Application of ADINA Fluid Element for Transient Response Analysis of Fluid-Structure System

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Abstract

Pressure propagation and Fluid-Structure Interaction(FSI) in 3D space were simulated by general purpose finite element program ADINA using the displacement-based fluid element which presumes inviscid and compressible fluid with no net flow.

Numerical transient solution was compared with the measured data of an FSI experiment and was found to fairly agree with the measured. In the next step, post analysis was conducted for a blowdown experiment performed with a 1/7 scaled reactor pressure vessel and a flexible core barrel and the code performance was found to be satisfactory.

It is concluded that the transient response of the core internal structure of a PWR during the initial stage of LOCA can be analyzed by the displacement-based finite fluid element and the structural element.

1. Introduction

In recent years efforts have been made to analyze Fluid-Structure Interaction(FSI) phenomena especially in LOCA blowdown in nuclear safety.

For the HDR blowdown test series performed in Germany, computer codes were used to predict the test results, such as FLUX, STEALTH/WHAMSE, PISCES-3DELK and so forth.[1] These codes incorporate Finite Difference Method in fluid region while techniques are investigated for using Finite Element Method in the fluid region.[2],[3]

General purpose finite element program ADINA has in its element library 2D and 3D fluid elements which presume inviscid and compressible fluid with no net flow. The theoretical formulation and some applications of ADINA fluid elements to FSI problems are reported.[4],[5],[6] For the application to LOCA blowdown, usage of 3D fluid element needs to be studied in 3D space where pressure wave turns around an edge which is a weakness of finite element modeling and is supposed to have a fine mesh in the fluid region.

The objective of this paper is to report on an application of ADINA for solving pressure propagation and FSI.

2. Finite Elements and their Interface

The 8-node 3D fluid element was used with 1-point integration order which has no stiffness against form change except for volume change,[5] the 9-midsurface node shell element with 2x2x2 integration order and both of these with consistent mass matrix. The Total Lagrangian formulation is employed to describe the motion.

Relative sliding is permitted at the fluid-structure interface by means of constraint equations. Each point of the interface is described by two nodes; one is for structure and the other is for fluid. In the normal direction to structure the two nodes are coupled, but in the tangent direction the two are decoupled, thus enabling the two faces to slide on each other. On a discontinuous portion such as an edge, fluid nodes are coupled to structural nodes except in the direction along the edge. Experience shows this manipulation produces little effects on pressure propagation around the edge due to 1-point integration order employed in the fluid element.

Newmark β method was used for time integration.

3. Pressure Propagation

Prior to FSI analysis, pressure propagation was investigated in two configurations of rigidly-contained water using 3D fluid elements. One is a simple straight water column (Fig.-1-(a)). The other is a cylindrical annulus with a nozzle: a simulation of reactor pressure vessel inlet nozzle and a portion of downcomer annulus (Fig.-2-(a)). Step function was used as a pressure forcing function input to the open end.

The numerical solutions fairly agree with the theoretical ones as shown in Fig.-1-(b) and Fig.-2-(b), respectively. In Fig.-2-(b) the theoretical curve is based on zero rise-time step input and on purely one dimensional pressure propagation. Fluctuation observed at the open end element is attributed to the element's integration point, at which pressure is calculated, apart from the surface by half of the element width. Note that in Fig.-1-(b), a spike at the time of two travels is due to an interference of the input wave and the wave reflected from the dead end and that this spike propagates and shows up at four travels.

Different finite element discretizations, mass idealizations (lumped or consistent) and time steps were parametrically studied. It was found that consistent mass gives stabler solution than lumped mass and that as pressure propagates, one time step in one element is sufficient and desirable to reduce numerical fluctuation.

4. FSI Experiment and Analysis

4.1 Test

Fig.-3 depicts a test apparatus of rigidly sustained pipe and a chamber filled with water of atmosphere pressure at room temperature. A part of impulsive compression wave generated by a piston hit by a dropped hammer propagates directly into one side of a chamber while the rest of the wave travels through a detour and comes with time lag into the other side of the chamber which is screened by a flexible stainless steel plate (300x100x5mm). Thus the plate vibrates under FSI effect.

Measured are pressures in the pipe and in the chamber in a transient manner.

4.2 FEM Model

The chamber and the connecting pipes up to pressure gauges P5, P6 are modeled with six shell elements for the flexible plate and fifty six 3-D fluid elements for the water (Fig.-4). The FEM model, where the pipe is taken rectangular with the same cross section, is a symmetry half of the chamber with adequate boundary conditions imposed on the symmetry plane.

Forcing functions input to the open ends are the measured pressure transients at P5 and P6 which serve as pressure boundary condition. 0∿2.7 msec was calculated which corresponds to more than six round-travels of pressure propagation within the chamber.

4.3 Results

Comparison of the numerical solution of pressures with the measured shows a good agreement (Fig.-5).

Regardless of the relatively coarse mesh, pressure wave thoroughly propagates through the 90-degree turn-round region.

