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NUMERICAL PREDICTION OF SLOSHING LOADS IN FLEXIBLE TANKS

G. Fotia, L. Massidda and G. Siddi

CRS4, Area of Waves and Structures
Cagliari, Italy

1 Introduction

The scope of the presentation is to review our ongoing research on the numerical modeling of sloshing in deformable tanks, [6, 7].

In marine engineering, sloshing flows, i.e. resonant fluid motion in confined domains, play a significant role in many practical circumstances. For example, ship response to incoming waves can excite violent motions of transported liquids (crude oil, liquefied gas, etc.) which, in turn, modifies the dynamic behavior of the entire vessel and its seakeeping characteristics.

Therefore, accurate prediction of sloshing loads is of main concern for the design stage of ship tanks. In most of the cases, the dynamic interaction between the structural vibrations and the flow field is neglected, i.e. fluid loads are determined by studying liquid sloshing in rigid tanks. However, the accuracy of this simplified analysis is questionable when dealing with lighter structures or high-strength structural steels. This latter case is of growing importance in current design practice [5, 8], and the modeling of fluid-structure interaction is needed to understand the various associated hydroelastic phenomena and to assess the safety of the system.

2 Fluid-Structure Interaction Modeling

Two different coupling strategies (a *strong coupling* and a *loose coupling* interaction model) are possible for modeling fluid-structure interaction. Both methods consist in a partition of the non-linear time-dependent fluid–solid coupled problem. Partitioning may be achieved either through an explicit time stepping procedure [2, 4], or by reformulating the problem as a sequence of sub-problems on fluid and solid domains, in the frame of an implicit semi-implicit *predictor–corrector* time advancing scheme [3, 9].

In particular, the *strong coupling* algorithm has showed interesting possibilities in capturing the interaction phenomena of fluid and structure and to predict their amplitude and frequency. Our main purpose was to assess the potential of this formulation for the prediction of the sloshing loads in tanks. To our knowledge, this has not been attempted so far in the literature, in particular for non-linear free surface conditions (see e.g. [1] and references therein).

This *strong coupling* algorithm results from the use of a fully explicit time advancing algorithm for the solid domain and a semi implicit solver for the fluid. The interaction forces are rigorously computed by imposing the continuity of the velocities of fluid and solid at the interface, through a Lagrangian multipliers technique. Nonlinearities due to the free surface and to the nonlinear fluid-solid coupling are accounted for through an Arbitrary Lagrangian Eulerian formulation of the relevant equations.

3 Numerical Results

The applicability of the *strong coupling* algorithm in the frame of the incompressible Navier-Stokes equations for the fluid and a linear elastic continuum model for the solid domain is demonstrated through various examples. In particular, we have studied the response of flexible two dimensional rectangular containers to free and forced vibrations.

3.1 Free vibration

The first problem involve the free vibration response of an open container with flexible bottom partially filled with water. This problem was chosen to test the feature of the *strong coupling* fluid-structure interaction model in presence of a free surface.

The tank has a width of $0.8m$ and is filled with water to a depth of $0.3m$. The bottom of the container is made of a sheet of Aluminum with a thickness of $5mm$, a density of $2700kg/m^3$, Young modulus of $70GPa$ and Poisson ratio $\nu = 0.30$. The lateral and vertical displacements of the extremities of the tank bottom sheet are blocked.

The tank is initially at rest with no load acting on it. The coupled response of the fluid-solid system is excited by applying instantaneously a constant gravity acceleration directed downward.

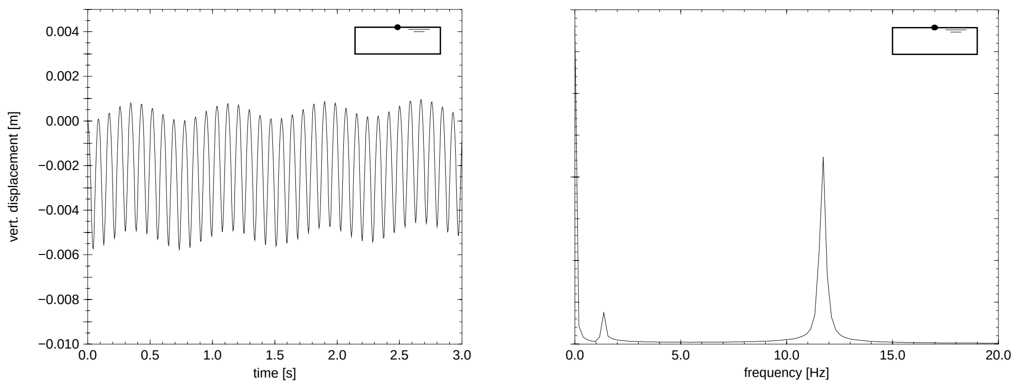


Figure 1: Vibration of a partially filled container with flexible bottom. Vertical displacement of the free surface centerpoint.

Inspection of the results show that the high frequency vibration of the fluid-structure system appears to be capable of exciting a lower frequency vibration mode of the free surface, both the frequencies appear in the time history of the displacement of the center node of the free surface and in the Frequency spectrum of this result.

The corresponding computed frequency for this liquid mode is 1.30 Hz. This value can be compared with the value calculated by the linear theory for a rigid tank (1.41 Hz). As it would expected, the presence of a flexible bottom reduces the value of the first sloshing frequency.

