Paper:

A Multiphysics Multiscale 3-D Computational Wave Basin Model for Wave Impact Load on a Cylindrical Structure

Solomon C. Yim and Wenbin Zhang

Ocean Engineering Program Oregon State University
Corvallis, OR 97331, USA
E-mail: solomon.yim@oregonstate.edu

[Received July 27, 2009; accepted October 29, 2009]

A multiphysics multiscale finite-element based nonlinear computational wave basin (CWB) model is developed using LS-DYNA. Its predictive capability is calibrated using a large-scale fluid-structure interaction experiment conducted in a 3-dimensional wave basin to determine wave impact on a cylindrical structure. This study focuses on evaluating CWB accuracy using two wave excitation conditions – plane and focused solitary waves – and two cylinder arrangements – single and multiple cylinders. Water surface elevation and water particle velocity are predicted numerically for the fluid domain, obtaining horizontal force, overturning moment, and dynamic pressure on the cylindrical structure and calibrated against experimental measurement. The CWB model predicts wave motion characteristics – water surface elevation and velocity, and integrated structural response – horizontal force and overturning moment, for the given wave conditions well. Computation time increases and the predictive accuracy decreases as nonlinear fluid-structure interaction becomes increasingly complex. A study of computation settings for improving computation performance showed that a high-performance parallel-computing hardware platform is needed to model details of highly nonlinear physics of fluid flow including wave breaking and turbulence.

Keywords: multiphysics, multiscale, fluid-structure interaction

1. Introduction

With computers becoming faster and more accessible, numerical modeling demand has grown for practical applications in coastal, ocean, and offshore engineering. Nonlinear fluid-motion characteristics, the multiphysics and multiscale nature of coupling different materials, and exigencies in understanding the physics of wave breaking, turbulence, wave impact on structures, and seabed friction make many fluid-structure interaction problems difficult to predict and analyze.

Numerical tsunami-propagation simulation using computational code such as MOST (Titov and Synolakis 1998), COMCOT (Liu et al. 1994), and TSUNAMI2 (Imamura 1996) requires large-scale laboratory experiments and field data for validation. The December 26, 2004, Indian Ocean tsunami was numerically simulated using a higher-order Boussinesq model (Watts et al. 2005). Developing a 3-dimensional (3-D) numerical model to computed solitary wave force on slender piles, the comparison of Liu (2006) showed that the numerical model predicts free-surface displacement, fluid-particle velocity, and dynamic pressure on piles, although significant disagreement appears among force on the cylinder.

Some of the recently developed commercial finite-element analysis (FEA) packages – e.g., MSC.Dytran, ANSYS, ABAQUS, FLUENT and LS-DYNA – specialize in explicit time integration and other functions dealing with highly nonlinear problems such as fluid-structure interaction. ANSYS incorporated an LS-DYNA solver with its own pre/postprocessing. MSC.Dytran evolved from an early DYNA-3D version combining the capabilities of PISCES. FLUENT has broad physical modeling capabilities and is applied to industrial applications, but its true strength lies in simulating confined-area fluid flow. LS-DYNA, developed by Livermore Software Technology Corporation, is a multiphysics code with explicit and implicit finite elements to simulate and analyze highly nonlinear physical phenomena involving structural and fluid contact and impact with large deformation (LSTC (2007)).

Some fluid-structure interaction (FSI) models in industry have been developed using commercial FE codes with arbitrary Lagrangian-Eulerian (ALE) formulation maximizing the two classical descriptions of motion – Lagrangian and Eulerian. The Lagrangian description is mainly used in structural mechanics due to its precise, straightforward tracking of free surfaces and interfaces between different materials. Lagrangian formulation has difficulty, however, in tracking large distortions without resorting to costly frequent remeshing. Eulerian description is widely used in computational fluid dynamics because it handles large distortion due to fluid particle movement efficiently.

Some FSI models in the industry use FE code with ALE formulation and a contact algorithm in LS-DYNA based on its unique modeling of contact and impact in coupled FSI problems. An FSI model differs from general structural mechanic models because large fluid-flow material deformation often severely distorts the mesh and loses accuracy. The ALE formulation used in LS-DYNA specifically minimizes such element distortion. We briefly review the literature on FE/ALE pertinent to LS-DYNA modeling and applications.

