

2-D Tank Sloshing Using the Coupled Eulerian-LaGrangian (CEL) Capability of Abaqus/Explicit

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Abstract: Tank sloshing has been a unique challenge in many civil, aerospace, and energy applications, and it can cause forces that are difficult to predict using traditional simulation techniques. Abaqus/Explicit includes a coupled Eulerian-LaGrangian (CEL) capability that is useful for tank sloshing simulations. The CEL capability allows for the interaction between the LaGrangian tank domain where the material is fixed to the mesh and the Eulerian fluid domain where material can flow through the mesh. The use of Eulerian elements removes the problem of extreme element deformation associated with LaGrangian fluid meshes. Furthermore, the coupled domains allow modeling of either rigid or flexible tank walls and the stress results can be obtained directly from the tank sloshing simulation. In the present paper, a two-dimensional (2-D) tank sloshing model using the CEL capability of Abaqus/Explicit is examined and the results are compared to those from a similar CFD solution. In addition, a simple flexible tank problem in Abaqus/Explicit is discussed.

Keywords: sloshing, coupled Eulerian-LaGrangian, fluid-structure interaction

1. Introduction

Coupled Eulerian-LaGrangian method for Abaqus/Explicit was released by SIMULIA starting version v6.7EF. This method allows for an Eulerian element domain to interact with a LaGrangian domain through Abaqus's traditional method for contact definition, namely general contact in Abaqus/Explicit. The new coupling of the Eulerian domain and LaGrangian domain makes new types of analysis capabilities available that may not have been available before, one of them being sloshing in a flexible tank. Before CEL, tank sloshing in Abaqus involved modeling the fluid as a deformable mesh within classical LaGrangian framework [1]. For deformable mesh, the wave height must be kept small enough to avoid any large deformation issues within the fluid mesh, severely limiting the range of inputs the analysis can take. The LaGrangian fluid mesh does not allow for flow through the mesh. The new CEL method allows for the fluid part of the mesh to be

defined as a traditional Eulerian mesh, significantly expanding the tank sloshing capabilities in Abaqus.

This paper addresses the first steps in being able to analyze a tank sloshing problem completely within Abaqus. In the absence of an analytical solution, the results from Abaqus simulation are compared to an equivalent CFD solution generated in STAR-CCM+ for validations. The model was analyzed using several different driving frequencies of the rigid tank to create the sloshing phenomenon in the tank; the height predicted for the water at one end of the tank was compared for the two types of simulations.

2. Tank Modeling

The 2-D tank dimensions are listed below in Table 1, referencing Figure 1. The length and the height were chosen to have a natural frequency of 1 Hz. Since Abaqus/Explicit CEL analyses only support 3-D Eulerian elements, the model was constructed in Abaqus/CAE as a 3-D model, even though the analysis is referred to as a 2-D analysis. The out-of-plane dimension was modeled with an appropriate thickness to avoid elements with high aspect ratios.

Table 1. Tank Dimensions.

Tank Dimensions	
Length, L (in)	24
Height, h (in)	7.929

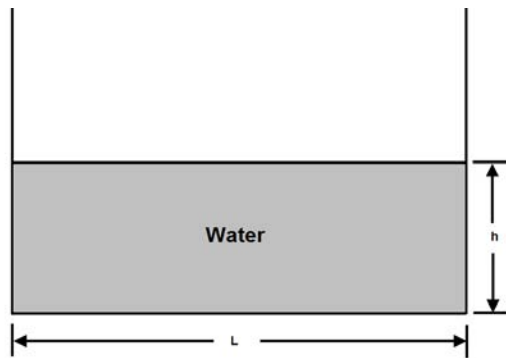


Figure 1. Tank schematic.

The tank was modeled using two parts, the tank wall with LaGrangian elements, and water with Eulerian elements. Shell elements with a very small thickness were used for the walls since the tank is constrained as a rigid part. The Eulerian water part is partitioned in order to provide a region for the initial location of the water material. All other partitions are assigned the void material option during the material assignment step.

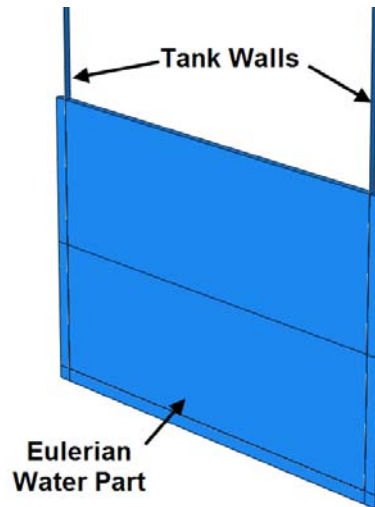


Figure 2. Modeling of geometry.

