1 INTRODUCTION

Transient analysis of submerged components and structures is an important research and development activity which has attracted a great deal of interest in the last decade for the design of nuclear fuel assemblies, reactor internals, steam generator and heat exchanger tubes. Under the postulated accident condition submerged tubes may be subjected to high pressure fluid impulse and the interaction of the neighbouring components has to be studied in a coupled manner. In the present paper method of partitioning is effectively utilized for the transient analysis of the three-field coupled problems involving fluid and two structures. With a suitable development in the standard sky line profile solver the fluid multi-structure interaction problem is formulated in an economical manner in a 3-D finite element shell-fluid interaction code FLUSHEL[1-3] and solution of Geers and Ruzicka[4-5] twin submerged tubes is presented which had been earlier studied for plane strain condition alone. The effect of bending mode is recognized and cases of bulk pressurization and line wave loadings are studied in detail.

2 THEORETICAL BACKGROUND FOR COUPLED MULTFIELD PROBLEMS

The code FLUSHEL[1-3] is based on the development of a 2-D degenerate 9 noded shell element with displacement variable and 8 noded trilinear brick element with pressure variable as unknown. In this code method of partitioning is used to solve the coupled shell-fluid equations in an optimum manner. The modular nature of this method permits further extension in a simple manner for analyzing the multifield coupled problems. We consider the fluid field \( \Omega_f \) coupled to two cylindrical shells \( \Omega_1 \) and \( \Omega_2 \) as shown in fig.1. The dynamics of the three field problem can be presented by the second order semidiscrete coupled ordinary differential equations of following form,

\[
\begin{bmatrix}
M & -q & 0 & -q & 0 \\
-f & f & -f_1 & f & -f_2 \\
0 & M & 0 & 0 & 0 \\
0 & 0 & M & 0 & 0 \\
0 & 0 & 0 & M & 0 \\
\end{bmatrix}
\begin{bmatrix}
p \\
\dot{p} \\
\ddot{p} \\
\dddot{p} \\
\dddot{p} \\
\end{bmatrix}
+
\begin{bmatrix}
C & 0 & 0 \\
0 & -C & 0 & 0 \\
0 & 0 & -C & 0 & 0 \\
0 & 0 & 0 & -C & 0 \\
0 & 0 & 0 & 0 & -C \\
\end{bmatrix}
\begin{bmatrix}
\dddot{u} \\
\dddot{u} \\
\dddot{u} \\
\dddot{u} \\
\dddot{u} \\
\end{bmatrix}
= \begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
0 \\
\end{bmatrix}
\]
In the above equation \( M \), \( C \) and \( K \) are the fluid mass, damping and stiffness matrices respectively, \( Q_{f1} \) and \( Q_{f2} \) are the coupling terms to transfer the acceleration data from \( C_{1} \) and \( C_{2} \) structures to the fluid domain, \( \rho_{f} \) is the fluid density, \( u_{n} \) and \( u'_{n} \) are the ground motions of the two structures, \( \lambda_{f} \) is the applied fluid force and \( p \) denotes the pressure field. \( M_{i}, C_{i}, \) and \( K_{i} \) denote the mass, damping and stiffness respectively of the ith structure, \( \Omega_{i} \) is the coupling matrix to transfer the fluid pressure to the shell surface, \( u_{s}^{i} \) is the displacement vector and \( f_{s}^{i} \) is the specified structure force vector (i=1, no. of structures: 2 in this case).

It is noted from eqn.(1) that the bandedness of the set of equations is lost due to the coupling terms. However the structure and fluid meshes can be integrated on two different meshes with provision for flow of interface data from one field to another field. Thus at each time step the fluid pressure is transferred to the structure boundaries and the structural normal acceleration is transferred to the fluid mesh in an iterative manner till the convergence is met. In this method single field codes, capable of analyzing structure dynamics problems and fluid transient problems individually, can be coupled effectively. Compared to single field analyzers only the coupling matrix \( Q_{f1} \) and \( Q_{f2} \) are introduced additionally to transfer the field variables. In order to optimize the storage space requirement \( M, C \) and \( K \) for each fields are stored in sky-line storage scheme. However it is recognized that the coupling matrices \( Q_{ii} \) and \( Q_{ij} \) are active only at the fluid-structure interface for "wet nodes". So for \( Q_{ii} \) or \( Q_{ij} \), a separate local equation numbering system is evolved. Thus size of \( Q_{ii} \) or \( Q_{ij} \) depends on the size of interface boundary and all other nodes are removed from the active core. New diagonal identifiers keep the record of diagonal terms of all the local equation numbers for structure and fluid domains respectively. The diagonal identifiers are one dimensional arrays, as the variables which are to be transferred are on each wet node (pressure for structure and normal acceleration for fluid). The matrix multiplications \( Q_{f} \), \( Q_{s} \), \( u_{s} \), \( u_{n} \), and \( \Omega_{ij} \) are carried out for local equation numbers and the interaction terms are finally transferred to the global equation numbers. This scheme thus requires additionally very small storage space compared to the single field analyzers. Further reduction in storage space is achieved by recognizing the fact that \( Q_{ij} = -Q_{ji} \). To save the computer time and storage space, identical meshes are chosen for the two cylinders, thus all the structural matrices have to be evaluated only once if both the cylinders are identical in all respects. Thus different node numbers are assigned to the two cylinders only for recognizing the field variables alone. The advantages of the method of partitioning may be recognized here. Although the eqn.(1) is fully populated, sequential treatment of the individual fields (or parallel treatment if parallel processors are available) makes this method very powerful to treat the coupled multifield problems. In this case also either an explicit or an implicit integrator can be selected for
various fields depending on the critical time periods of each mesh.

