ABSTRACT

Sloshing is a fascinating physical phenomenon characterized by the oscillation of the unrestrained free surface of the liquid in a partially filled container due to external excitation. The phenomenon is of great engineering importance associated with several engineering applications and is a potential source of disturbance in liquid storage containers in general. This is a challenging problem in the field of mechanics and is also mathematically quite difficult. The completely general problem involves the viscosity and compressibility of the liquid, complicated temporal and spatial motion of the liquid free surface, the elasticity of the container walls and the inertias of both. Often, a liquid tank contains submerged components that contribute greatly to the overall dynamical behavior of the system. The surface tension at the free surface may become important in situations where the gravity force is small. The general problem is difficult to treat analytically, or even numerically. In addition, the dynamic boundary condition at the fluid free surface is nonlinear and the position of the free surface varies with time in a manner not known a priori. The complexity increases many folds when the contained structure is flexible resulting in coupled interaction between the container and the contained fluid. In such a situation, neither the fluid domain nor the structural domain can be solved independently of the other due to the unknown interface forces. Such dynamic interaction between a partially filled flexible container and its contained fluid, due to oscillation of the unrestrained fluid free surface, is generally referred as "coupled slosh dynamics", since the interaction that couples the dynamics of the liquid with that of the contained structure is primarily due to sloshing of the fluid.

However, the solution of the completely general problem is not essential in many practical applications and many simplifying assumptions can be made. The effect of fluid viscosity on sloshing is usually very small except for the cases where the container is very small and/or rough. The fluid compressibility also plays a negligible role in the free surface wave motion if the fluid is homogeneous and the container is assumed rigid. If the fluid is inhomogeneous or in multi-phase and/or the container flexibility is important, the compressibility of the fluid needs to be considered. Further, if the resulting fluid motion is small, which is usually the case, then the convective momentum transport can be neglected and the governing equations of the fluid motion become linear. Except for the cases where the exciting frequencies and the system natural frequencies are quite close or the exciting amplitudes are large, the free surface displacements can be assumed small. The free surface boundary conditions can, then, also be linearized. All these assumptions are found to work quite satisfactorily for both the uncoupled and the coupled slosh dynamic problems.

In the present study, the slosh dynamic problems, both coupled and uncoupled, are modeled considering compressible fluid with small free surface displacements. The problem is semi-discretized in both the fluid and the structure domain using Galerkin finite element with isoparametric elements. The finite element semi-discretized equations are integrated in time using finite difference based iterative time-stepping techniques. The resulting set of sparse linear algebraic equations at each time step is solved using a skyline solver. The complete numerical algorithm is coded in FORTRAN 95 and has been used to solve large number of sloshing and sloshing associated interaction problems.

Flow-induced vibration of structural components is another very important fluid-structure interaction problem. A structure immersed in flowing fluid experiences unsteady aerodynamic forces due to vortex shedding, turbulence, acoustic and similar other mechanisms. The resulting vibrational motion of the structure influences the aerodynamic forces through a complex interaction. The problem is encountered in aerospace, civil, marine and offshore and nuclear industries. The vortex-induced vibration of cylindrical structures is of particular concern in marine and offshore and nuclear industries. The heat exchanger tube bundle in a nuclear reactor is one of the most sufferers from flow-induced vibration problems. The tubes, both the fuel rods and the guide tubes, need to qualify for safe and efficient operation of the reactor. The general problem necessitates the coupled solution of the unsteady turbulent flow Navier-Stokes equation with structural dynamics of the tube bundle. Even the numerical treatment of the general problem is beyond reach and many simplifying assumptions are included.

The present study models the flow problem as an unsteady laminar flow and assumes the coupling to be weak such that the structural motion does not affect the flow pattern considerably. Under such assumption, the flow field can be computed on a fixed computational mesh and the effects of structural motion dependent fluid forces on structural vibration can be incorporated through added mass and damping. The unsteady Navier-Stokes equations are solved using an explicit implicit Galerkin finite element technique on unstructured triangular meshes. The solver is written in C++. The structural dynamics is simulated using a generalized shell element with nine noded elements having five degrees of freedom per node. Numerical results are presented that assess the applicability of the developed code.