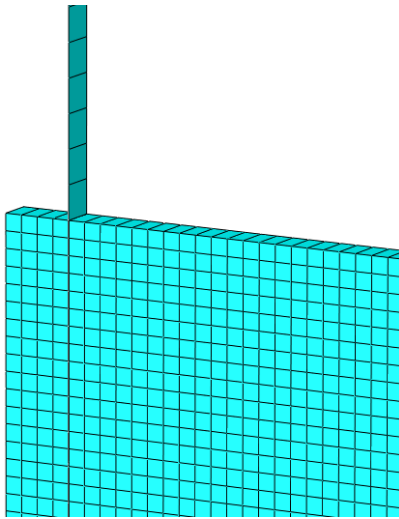


Figure 3. Mesh density used for the analysis.

The mesh density, as seen in Figure 3, is a compromise between the solve time of the simulation and the coarseness of the results. With this model being a 2-D approximation, only one element is modeled through the thickness.

Another parameter affecting the solve time is the sound wave speed in the fluid material. The material used in this Abaqus/Explicit analysis is an Equation of State model, with no viscosity. This material model represents an inviscid Euler fluid. Because the flow in this problem is essentially incompressible, the modeled speed of sound must only be sufficiently large relative to the flow velocities in order to accurately approximate the governing equations.

To minimize simulation run time, the sound wave speed used in the analysis, 583.86 in/s, was 1/100 of the actual sound wave speed of water, 58386 in/s. The compressibility of the system during the simulations was less than 1.5%. The results compare very well between the simulation with the actual wave speed and the simulation with the reduced wave speed. All results presented here are analyzed using a sound wave speed of 583.86 in/s.

2.1 Modeling Fluid Tank Interface

The unique feature of the CEL capability is contact definition between the Eulerian material and the LaGrangian mesh using the general contact capability of Abaqus/Explicit. While general contact capability allows the very powerful all-inclusive general contact definition, it is often prudent to eliminate unnecessary contact surfaces from the CEL analysis to improve the efficiency.

It was also learned that CEL contact detection and enforcement at sharp corners poses numerical issues that require special handling. It is advisable to fillet sharp corners in realistic problems or avoid them completely if the problem definition is simplistic. In this particular problem, there are

two sharp corners at the bottom of both sides of the tank. If the bottom of the tank is modeled as LaGrangian shell elements, then liquid will penetrate and leak from the sharp corners during the simulation.

A simple modeling strategy to alleviate this mass loss and prevent the flow of fluid in the vertical direction at the tank bottom is to define a boundary condition on normal velocity and not enforce the contact constraint between the tank bottom and the fluid. Figure 4 shows the mass loss for cases when the bottom wall has a boundary condition applied and when there is no boundary condition but rather a CEL contact applied. As is evident from the Figure 4, using a boundary condition on normal velocity at the tank bottom wall eliminates the need to enforce CEL contact at sharp corners and eliminates any penetration/leakage from these sharp corners.

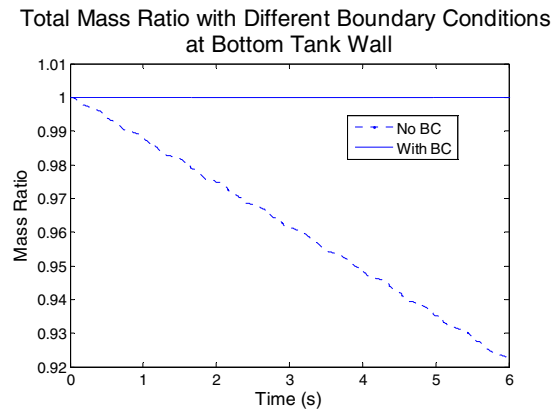


Figure 4. Mass ratio as a function of time with and without a boundary condition applied.

3. Lateral Excitation of Tank

Potential theory can be used to express the natural frequency of the fluid in the tank as

$$\omega_n^2 = gk_m \tanh(k_m h)$$

where for the first mode, $k_m = \pi/L$ [2]. For the tank geometry in this problem, the natural frequency is equal to 1 Hz.

