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Recent Developments of Three-Dimensional Piping Code SHAPS

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Abstract

This paper describes the recent development of the three-dimensional, structural, and hydrodynamic analysis piping code SHAPS. Several new features have been incorporated into the program, including (1) an elbow hydrodynamic model for analyzing the effect of global motion on the pressure-wave propagation, (2) a component hydrodynamic model for treating fluid motion in the vicinity of rigid obstacles and baffle plates, (3) the addition of the implicit time integration scheme in the structural-dynamic analysis, (4) the option of an implicit-implicit fluid-structural linking scheme, and (5) provisions for two constitutive equations for materials under various loading conditions. Sample problems are given to illustrate these features. Their results are discussed in detail.

1. Introduction

The three-dimensional piping code, SHAPS, developed at Argonne National Laboratory, has been used for (1) the study of piping-system integrity under severe hydrodynamic transients, (2) the evaluation and interpretation of test results of small-scale experiments, and (3) project support in areas related to the safety of piping systems. The capabilities of the SHAPS code have been described at SMiRT-6 (Paris, 1981) and elsewhere [1-3]. The salient features of SHAPS during these earlier stages of development were (1) the two-dimensional implicit or semi-implicit calculation of compressible flows; (2) three-dimensional explicit analysis of piping structural response including hoop, axial, bending, and torsional modes of the pipe elements; (3) treatment of global and local structural motions on the pressure-wave transient for the straight pipes; and (4) thermal transient capabilities developed for thermal-stress calculations.

Since 1981, development of the SHAPS code has continued not only in expanding its calculational capabilities, but also in improving its theoretical models as observed from extensive applications and various comparisons between analytical predictions and experimental data. The present version contains many salient features based on modifications and consolidations of the development versions of the code over recent years, particularly in the area of three-dimensional piping fluid-structure-interaction analysis.

In this paper, many improvements are described. Sample problems illustrating these analytical developments are given.

2. Hydrodynamics

2.1 Global Motion of a Pipe-Elbow Loop

To account for the global structural motion of a pipe-elbow loop, the governing hydrodynamic equations are written with coordinates fixed to the piping. In the mathematical formulation, we assumed that the grid lines of the Eulerian cell moves with the structural nodes in the longitudinal direction. This avoids the creation of the irregular cells at various junctions. However, in the transverse direction the grid lines are assumed to be stationary. The reason for such an assumption is that the treatment of fluid-structure interaction can be done by the existing relaxation iterative technique.

2.2 Considerations for In-Line Components

The in-line components of LMFBR piping systems may consist of baffle plates, tube bundles, and ring-shaped regions isolated from the main flow. In the analysis, the flow in the in-line component is assumed to be two-dimensional and axisymmetric which can be characterized by the radial (r) and axial (z) coordinates. Here, a well-validated scheme [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.

3. Implicit Structural Dynamic Analysis

As discussed at SMiRT-6 [1], the structural dynamic program of SHAPS consists of a three-dimensional pipe element and a one-dimensional spring element. The three-dimensional pipe element utilizes eight degrees of freedom per node (i.e., three displacements, three rotations, one membrane displacement, and one bending rotation) to account for the stresses arising from internal pressurization as well as those arising from the flexural motion of the piping system. This element is formulated with the explicit time-integration scheme [5] developed for short-duration transients generated by internal hydrodynamic wave propagation. This explicit structural analysis is very efficient for problems involving short solution times and pressure loadings. However, for static or large-amplitude quasi-dynamic problems dealing with long-term calculations and slowly varying pressure loadings, the explicit structural analysis could become very expansive because of its small time steps.

In order to apply the SHAPS code to transient conditions with longer solution times, an optional program module, PIPE3D-IMP, which uses the implicit time-integration for finite-element structural analysis, has been developed. This implicit program is unconditionally stable and can be used for long-duration calculations of piping response under static or quasi-dynamic loads. Presently, this module consists only of the pipe element with eight degrees of freedom per node. This implicit three-dimensional pipe element can be used to model straight pipes, elbows, and in-line components. An implicit spring element will be added later to model the snubber and hanger. A detailed formulation of the implicit time-integration scheme is given in a companion SMiRT-8 paper [6].