3.2 Forced vibrations of a partially filled container

The forced response of a similar container to a periodic horizontal excitation is then investigated. The tank is filled with water for a depth of $0.5m$, and has an horizontal dimension of $1m$. The thickness of the bottom is 5 mm; the selected material for the elastic bottom is steel with density $7800kg/m^3$, Young modulus of $200GPa$ and Poisson ratio $\nu = 0.30$.
The imposed motion consists in an horizontal displacement varying sinusoidally in time with an amplitude 9.3 mm and a frequency ω of 5.311 Hz, which is close the first sloshing frequency predicted by the linear theory (5.316 Hz).

It is well known that for the problem at hand, the simulation of free surface effects greatly complicates the simulation. In particular, for the selected combination of amplitude and frequency of excitation, strong nonlinearities are to be expected in the liquid response.

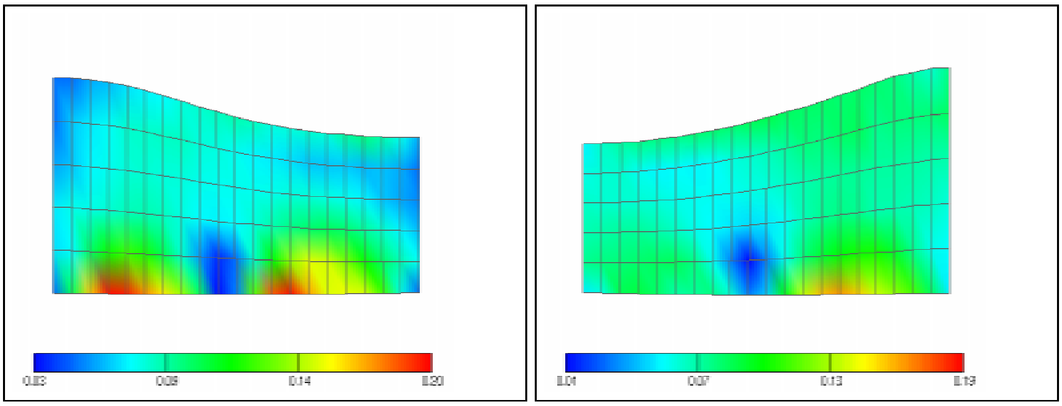


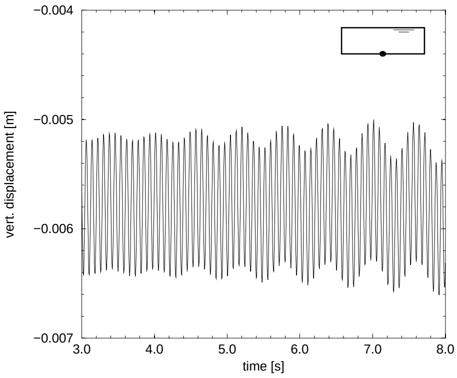
Figure 2: Forced vibrations of a partially filled tank with flexible bottom. Free surface profiles and magnitude of the velocity at 4.0 and 4.6 sec.

A careful analysis of the motion of the flexible bottom show some interesting features, in Fig. 3 the time history of the response of the node located at the center of the bottom is illustrated, while Fig. 2 shows the deformed model at two relevant times.

From the analysis of these results, it is apparent that the response of the central node is composed of a high frequency component which essentially corresponds to the first vibration mode and of a low frequency component, whose amplitude is steadily growing in time. This latter effect is probably related to the growth in wave height due to the almost resonant behavior of the fluid contained in the tank.

4 Conclusions

The *strong coupling* interaction model proves relatively accurate in capturing both fluid and solid response. In fact, for adequate mesh resolution, most if not all the essential features of the non linear free surface flow are recovered. Moreover, the expected structural response appears to be captured in all the test cases that have been examined. Other results, not reported here, indicate this method as not being very robust for long time integration. This fact, may be due to the explicit character of the time-stepping algorithm for fluid analysis, and most of all to the remapping ALE algorithm for the free surface that needs some improvement.



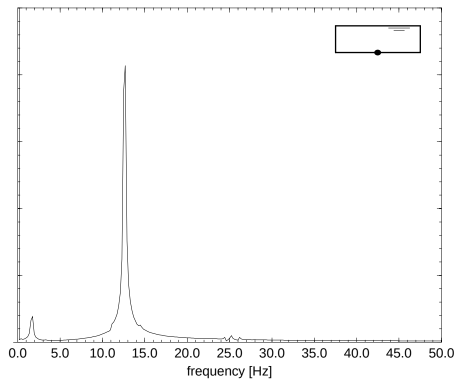


Figure 3: Forced vibrations of a partially filled container with flexible bottom. Motion of the bottom centerpoint and Frequency spectrum. The span t $= 3.0 - 8.0$ s is representative of the entire simulation.

As a conclusion, we may state that the *strong coupling* interaction model exhibits a satisfactory behavior when the time-scales of the problems are not significantly different to each other, as it was the case for the problems investigated.

It is worth mentioning that other numerical experiments not reported here (see e.g. [7]) show that a *loose coupling* interaction model has the potential for better stability properties. We are still investigating the relative advantages of both algorithms either in two- and three-dimensional problems. This work is currently in progress and its results will be reported in a forthcoming paper.

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Correspondence to:

Giorgio Fotia
CRS4, Center for Advanced Studies,
Research and Development in Sardinia
6a strada ovest, z.i. Macchiareddu
area Casic - 09010 Uta - Cagliari - Italy
Ph : (+39) 070 2796 1
Fax: (+39) 070 2796 216
e-mail: Giorgio.Fotia@crs4.it