APPLICATION OF ANSYS FLUID ELEMENTS IN FLUID-STRUCTURAL INTERACTION PROBLEMS

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In order to evaluate the recently developed fluid elements included in ANSYS for use in fluid-structure interaction problems, a series of test problems were executed which use these new elements in various solution contexts. ANSYS is a program based on finite element modeling and solution techniques for use in the stress analyses of complex structures subjected to static and dynamic loads. New 2-D and 3-D elements suitable for modeling quiescent fluid behavior have been included in ANSYS in such a manner that they can be combined with solid elements in modeling fluid-structure interaction problems.

The fluid elements are modifications of isoparametric solid elements and are intended to model fluids contained within vessels and having no net flow rate. The amount of flow permitted is limited to that which will not cause gross distortions in the element and the large deflection option should not be used. In a reduced analysis, dynamic degrees of freedom should be selected at all points normal to the fluid surface and not at interior points.

Several problems were considered in order to evaluate various aspects of the new elements. Some static and dynamic problems of a linear nature were compared to existing closed-form solutions to determine ranges of applicability and modeling "ground rules" for the new elements. In addition, nonlinear dynamic problems were considered and results compared to those obtained by other researchers.

The static problems considered include the response of fluids in a rigid container undergoing constant translational or rotational acceleration. The dynamic problems include (1) the free vibration of the fluid in a rigid container and in a flexible suspended cylindrical vessel; and (2) the time history analysis of the transient response to a pressure pulse in an elasto-plastic tank immersed in constrained fluid medium.

Results obtained indicate close agreement with theoretical results in the statical and modal analysis problems when regular shaped elements are used and qualitative agreement with numerical results obtained by others in the transient response problem. With irregular elements near skewed boundaries, difficulties were uncovered when free surface effects are included. Ground rules for use of the 2-D and 3-D fluid elements when combined with structural elements in finite element analyses of coupled fluid-solid problems were developed. Limitations and procedures for mesh generation, assignment of dynamic degrees of freedom, specification of boundary conditions, and interface coupling techniques were determined.

1. INTRODUCTION - The 2D and 3D fluid elements in ANSYS (1) are modifications of the isoparametric solid elements without incompatible displacement shapes. They are intended for use in modeling fluids having no net flow rates and contained within vessels. The amount of flow permitted is limited to that which will cause no gross distortions of the elements. The large deflection option should not be used.

A single integration point at the element centroid is used with a Gaussian integration procedure for evaluation of bulk compression and thermal expansion effects. A 2 x 2 or 2 x 2 x 2 integration point set is used for the shear and rotation effects. A pseudo-stiffness of $E \times 10^{-9}$ is associated with the shear and rotational strains to ensure static stability. The isotropic Young's modulus is taken as the fluid bulk modulus.

At fluid-solid interfaces two nodes should be defined, one on the fluid and one on the solid, at the same coordinate locations. The interface nodes should be defined in a local displacement coordinate system coinciding with the interface normal direction and the local normal displacement of those nodes constrained to move together; relative slip is permitted. In a reduced dynamic analysis, dynamic degrees of freedom should be defined at all points normal to the fluid free surfaces and at no interior points.

Several example validation problems were considered using both the 2-D and 3-D fluid elements to model statical and dynamical problems. Four examples are reported here: (1) accelerating rigid container status; (2) rotating rigid container statics; (3) immersed elasto-plastic cylinder transient dynamics; and (4) free vibrations of a rigid container.

2. ACCELERATING RIGID CONTAINER STATICS - A 2" x 4" rigid rectangular container of water subjected to a uniform acceleration field a_X = 100 ft/sec^2 was modeled using 2-D fluid elements. Three successively refined grids (4 x 2, 8 x 4, 16 x 8) were used. In Fig. 1 are displayed the surface displacements for the left half of the 8 x 4 and 16 x 8 meshes. Anti-symmetric results were obtained. The pseudo-stiffness in the fluid element introduces distortions at the fluid-solid interface. Convergence to theoretical results can be seen in Fig. 1, where maximum deflections at the interface are extrapolated from the 4 x 2, 8 x 4 and 16 x 8 meshes.

