertical plane through the feedwater nozzle. In both calculations, the divider plate, thermal plate, second baffle plate and wall of the heat exchanger were treated as rigid boundaries. No flow was permitted across the second baffle plate into the upper regions of the steam generator. In the second calculation, the flexible baffle plate was clamped along the perimeter of the heat exchanger and free at the open end.

A two phase thermal equilibrium equation of state was used to model the water inside the steam generator. The water had an initial pressure of 4.2 MPa with temperature varying linearly from 450° K at the feedwater nozzle to 476° K at the divider plate. The transient was initiated by applying a constant pressure of 1.64 MPa over the area where the feedwater pipe penetrates the wall of the heat exchanger (see Figure 6).

Figures 7-9 are pressure histories at the locations shown in Figure 6. Figures 7 and 8 show locations in the lower region between the thermal plate and the first baffle plate. In the second calculation, the flexible baffle plate is deflected downward, compressing the lower region. Consequently, in this region, depressurization occurs more slowly compared to the calculation with the rigid baffle plate. Figure 9 shows the pressure history at a location in the upper region between the two baffle plates. Pressures in this region are reduced earlier by movement of the baffle plate.

We can conclude from these analyses that flexibility of the baffle plate significantly mitigates the loading on both the central divider plate and the baffle plate itself.

4. Conclusion

In the field of reactor safety, PISCES 2DELK has a proven reputation for analyzing complex wave propagation problems in two-dimensional space [13,14]. PISCES 3DELK offers an extension of these capabilities to three dimensions. The code is fully supported and well documented [15].

The code takes advantage of the best features of both Eulerian and Lagrangian computational methods to allow efficient solution of a variety of fluid-structure interaction problems.

The applications described in this paper, and in references [1] and [3], show that PISCES 3DELK can produce accurate predictions of three-dimensional effects which may mitigate structural loads resulting from reactor accidents.

References

[1] Chu, H. Y., Ruhl, S. F., and Cowler, M. S., "An Overview of the 3D Test Calculations for the Validation of the Shell Processor and the Preparation of the Blowdown Analysis," Technical Report TCAM 83-1, PISCES International Co., 2700 Merced St., San Leandro, CA 94577, Jan. 1983.

[2] Rose, H., "Three-Dimensional Steam Pipe Break and Subsequent Loading of the Secondary Containment". Brown-Boveri, GMBH, West Germany, Internal Report, 1980.

[3] Chu, H. Y., Cowler, M. S., Hancock, H. L., "Analysis of the Fluid-Structure Interactions in 3-D Space Using the PISCES 3DELK Code," accepted for presentation at the ASME Fourth National Conference on Pressure Vessel and Piping Technology, Portland, Oregon, June 1983.

[4] Noh, W. and Woodward, P., "SLIC (Simple Line Interface Calculation)," Proc, 5th Int. Conf. on Fluid Dynamics, Springer-Verlag, 1976.

[5] Belytschko, T. and Hsieh, B. J., "Nonlinear Transient Finite Element Analysis with Convected Coordinates," Int. J. Num. Method ENG. 7, 1973.

[6] Belytschko, T. and Hsieh, B. J., "Nonlinear Transient Analysis of Shell and Solids of Revolution by convected Elements," Proc. AIAA/ASME/SAE 14th Structures, Structural Dynamics and Material Conf., Williamsburg, Va., 1973.

[7] Marchertas, A.H. and Belytschko, T., "Nonlinear Finite-Element Formulation for Transient Analysis of Three-Dimensional Thin Structures," ANL-8104, Argonne National Lab., June 1974.

[8] Yamada, Y., Yoshimura, N. and Sakuri, T., "Plastic Stress-Strain Matrix and its Application for the Solution of Elastic-Plastic Problems by the Finite Element Methods," Intl. J. Mech. Science, Vol. 10, p. 343, 1968.

[9] Gehrmann, R., "Comparison of Experimental HDR Blow-down Data with the Results of a Fluid-structure-coupled and Uncoupled Calculation," Brown-Boveri-Reaktor GMBH, West Germany, 7th International Conference on SMIRT, paper B 6/5, Chicago, Illinois, August 1983.

[10] Krieg, R., Schleachtendahl, E. G., Scholl, K. H. and Schumann, U., "Full-Scale HDR Blowdown Experiments as a Tool for Investigating Dynamic Fluid-Structural Coupling," Paper B 5/1, 4th SMIRT Conference, San Francisco, U. S. A., 1977.

[11] Rivard, W. C. and Torrey, M. D., "Fluid-Structure Response of a Pressurized Water Reactor Core Barrel During Blowdown," LASL Report NUREG/CR-0264, LA-7404, 1978.

[12] Rivard, W. C. and Torrey, M. D., "K-FIX: A Computer Program for Transient, Two-Dimensional, Two-Fluid Flow," LASL Report LA-NUREG-6623, 1977.