5. 1/7 Scaled Blowdown Experiment and Analysis

5.1 Test

Fig.-6 shows a blowdown test apparatus of a 1/7 scaled reactor pressure vessel(RPV) filled with pressurized (80 kg/cm^2g) water at room temperature, a flexible core barrel(C/B) and two mass rings simulating the mass of fuel assembly at upper and lower core plates. The mass rings are attached to the C/B shell with key-clevises allowing the C/B to freely vibrate in shell modes.

An impulsive decompression wave is generated by a main rupture disk which is triggered by a burst of a pre-rupture disk. As the decompression wave travels through the medium in RPV inducing the flexible C/B shell to vibrate, pressures in the downcomer and inside the C/B were recorded in a transient way. Four radial supports are located at the bottom of the C/B and preloaded against the C/B eliminating an impact non-linearity.

5.2 FEM Model

Half(0∿180°) of the system was modeled with adequate boundary conditions in the symmetry plane (Fig.-7). The C/B is modeled with 24 shell elements, the radial supports with 3 truss elements and the water is spatially represented by 230 3-D fluid elements. The spherical lower plenum is taken cylindrical with the same volume. Measured pressure transient was used as boundary condition applied to the nozzle open end.

5.3 Results

As seen in Fig.-8, the numerical solution was approximately coincident with the measured.

Ideally the fluid region is supposed to be discretized with "dices" with all of the same size to simulate pressure radiation in 3D space. Discrepancies between the measured data and the numerical solutions are attributed to an insufficient simulation of pressure propagation caused by the coarse mesh in the lower plenum region where pressure wave coming down in the annulus turns 360 degrees to go up inside the C/B. This attribution was thereafter confirmed by a separate calculation with a partial model of the plenum.

6. Concluding Remarks

Assessment of pressure propagation and fluid-structure interaction in 3-D space indicates a satisfactory agreement with the measured data. Although more detail analysis and experiment will be required to verify the applicability of a finite fluid element to LOCA blowdown analysis in design and licensing, it is admitted that the fluid element is capable for FSI analysis during the initial stage of LOCA.

The fluid element's inherence, such as one-phase inviscid fluid with no net flow, will be overcome by conservative assumptions in the application. In addition, the use of a gap element might be useful to simulate two phase fluid.

Encouraging are ADINA's good performance of dynamic non-linear solution and its accessibility for modifying and upgrading.

7. Acknowledgment

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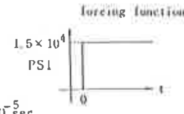
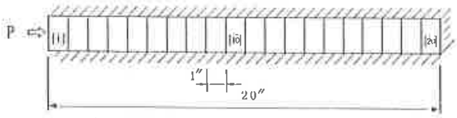
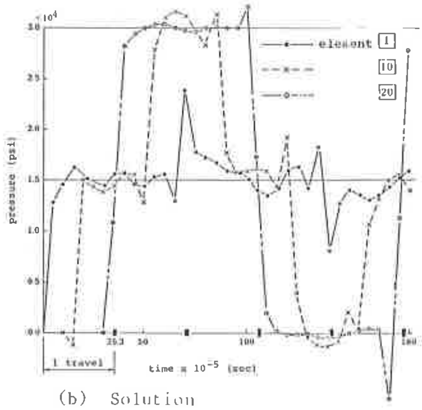
3D fluid element

- bulk modulus $K = 3.0 \times 10^{4}$ PSI
- density $\rho = 9.36 \times 10^{-5}$ lbs^{2}/in^{4}
- sound velocity
  $a = \sqrt{K/\rho} = 5.661 \times 10^{4}$ in/sec
- integration time step $\Delta t = 1.0 \times 10^{-5}$ sec