3. ROTATING RIGID CONTAINER - The second problem reported is that of a rigid cylindrical container containing water subjected to a uniform angular rotation. See Fig. 2, where are displayed the cylinder rotating at an angular velocity ω = 2.78 rad/sec and the typical 10° wedge of 3-D fluid elements used to model the container behavior.

The theoretical solution (2) for pressure P throughout the container and for liquid surface profile z are:

$$p = \frac{\rho \omega^2 r^2}{2} - \rho g z + P_a$$

$$z = \frac{\omega^2 r^2}{2g}$$

where ρ = density, r = radial coordinate, g = gravity, P_a = atmospheric pressure.

In Fig. 2 are compared the liquid surface profiles obtained using theoretical, 2-D and 3-D fluid elements. The 3-D results at the centerline where the "brick" element degenerates to a wedge element exhibit significant error. This is because the fluid element formulations did not accept such shaped elements at the time these models were generated. At the liquid-container interface the pseudo-stiffness again introduces errors as in the first problem reported. Elsewhere, the 2-D and 3-D elements are in close agreement with exact results (2).

4. IMMERSED ELASTO-PLASTIC CYLINDER - In order to validate the use of fluid elements in combination with other structural elements in the ANSYS Library to solve dynamics problems, a sample problem considered by other investigators (3) using a different fluid-solid interaction formulation was modeled. The problem consisted of an abrupt pressure pulse ($P = 30$ ksi) applied and removed ($0 < t < 10^{-5}$ sec) from the internal walls of a cylindrical steel tank immersed in water. See Fig. 8 for a description of the structure. The tank material was assumed elastic - perfectly plastic with yield stress $\sigma y = 36$ ksi. The three-dimensional finite element model used is shown in Fig. 3. The results obtained are from ANSYS executions of the nonlinear transient option.

The time histories of vertical displacement at the axis of revolution are shown in Fig. 4 for three models: Ref. (3), 2-D model, 3-D model. Also shown are the time histories of horizontal displacement at the tank base for the three models. Qualitative agreement between results can be observed. Note the ANSYS results yield conservative answers when compared to the Shantram, Owens and Zienkiewicz (3) results.

5. RECTANGULAR RIGID CONTAINER FREE VIBRATIONS - To confirm the use of the fluid elements in a reduced modal analysis, the problem of determining the natural frequencies of a fluid in a 2" x 5" x 5" rigid rectangular container was solved. A 3-D mesh of 1" cubical elements was used. The modal analysis for the two and three dimensional models are summarized in Table 1. The theoretical result (4) is ($g = 386.4$ in/sec^2):

$$\omega_{mn}^2 = g k \tan h (kh)$$

$$k^2 = \pi^2 \left(\frac{m^2}{a^2} + \frac{n^2}{b^2} \right)$$

6. REFERENCES

(1) ANSYS User's manual.

(2) Abranson, H. N., "The Dynamic Behavior of Liquids in Moving Containers," NASA-SP-106, 1966.

(3) Shantram, D., Owen, D. R. J., and Zienkiewicz, O. C., "Dynamic Transient Behavior of Two- and Three-Dimensional Structures Including Plasticity, Large Deformation Effects and Fluid Interaction," Earthquake Engineering and Structural Dynamics, Vol. 4, pp. 561-578 (1976).

