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An Advanced Multi-Dimensional Method for Structural and Hydrodynamic Analyses of LMFBR Piping Systems*

by

C. Y. Wang and W. R. Zeuch
Reactor Analysis and Safety Division
Argonne National Laboratory
Argonne, Illinois 60439 U.S.A.

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Summary

Maintaining the structural integrity of the piping system of Liquid Metal Fast Breeder Reactors (LMFBRs) is essential to the safe operation of the reactor and steam supply systems. In the safety analysis various transient loads can be imposed on the piping systems, which may pose threats to the integrity of the piping structure. They are: (1) hydrodynamic loading resulting from pressure-wave propagation; (2) thermal loading generated by hot coolant suddenly entering into the piping system; (3) structural loads due to seismic events; and (4) loads encountered during normal reactor operational transients such as internal pressurization, thermal effects, and creep phenomena. These transient loads can further be classified into two categories. The first represents dynamic loads resulting from the hydrodynamic pressure-wave propagation or seismic events. The second represents static or quasi-dynamic loads generated by thermal wave propagation, normal operation transient, or creep phenomena.

At Argonne National Laboratory, a multi-dimensional method [1,2] has been developed for the integrated analysis of piping systems under these transient loading conditions. It utilizes a 2-D implicit finite-difference hydrodynamics in conjunction with a 3-D explicit finite-element structural analysis. A thermal capability was included to establish fluid and structure

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temperature distributions for the thermal stress calculations. Recently, many capabilities have been added and substantial improvements have been made in order to enhance the usefulness of the multi-dimensional method, as well as to broaden its applicability. These improvements and developments have resulted in an advanced multi-dimensional method. A selection of many developments are given in this paper.

In the fluid-dynamic calculations an elbow hydrodynamic model has been developed to rigorously account for the effects of global elbow motion on the pressure transient. The analysis utilizes a control-volume technique relative to the moving structure to solve the conservation equations of mass, momentum, and energy. A modified Poisson equation is derived, which considers structural velocities in the convective-flux calculation. Regarding the hydrodynamics for in-line components, a well-validated Eulerian scheme [3,4] has been adopted to treat the fluid motion in the vicinity of the baffle plates, rigid obstacles, and the isolated flow regions. The approach appropriately adjusts the velocity field in calculating the source terms of the momentum and Poisson equations in accordance with the inviscid fluid boundary conditions.

The structural capability was originally limited to the explicit time-integration scheme which requires the use of small, stability-controlled time steps. Although it has proved surprisingly efficient for dynamic problems with short solution times, it did preclude the application to quasi-dynamic analyses under long-duration loadings or static problems. Presently, effort has been made to augment the structural analysis by adding an implicit-integration scheme with long-time capability so that, together, the two schemes can treat the large variety of time scales found in LMFBR piping safety evaluations.

The implicit, iterative method described here is formulated within a corotational coordinate system. The corotational coordinates facilitate the formulation of element-related quantities. For convenience, the translational, membrane, and bending equations of motion are written with respect to the fixed global coordinates. The rotational equations of motion are written with respect to the moving body coordinates. An elastic stiffness matrix is derived for each element. The governing equations are integrated in time, based on the Newmark-Beta formulas.

A predictor-corrector iterative approach is employed. The iteration begins with the predicting phase in which the new displacement field, associated with the eight degrees of freedom per node, is approximately computed using the previous cycle values. This displacement field is utilized to estimate the nodal internal forces. The incremental displacement is solved by the equations of equilibrium expressed by the global stiffness matrix. The incremental displacement field is then utilized as a corrector to recompute the nodal internal force. The procedure is repeated until convergence is reached. The algorithm is fairly general and is capable of treating elastic-plastic material with thermal and strain-rate properties. It also permits the element to undergo arbitrarily large rotations and translations, but in its present form it is restricted to small strains.

In order to deal with problems involving thermal shock, the existing method has the capability of generating fluid temperatures for straight pipes. In addition, an elbow thermal model has been developed. A system energy equation, written in terms of the tangential θ coordinate, is utilized to calculate the coolant temperatures inside the elbow region due mainly to the fluid convection. Such a capability enables the thermal transient analysis of a pipe-elbow loop to be adequately performed.

The treatment of fluid-structure interaction (FSI) depends on the time-integration scheme used in the hydrodynamic and structural calculations. In the past, the hydrodynamic equations were integrated implicitly while the structural equations were integrated explicitly, and an implicit-explicit (I-E) coupling was utilized. Since, in general, the hydrodynamic time step is much larger than the stability-governed structural time step, several structural subcycles must be performed to match one hydrodynamic calculation. This I-E coupling via structural subcycling could become time consuming for problems involving slowly varying pressures where large hydrodynamic time steps can be utilized. Following the development of the implicit structural module, we have introduced an option which uses implicit-implicit (I-I) coupling in the FSI analysis, with both hydrodynamic and structural equations integrated implicitly. This avoids the structural subcycling and yet maintains the numerical stability.

Many illustrative problems are given, including analyses of: (1) fluid-structure-interaction experiments performed by Stanford Research International (SRI), (2) pressure-wave attenuation in a U-bend tube from a steam generator, (3) effects of local and global structural motion on the pressure pulse propagation in a pipe-elbow loop, (4) fluid transient in a primary coolant loop with in-line components, and (5) seismic response of a pipe-elbow loop. Results indicate that the advanced multi-dimensional method described in this paper is not only very accurate, but also is very effective and versatile in analyzing complex LMFBR piping systems under various transient conditions.

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