3 CASE STUDIES

Fig. 2 shows the radial velocity response \( \gamma_e \) of both the cylinders \( C_1 \) and \( C_2 \) at the front edge of quarter span \( x_0 = \pi, L/4 \), and at the rear edge of quarter span \( x_0 = 0, L/4 \). In this figure, the response of single submerged cylinder in plane strain condition is also included. In cylinder \( C_1 \), the front edge \( (x_0 = \pi) \) responds in a manner similar to the single submerged cylinder case, while the rear edge \( (x_0 = 0) \) shows a higher response compared to the single cylinder case. The response at the front edge \( (x_0 = \pi) \) of \( C_2 \) cylinder is significantly higher than the single submerged cylinder response. At the rear edge of \( C_2 \) cylinder initially the velocity response is low, but it approaches the plane strain value as the wave reaches the rear shell \( C_2 \). This time lag is also noted in the case of response at the front edge of \( C_2 \) cylinder. Once the scattered wave reaches from \( C_1 \) cylinder to \( C_2 \) cylinder the velocity response increases significantly. Similar results have been reported by Geers and Ruzicka [4, 5] for plane strain case.

The other case of interest is of two simply supported submerged cylindrical tubes excited with a surface wave through the full span (case SSASWU) to consider the case of bulk pressurization. The tubes are assumed to be axially constrained. In the present case the dry tubes have the fundamental frequency of 86.4 Hz in \( m = 1 \) and \( n = 3 \) mode. Figs. 3 and 4 present the velocity responses of \( C_1 \) and \( C_2 \) cylinders respectively for case SSASWU along with the earlier results for 2-D plane strain case (PS). Significant increase in velocity response is apparent for \( C_1 \) cylinder compared to the 2-D PS response. The velocity response of \( C_2 \) cylinder is also seen to be higher than the PS case at \( x_0 = 0 \), however it is less significant than the case of \( C_1 \) cylinder (at \( x_0 = 0 \)). This is due to the effect of wave scattering from \( C_1 \) cylinder which increases the velocity response in \( C_2 \) cylinder at the rear edge \( (x_0 = 0) \) significantly. Effect of wave scattering is also recognised at the front edge of \( C_2 \) cylinder, however to a lesser extent due to loss in energy of the wave coming from \( C_1 \) to \( C_2 \) and smaller pressure difference between the front edge and the rear edge of \( C_2 \) cylinder compared to that of \( C_1 \) cylinder.

Next we consider the effect of line wave loading which originates in between the ligament. The length of the line wave in the present model is assumed to be of 11.82 in, which is equivalent to the assumption of complete failure of any one of the neighbouring tubes leading to an impulsive line wave. Figs. 5 shows the radial velocity response of \( C_1 \) cylinder. Typical pressure response at the above locations are shown in fig. 6 for \( C_1 \) cylinder. The circumferential membrane force \( (N_{x_0}) \) response is presented in fig 7 and the axial moment \( (M_{xx}) \) is shown in fig 8 for \( C_1 \) cylinder.

4 CONCLUSIONS

Coupled transient analysis of multiple field problems can be efficiently carried out by the method of partitioning. The example problems presented in this paper demonstrate that the bending mode is important for two neighbouring submerged cylinders excited either by a surface wave or a line wave. The analysis shows that the fluid field is three dimensional in nature and simplified two dimensional plane strain analysis need not be conservative for such coupled submerged tubes.
5 REFERENCES


FIG. 3  TWO SUBMERGED CYLINDERS IN INFINITE FLUID CI (SSASMU)

FIG. 4  TWO SUBMERGED CYLINDERS IN INFINITE FLUID CI (SSASMU)

FIG. 5  VELOCITY RESPONSE IN CI CYLINDER (FIX-RAD)
**FIG. 6** PRESSURE RESPONSE IN C1 CYLINDER (FIX-RAD)

**FIG. 7** MEMBRANE FORCE MY IN C1 CYLINDER (FIX-RAD)

**FIG. 8** MOMENT MX IN C1 CYLINDER (FIX-RAD)