[13] Hancock, S. L., "Finite Difference Equations for PISCES 2DELK, A Coupled Euler-Lagrange Continuum Mechanics Computer Program," Physics International Company, Technical Memo TCAM 76-2, 1976.

[14] Cowler, M. S. and Hancock, S. L., "Dynamic Fluid-Structure Analysis of Shells Using the PISCES 2DELK Computer Code," Paper B 1/6, 5th SMIRT Conference, Berlin, Germany, 1979.

[15] Trigg, M., Hancock, H., Cowler, M. S. and Abbott, K., "PISCES 3DE User's Manuals," Physics International Co., 2700 Merced St., San Leandro, CA 94577

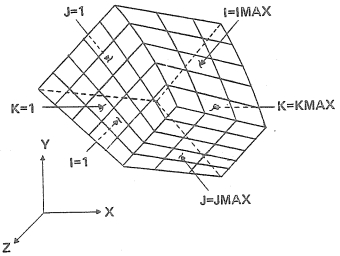


Figure 1. Euler grid indices.

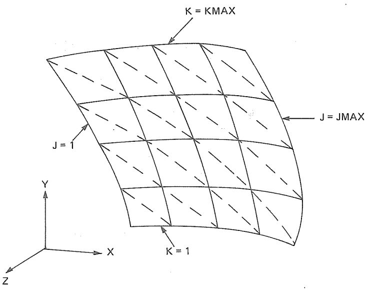


Figure 2. Lagrange grid indices.

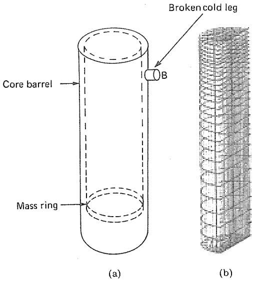
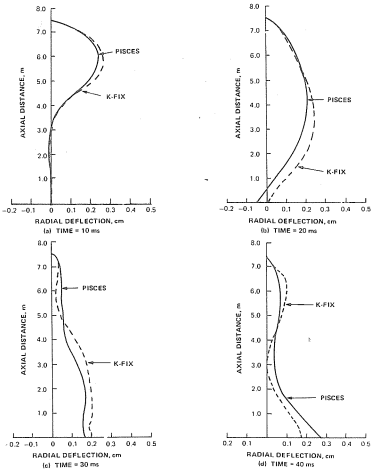


Figure 3. Geometry of HDR reactor vessel.



(a) TIME = 10 ms

(b) TIME = 20 ms

(c) TIME = 30 ms

(d) TIME = 40 ms

Figure 4. Radial deflection of the core barrel in the plane nearest the broken pipe.

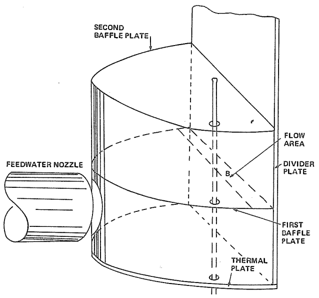


Figure 5. Area of heat exchanger for calculation.

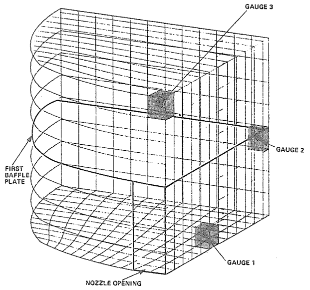


Figure 6. PISCES 3DELK model for heat exchanger.

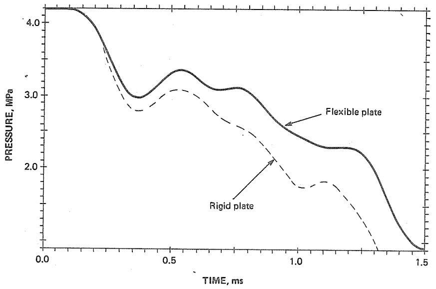


Figure 7. Pressure time history at Gauge 1.

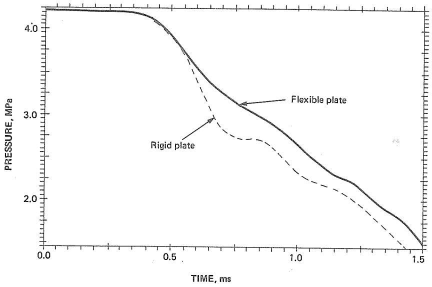


Figure 8. Pressure time history at Gauge 2.

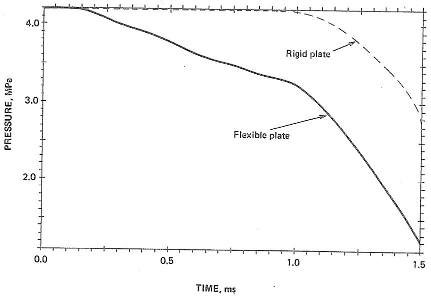


Figure 9. Pressure time history at Gauge 3.