The rigid tank is excited in the lateral direction using the following sinusoidal function with a driving frequency ω_d :

$$X(t) = X_0 \sin(\omega_d t)$$

Driving frequencies of $0.75 \omega_n$, $0.9 \omega_n$, $1.09 \omega_n$, and $1.3 \omega_n$ were used with an amplitude, X_0 , of 0.213 in for all simulations, and the results for free surface elevation are shown in Figure 5. This elevation was computed at the left side of the tank by using the volume fraction values of the first column of elements that the tank surface does not penetrate. The method for computing the free surface elevation is simply the summing of all of the water volume fraction values for the vertical column of elements multiplied by the constant element height. Even though the surface elevation is not measured directly at the left side of the tank, the surface height is practically identical when taken only a couple of elements away.

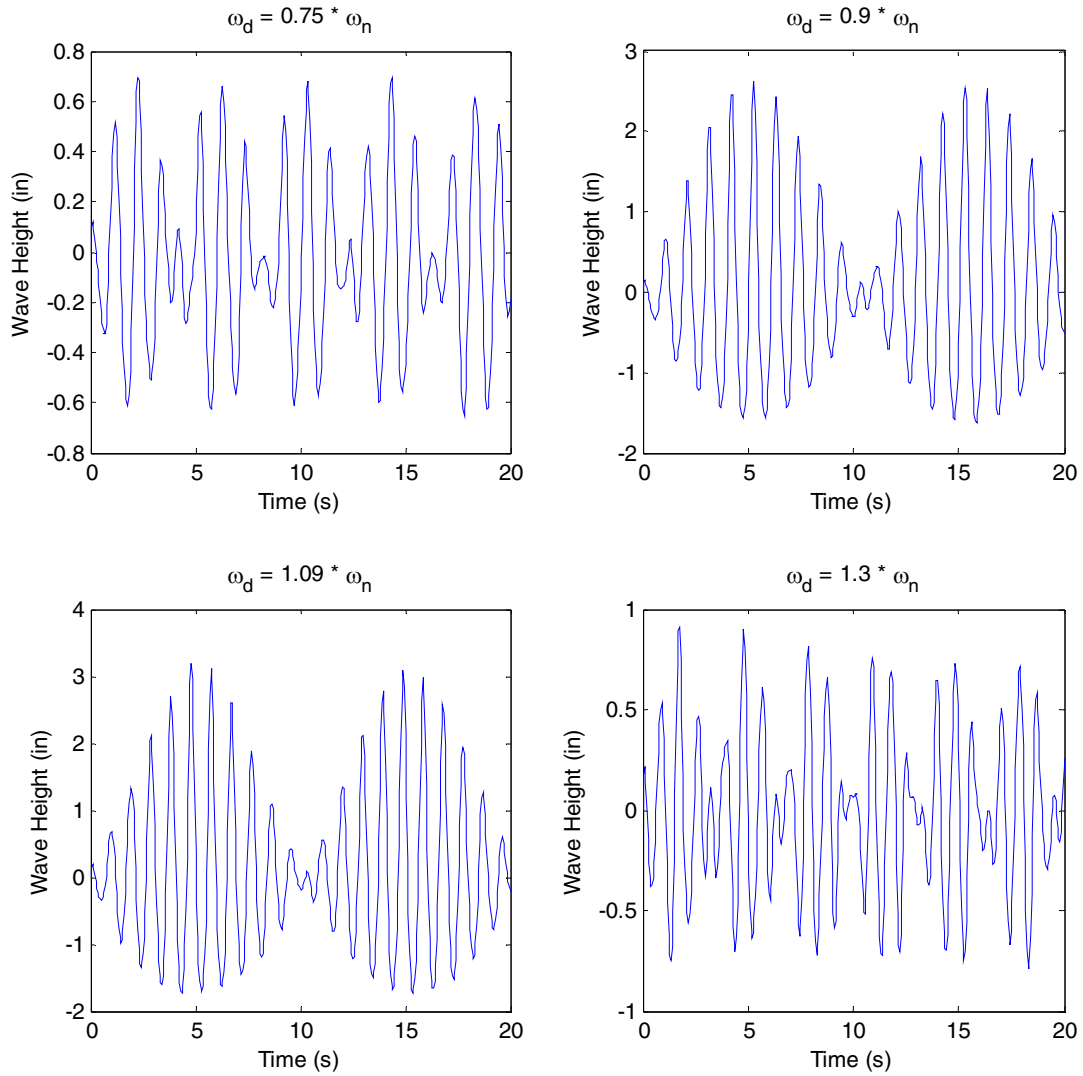


Figure 5. Free surface elevation as a function of time for the different drive frequencies.

These results show that the wave height varies sinusoidally, but the amplitude also shows a beating phenomenon. The analytical method presented by Faltinsen (2005) provide some validation of these results in that they also show a beating phenomenon [3]. The beating occurs at the difference between the natural frequency of the system and the driving frequency. This beating phenomenon is not seen in equations derived for steady-state applications [2].