4. Fluid-Structure Interaction

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.

5. Other Improvements

As discussed at SMiRT-6 in Paris [1], the SHAPS code utilizes a thermoviscoplastic constitutive equation to calculate the thermal stress field. This equation, although general, is slow for temperature-independent problems due to additional treatment specifically formulated for thermal effects. Recently, a fast-running, non-linear, purely elastic-plastic constitutive model has been incorporated into SHAPS to treat temperature-independent problems. The governing equations are integrated with a tangent predictor radial return algorithm. Moreover, improvement of efficiency has been made in evaluating stress at various Gaussian stations, which has resulted in a 30-50% reduction of CPU time in many test calculations.

6. Sample Problems

Because of space limitations, only two sample problems are presented here. For additional problems illustrating analyses of three-dimensional piping FSI, seismic excitation, as well as structural response under static or long-duration loads, the reader may refer to two companion papers in this conference [6,7].

6.1 Hydrodynamic Analysis of LMFBR PHTS

One salient feature of the advanced method is its ability to perform detailed multi-dimensional analysis of pressure-wave transients in an LMFBR primary heat transport system (PHTS) consisting of complicated components such as pumps, IHXs, and check valves. Figure 1 shows a schematic of a typical PHTS for a prototype LMFBR. The system consists of fourteen pipes and fifteen junctions. Two of the junctions (1 and 15) are the P-t input pulses from the outlet and inlet pipes of the reactor vessel, respectively. The inlet pressure source term is a triangular shape of 2-MPa peak value and 10-ms duration. The outlet pressure pulse is a trapezoidal pulse, rising from 0 to 4-MPa during 0 to 5-ms span, remaining constant to 10 ms, and decreasing to zero at 15 ms.

A sequence of pressure profiles of the coolant loop appears in Figs. 2 and 3. In these figures, the loop is stretched out linearly with the outlet pipe on the left and the inlet pipe on the right. The overall length of the loop is 82.7 m. At 20 ms, the outlet pulse has begun to interact with the pump. At 30 ms, the inlet and outlet pulses reach superposition and the peak pressure of 6.5 MPa is recorded in pipe number 8 (Location "A" in Fig. 1) in the crossover leg. The principal pulses continue around the loop, attenuate to approximately 3.5 MPa and 0.7 MPa, and return to the primary vessel. Figure 4 depicts the pressure history at Location "B" inside the IHX (see Fig. 1), as obtained from the two-dimensional hydrodynamic analysis. The pulse width is considerably wider than the input pulse applied at the inlet nozzle due to interaction of the fluid with components and baffle plates.

6.2 Fluid-Structure Interactions

A test problem of a straight pipe was used to check the performance of the implicit-implicit (I-I) hydrodynamic-structural coupling. A 20-axial zone representation of a straight pipe with inside radius 21.43 cm and length 609.6 cm is utilized as the numerical model as shown in Fig. 5. A non-reflecting boundary is assumed at the junction after the pipe, while a 5-MPa square pulse of 2-ms duration is applied to the junction before the pipe. The thickness of the pipe was 1.428 cm. The yield stress is 6.30 x 10^9 MPa.

The pressure histories at the non-reflecting junction [zone (2,21)] are shown in Fig. 6. In this figure, the solid lines represent the results of the I-I analysis, while the dashed lines indicate the solutions of I-E calculation. It can be seen that the pressure pulse propagates along the pipe with little change in its shape or its magnitude. Figures 7 and 8 further depict the circumferential strain and stress at node 10 (see Fig. 5 for its location). Results of pressure, strain, and stress histories revealed the close similarity of solutions obtained from the I-I and I-E couplings.

7. Acknowledgments

This work was performed in the Engineering Mechanics Program of the Reactor Analysis and Safety Division at Argonne National Laboratory, under the auspices of the U.S. Department of Energy.