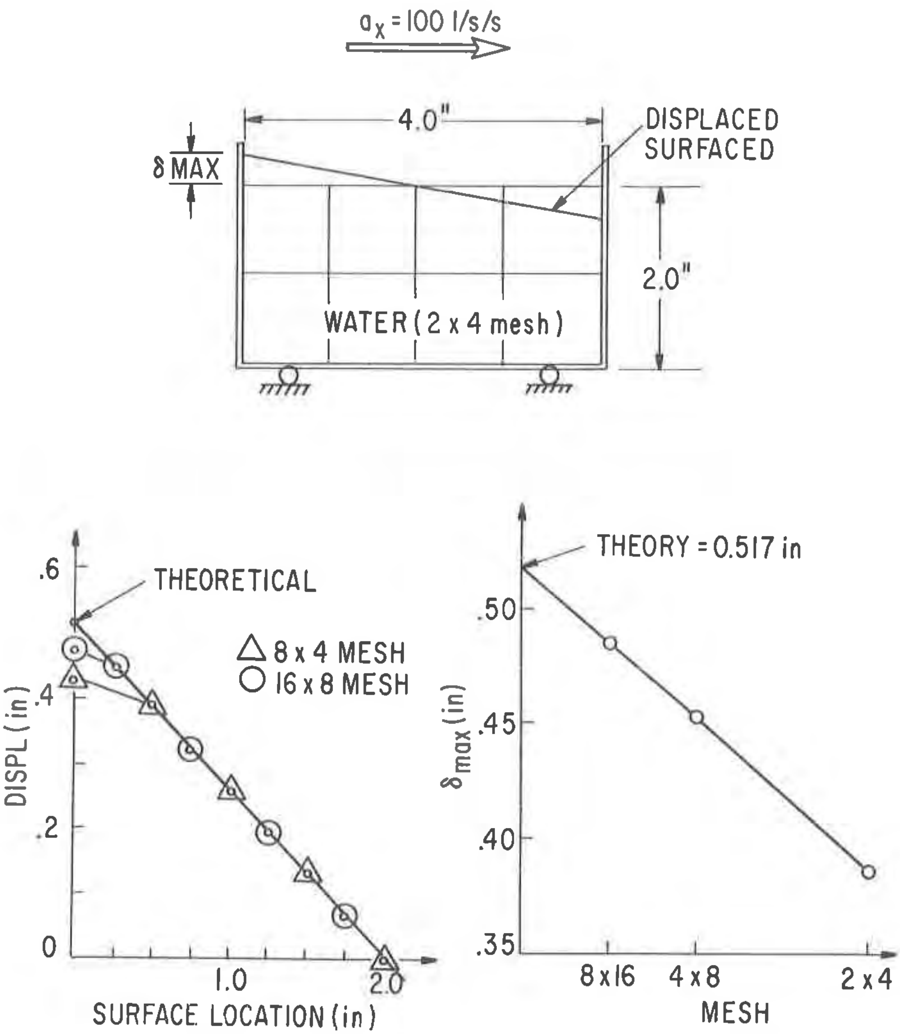

Fig. 1. Accelerating Rigid Container Problem

TABLE 1. Modal Analysis of a Rectangular Tank

m	n	Theory	ANSYS 2-D	ANSYS 3-D
1	0	2.286	2.298	2.299
0	1	2.286	-	2.299
1	1	2.865	-	2.829
2	0	3.484	3.583	3.585
0	2	3.484	-	3.585
2	1	3.694	-	3.670
1	2	3.694	-	3.670
2	2	4.167	-	4.135
3	0	4.293	4.505	4.505
0	3	4.293	-	4.505