A CFD solution generated in STAR-CCM+ (by CD-adapco) using a volume of fluids (VOF) model was also compared to the Abaqus results. The free surface height results show reasonable agreement, specifically the natural frequency, beat frequency, and wave height time history.

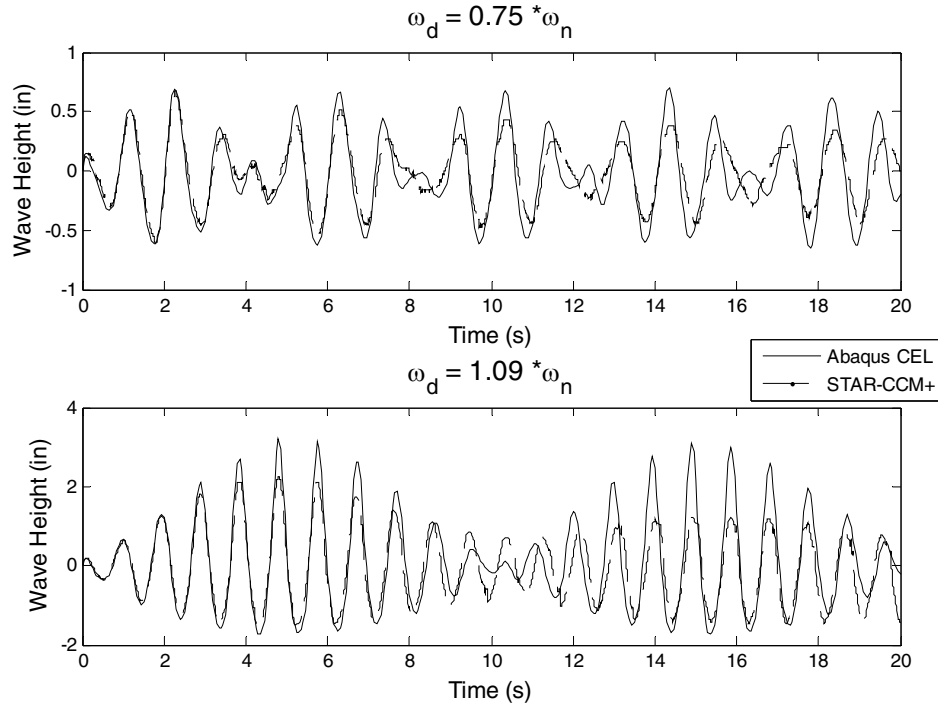


Figure 6. Comparison of Abaqus and STAR-CCM+ free surface height results.

4. Flexible Tank

Using the same model from the rigid tank analysis, the rigid constraint was removed to make the tank walls flexible, allowing for the tank walls to deform during the sloshing event. The tank walls have a thickness of 0.4 in and were assigned generic steel material properties. Because the flexible model increases the solve time, only one comparison with a driving frequency of $0.9 * \omega_n$ was simulated (0.9 Hz). The following figures show the free surface wave height and the tank displacement of a point above the water line. The flexible model shows a decrease in wave height as well as a change in natural frequency (Figure 7). The effect of tank flexibility can be seen in the higher-frequency component of the translational displacement of a tank node (Figure 8).