References

[1] WANG, C. Y., A-MONEIM, M. T., BELYTSCHKO, T. B. "Integrated Analysis of Piping Systems," Trans. 6th Int. Conf. on Structural Mechanics in Reactor Technology, Paper E 6/1, Paris, France (August, 1981).

[2] WANG, C. Y., "A Three-Dimensional Method for Integrated Transient Analysis of Reactor-Piping Systems," Nuclear Engineering and Design, Vol. 68, No. 2, pp. 175-184 (March, 1982).

[3] WANG, C. Y., "Theory and Application of a Three-Dimensional Code SHAPS to Complex Piping Systems," Advances in Fluid-Structure Interaction, 4th Int. Congress on Pressure Vessel Piping Technology, ASME PVP-75, Book No. H00261, pp. 139-157, Portland, OR (June, 1983).

[4] WANG, C. Y., "Analysis of Nonlinear Fluid-Structure Interaction Transient in Fast Reactors," ANL-78-103 (November, 1978).

[5] A-MONEIM, M. T., CHANG, Y. W., BELYTSCHKO, T. B., "Three-Dimensional Response of Piping Systems to Internally Propagating Pressure Pulses," Trans. 5th Int. Conf. on Structural Mechanics in Reactor Technology, Paper E 3/3, Berlin, Germany (August, 1979).

[6] WANG, C. Y., "An Implicit Finite Element Structural Dynamics Formulation for Long-Duration Accidents in Reactor Piping Systems," Trans. 8th Int. Conf. on Structural Mechanics in Reactor Technology, Paper B 2/4, Brussels, Belgium (August, 1985).

[7] ZEUCH, W. R., WANG, C. Y., "Analysis of Pressure Wave Transients and Seismic Response in LMFBR Piping Systems Using the SHAPS Code," Trans. 8th Int. Conf. on Structural Mechanics in Reactor Technology, Paper E 6/3, Brussels, Belgium (August, 1985).

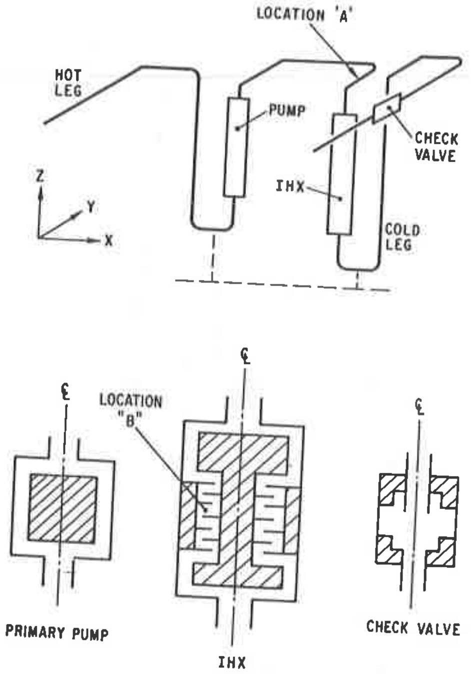

Fig. 1. Piping Configuration Used in the Analysis (a) Schematic of LMFBR PHTS, (b) Detail of Various Components

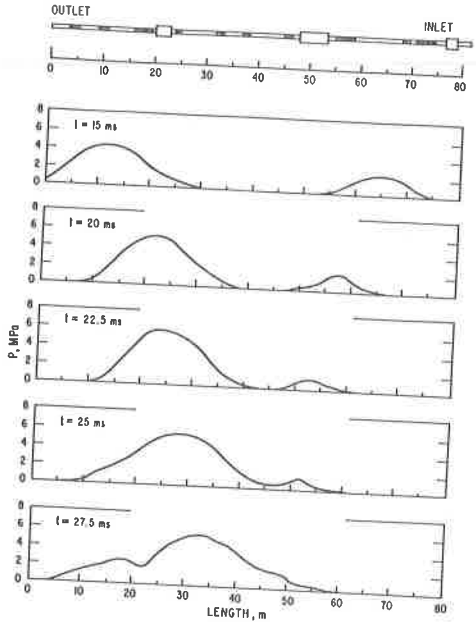

Fig. 2. Pressure Profiles at 15 ms Through 27.5 ms Along the Length of the Primary Coolant Loop