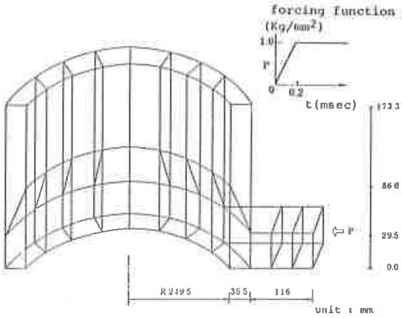


(a) FEM Model

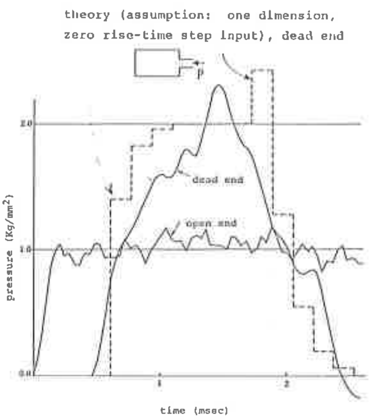


(b) Solution

Fig.-1 Water Column

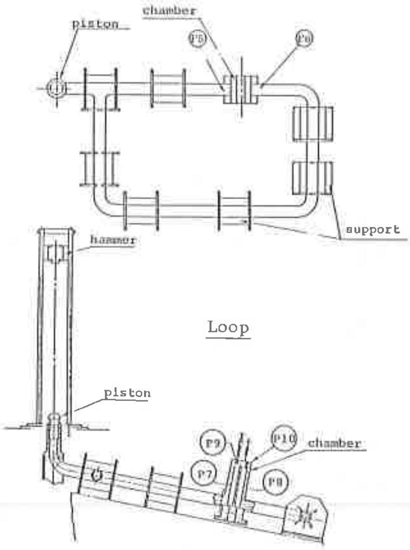


(a) FEM Model

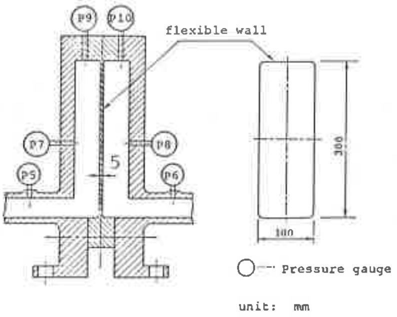


(b) Solution

Fig.-2 Water Annulus



Loop



Chamber

Fig.-3 FSI Test Apparatus

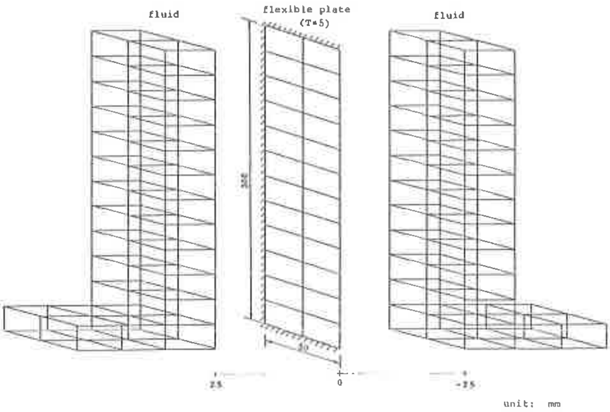


Fig.-4 FSI Test FEM Model

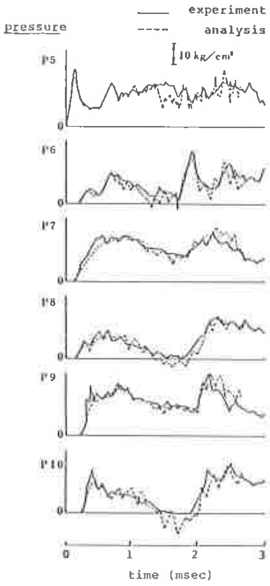


Fig.-5 FSI Test Results

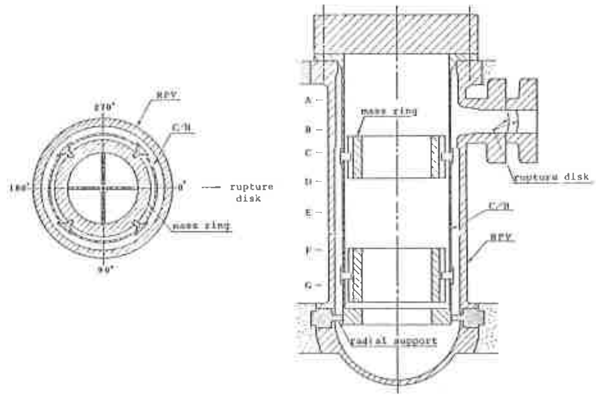


Fig.-6 1/7 Scaled Blowdown Test Apparatus

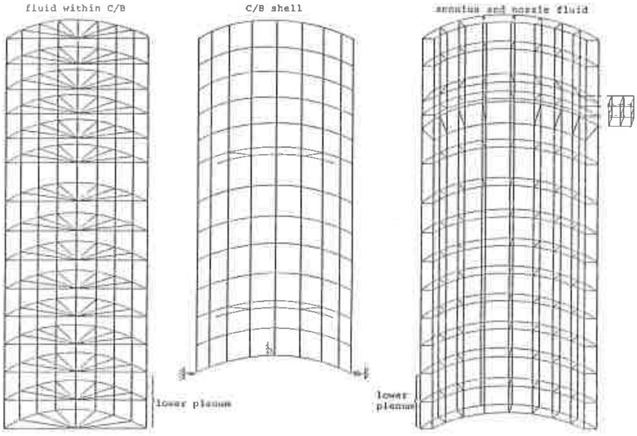
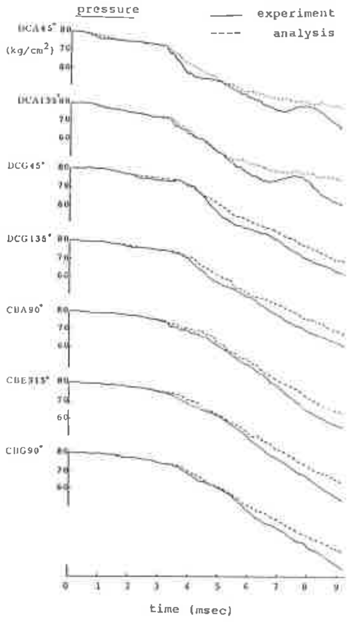


Fig.-7 Blowdown Test FEM Model



DC···downcomer, CB···inside C/B
A,E,G···elevation, degree···
orientation

Fig.-8 Blowdown Test Results