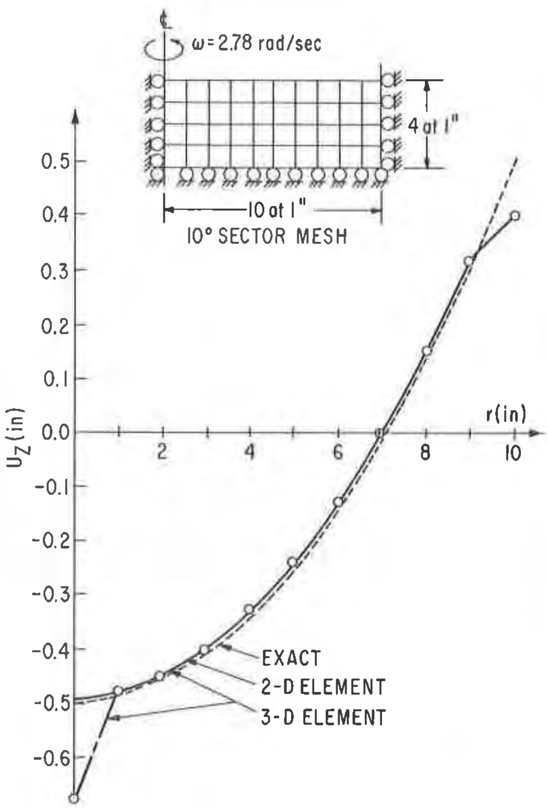

Fig. 2. Rotating Rigid Container Problem

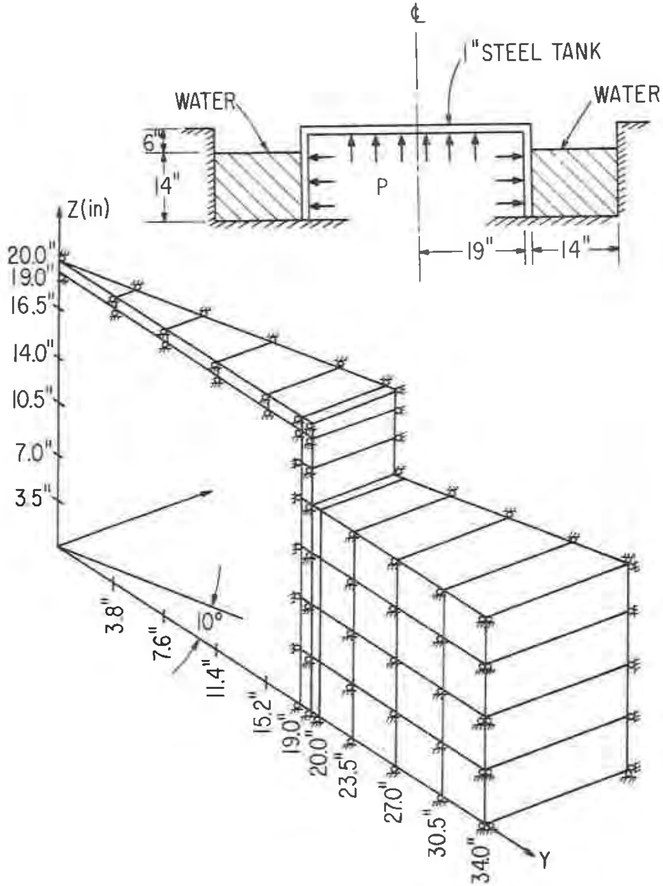

Fig. 3. Immersed Elasto-Plastic Cylinder

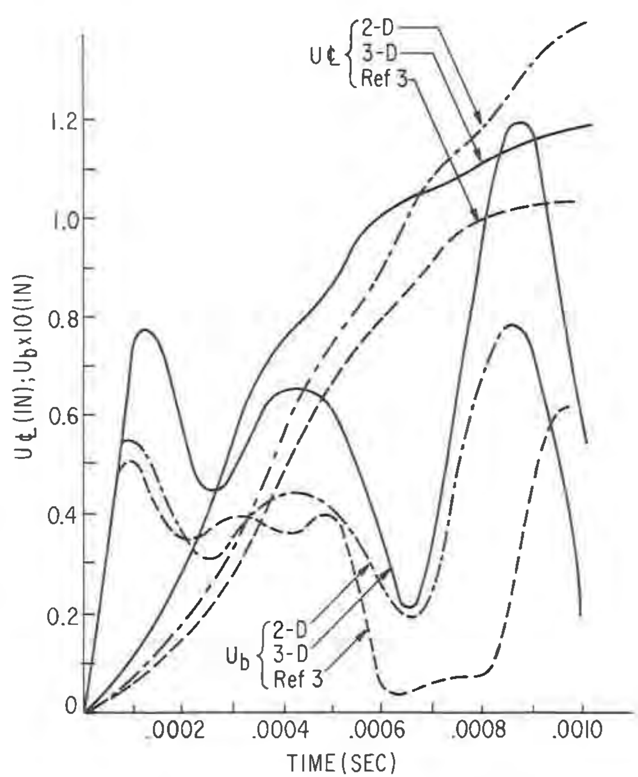

Fig. 4. Time Histories of Elasto-Plastic Cylinder Displacements