A numerical study on a wave propagation problem using the ALE formulation in LS-DYNA to model surface waves conducted by Nicolas (2007) confirmed the feasibility of the multimaterial ALE formulation and numerical convergence with mesh refinement. Other FE modeling of hydrodynamic hull-water impact load by Stenius and Rosen (2007) studied the angle-of-attack effect of impact, finding that solution stability depended strongly on mesh-density relation, and that lower mesh densities could be used if the pressure peak was negligible, such as in structural response and fluid structure interaction, confirming the appropriateness of a relative coarse mesh in FSI modeling. Wave mechanics simulated by Tokura and Ida (2005) with a model containing water, air, a wavemaker, and structure was limited to 2-dimensional (2-D) geometry and loads. The predictive capabilities of ALE formulation and FSI were evaluated by Olovsson and Souli (2002), who stated that improved multimaterial ALE made LS-DYNA more efficient in analyzing large deformation processes. Their basic computational models were, however, only for solid mechanics problems.

Because ALE formulation is often time-consuming, attempts were made to implement it with massive parallel processing (MPP) in LS-DYNA, as evaluated by Lin (2002), who stated that although MPP increased execution speed, MPP LS-DYNA scalability at that time was inadequate for practical coupled FSI problems.

Despite the many numerical studies discussed above, LS-DYNA predictive capability in modeling large-scale 3-D FSI experiments was not examined. This study therefore assesses state-of-the-art numerical modeling in FSI experiments conducted in a large-scale 3-D physical wave basin. For this purpose, an experiment on wave impact on a cylinder was conducted in the 3-D wave basin at the Oregon State University Hinsdale Wave Research Laboratory (OSU HWRL). Observations from comparison between numerical predictions using multiphysics multiscale computational software LS-DYNA and measured large-scale experimental results are presented to assess numerical predictive performance.

2. Large-Scale 3-D Wave Basin Model Test Overview

Experimental model tests of plane and focused solitary wave impact on a cylinder were conducted in the large-scale 3-D directional OSU HWRL wave basin, first to determine physics and obtain accurate wave run-up, pressure, impact and overturning moment on the cylinder and, second, to obtain data for validating numerical wave basin models. The wave basin, which is 48.8 m long, 26.5 m wide and 2.1 m deep, uses a directional piston wavemaker.

Figure 1(a) shows a physical model of a typical solitary wave impacting on a single cylinder. Note that, in this case, an arc is clearly observed on the crest of the solitary wave focusing on the cylinder. The clear, undistorted reflection of the cylinder, the impacting wave, and the structural frame above the wavemaker from the water-free surface indicates a perfectly plane still water surface behind the cylinder, confirming the expected calm water. Three wave input conditions are used – Eq. (1) plane-normal (nonbreaking) incident solitary waves, Eq. (2) nonbreaking focused solitary waves, and Eq. (3) breaking focused solitary waves. The waveform of a typical (nonbreaking) solitary wave is described by Dean and Dalrymple (1984) as follows:

$$\eta(x,t) = H \operatorname{sec}h^2(k(x-Ct)) \quad . \; . \; . \; . \; . \; . \quad (1)$$

$\eta(x,t)$ is water surface elevation, H maximum wave height, and C wave celerity. Parameter k is the "wave number" governed as follows:

$$k = \sqrt{\frac{3H}{4h^3}} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (2)$$

h is water depth. The experiment involved two cylinder configuration tests: Eq. (1) a single cylinder (**Fig. 1(a)**), and Eq. (2) three multiple-cylinder arrangements as shown in **Fig. 1(b)**. For the single cylinder, we tested three water depths – 0.75, 0.6, and 0.45 m. For multiple-cylinder arrangements, we conducted one set with three cylinders of identical diameter, and the distance between two front noninstrumented and dummy cylinders is 3 times the cylinder diameter and uses a water depth of 0.75 m. The second set of 3-cylinder tests was conducted with two front dummy cylinders at a double cylinder diameter and a water depth of 0.75 and 0.6 m. In each test case, the instrumented cylinder was 22.1 m from the wavemaker on the basin's center line.

3. Numerical Model Description

3.1. Model

The numerical model of wave impact on a cylinder in the 3-D directional wave basin was developed using LS-DYNA, a multiphysics-explicit, implicit finite-element code for analyzing and simulating highly nonlinear physical phenomena. The fluid (water) in the computational wave basin (CWB) is governed by compressible Navier-Stokes equations and solved numerically and explicitly using an arbitrary Lagrangian-Eulerian (ALE) formulation as follows:

$$\begin{aligned}\frac{D\rho}{Dt} + \rho\nabla\cdot\vec{u} &= 0\\ \frac{D\vec{u}}{Dt} + \vec{u}\cdot\nabla\vec{u} &= -\frac{1}{\rho}(\nabla P + \frac{2}{3}\mu\nabla\cdot\vec{u}) + \frac{\mu}{\rho}\nabla^2\vec{u} + \vec{g}\end{aligned} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (3)$$