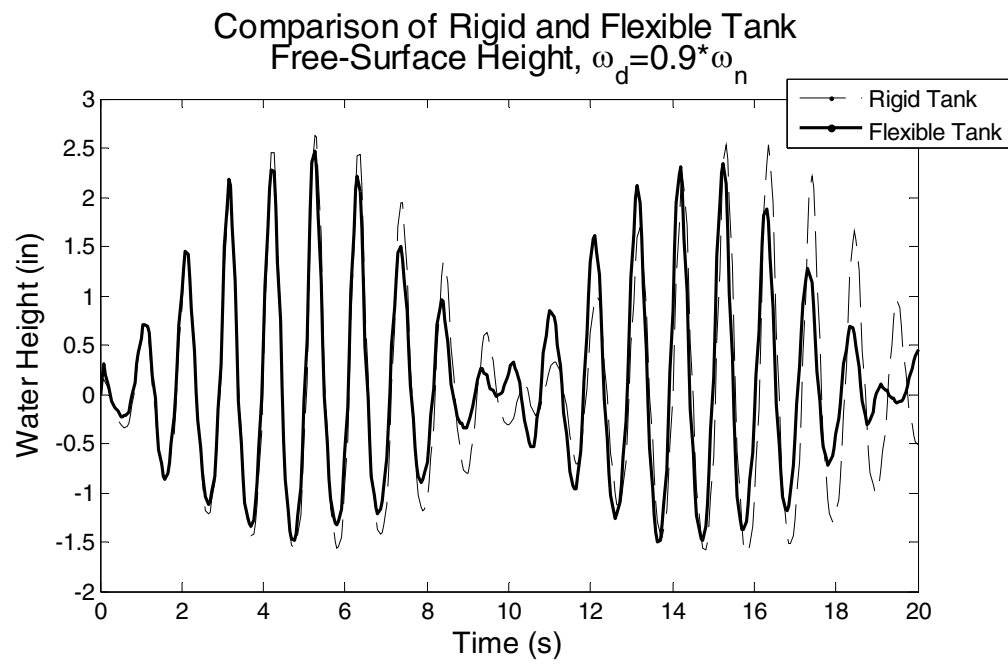


Figure 7. Comparison of rigid and flexible tank free surface height results.

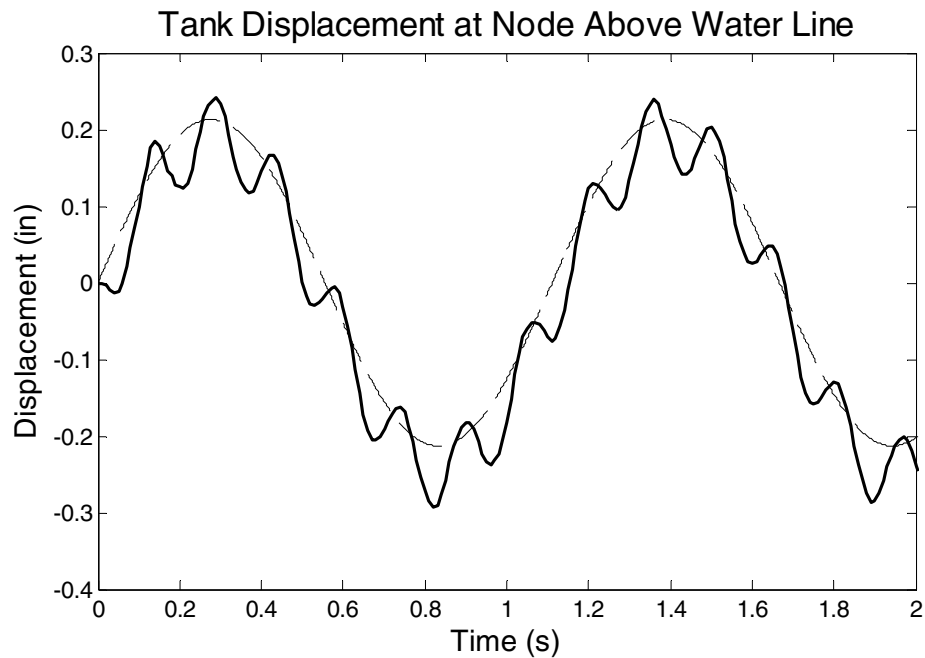


Figure 8. Tank flexibility shown through tank displacement as a function of time.

5. Summary

The CEL capability allows for the modeling of a tank sloshing problem in Abaqus. Several modeling assumptions were made to improve the accuracy and reduce simulation time. The sound wave speed input for the equation of state (EOS) material model is reduced to improve the solve time. An improved boundary condition helps avoid mass loss in the simulation caused by the numerical problems when sharp corners are included in the model. The solutions for a rigid tank force oscillation show the beating frequency at the difference of the driving frequency and natural frequency of the fluid, which is also reported in referenced literature. Additionally, the results are in reasonable agreement with those obtained from a similar simulation performed in STAR-CCM+. Furthermore, with the CEL capability, the tank geometry can be modeled as a deformable object, where stresses and deformations in the tank geometry can be recovered. This may be useful for problems where baffles made to decrease sloshing loads are constructed in the middle of the tank. Thus CEL not only provides a significant fluids capability but also a true fluid structure interaction for a certain class of problems.

6. References

1. Abaqus Version 6.8 Documentation, Dassault Systems Simulia Corp., 2008.
2. Ibrahim, Raouf A., "Liquid Sloshing Dynamics, Theory and Applications," Cambridge University Press, 2005.
3. Faltinsen, Odd M., Rognesbakke, Olav. F., Lukovsky, Ivan A., Timokha, Alexandar N., "Multidimensional modal analysis of nonlinear sloshing in rectangular tank with finite water depth." Journal of Fluid Mechanics, 2000, vol 407, pp 201-234.