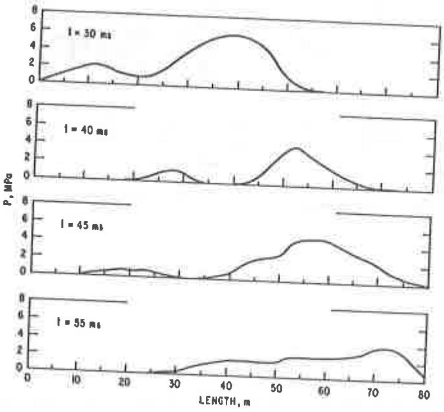

Fig. 3. Pressure Profiles at 30 ms Through 55 ms Along the Length of the Primary Coolant Loop

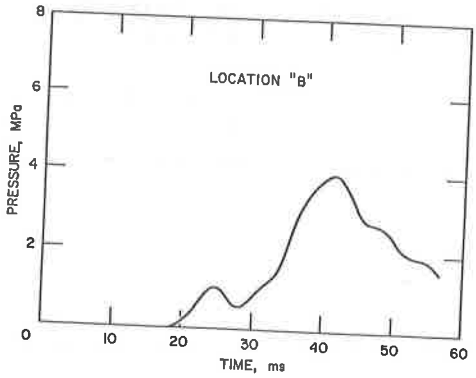

Fig. 4. Pressure History at Location "B" Inside the IHX

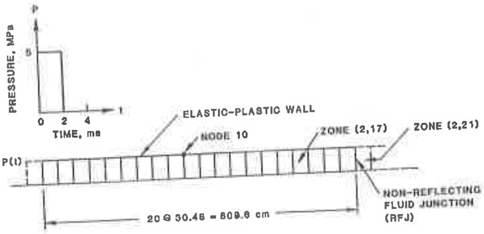

Fig. 5. Configuration of Straight Pipes Used in the SHAPS Analysis

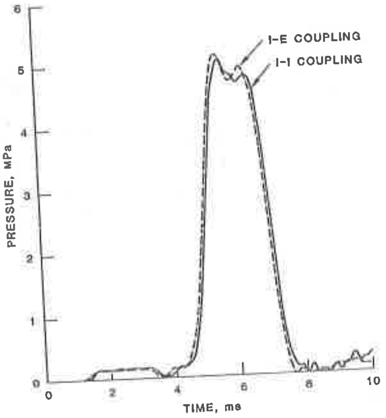

Fig. 6. Pressure Histories at Non-reflecting Fluid Junction, Zone (2,21)

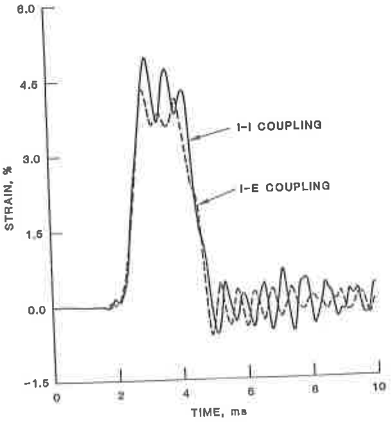

Fig. 7. Time Histories of the Circumferential Strain at Structural Node 10

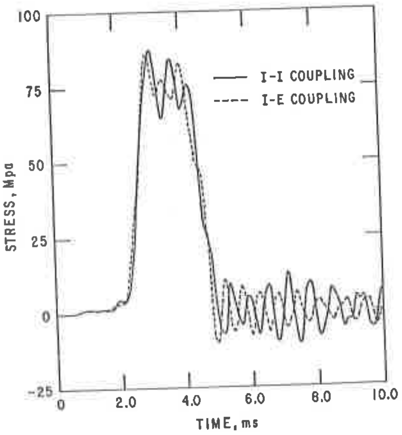

Fig. 8. Time Histories of the Circumferential Stress at Structural Node 10