Computers and Structures 138 (2014) 24–35

Contents lists available at ScienceDirect

Computers and Structures

journal homepage: www.elsevier.com/locate/compstruc

Hydroelastic analysis of hull slamming coupling lattice Boltzmann and finite element methods

Alessandro De Rosis [a], Giacomo Falcucci [b], Maurizio Porfiri [c,*], Francesco Ubertini [a], Stefano Ubertini [d]

[a] DICAM, University of Bologna, Bologna 40136, Italy
[b] Department of Technologies, University of Naples "Parthenope", Naples 80143, Italy
[c] Department of Mechanical and Aerospace Engineering, Polytechnic School of Engineering, New York University, Brooklyn, NY 11201, USA
[d] DEIM – Industrial Engineering School, University of Tuscia, Viterbo 01100, Italy

ARTICLE INFO

Article history:
Received 11 October 2013
Accepted 26 February 2014
Available online 22 March 2014

Keywords:
Finite element method
Fluid–structure interaction
Hull slamming
Lattice Boltzmann method

ABSTRACT

We propose a computational approach to study the response of compliant structures to impulsive loading due to impact on the free surface of a weakly compressible viscous fluid. The fluid flow is analyzed through the lattice Boltzmann method and the structural response by the finite element method. The time discontinuous Galerkin method is used to integrate the structural dynamics in time, and an explicit coupling strategy with the same time-step for the fluid and the solid is employed. Numerical results are compared to analytical and experimental findings for rigid and compliant wedges.

1. Introduction

Impacts between sea waves and ship hulls are generally responsible for large impulsive loadings. This phenomenon, known as hull slamming, occurs when the ship emerges from the water surface and then plunges again. The generated impulsive forces may induce considerable vibrations and local structural damages on the ship due to stress concentration and fatigue. Therefore, the accurate prediction of hydrodynamic forces acting on ship hulls plays a crucial role in the design of marine structures, see for example [1].

A closely related problem to hull slamming is the impact of a wedge on a water free surface. Such problem has received considerable attention in the research community for its geometric simplicity which, nonetheless, allows for rich nonlinear dynamics representative of hull slamming. In the vast majority of these studies, the wedge is considered as a rigid body. The first effort on this topic is reported in [2], where the impact of a seaplane during landing is modeled as a two-dimensional (2D) wedge entering quiescent water. Therein, the elevation of the water surface during the impact and gravity effects are neglected. Neglecting gravitational forces is very common across literature on hull slamming based on the fact that fluid acceleration due to the hull impact is much larger than the gravitational acceleration. In [3], the so called flat-disc approximation is adopted, where the actual shape of the impacting body in the contact region is modeled as a plate and linearized boundary conditions are imposed on the initially undisturbed free surface. The solution is obtained by using potential flow theory and neglecting gravitational force. Under these assumptions, the velocity potential and its spatial derivatives can be analytically obtained. Such theory is referred to as Wagner's theory and can be implemented on arbitrary shaped 2D bodies provided that the deadrise angle is small and no air trapping is present.

In [4,5], this approach is generalized to an arbitrary body section using conformal mapping techniques. The effect of structural compliance on the dynamics of the impacting wedge is studied in [6,7], by adapting the impact theory developed in [3]. Specifically, fluid–structure interactions during slamming of sandwich panel hulls are investigated in [6]. Therein, the face sheets of the sandwich panel are modeled using Kirchhoff plate theory, whereas the core is modeled using higher-order transverse shear and transverse normal deformation theory. Experimental results on water slamming of sandwich structures are presented in [8–11].

In the previously mentioned studies, the flow is assumed to be incompressible, yet a few analyses demonstrate the important role of compressibility effects on slamming forces. For example, compressible flows are considered in [12,13], where an acoustic approximation is used to describe the hydrodynamics of solid

* Corresponding author. Tel.: +1 7182603681.
E-mail addresses: giacomo.falcucci@uniparthenope.it (G. Falcucci), mporfiri@nyu.edu (M. Porfiri), francesco.ubertini@unibo.it (F. Ubertini), stefano.ubertini@unitus.it (S. Ubertini).

http://dx.doi.org/10.1016/j.compstruc.2014.02.007
0045-7949/

bodies impacting the water. Such approximation is used in [14] to describe the fluid motion for impacting rigid and elastic structures. Therein, three configurations are studied: a rigid wedge impacting the water with a constant uniform velocity, two rigid beams that are connected by a pin and a rotational spring, and a rigid wedge carrying a simple oscillator. In [15], a review of methods for both incompressible and compressible flows is presented; in addition, a stochastic extension of the impact load theory in [3] is proposed to account for air trapping effects. A thorough literature review and comparison between existing reduced-order modeling approaches is reported in [16] and similar findings for impulsive loading of fluid-immersed bodies are presented in [17,18].

Computational fluid dynamics (CFD) is used to study water slamming problems in [19–28]. The dynamics of rigid bodies slamming at a constant velocity is numerically investigated through boundary element and finite difference methods in [28,24], respectively. In [22], experimental data on the water impact of a free-falling rigid wedge are compared to predictions from different numerical methods, including boundary and finite element methods, and analytical results [3,29,30]. A finite-volume numerical analysis of the entry force and velocity for rigid wedges impacting the water surface at a constant velocity is presented in [23]. These findings are compared to experimental results at various water entry velocities in the presence or absence of gravity. In [26], drop-test experiments are conducted on rigid wedges and compared to numerical simulations. Therein, the smoothed particle hydrodynamics mesh-free Lagrangian method is used to model the fluid flow. Euler–Lagrange coupling with damping effects is presented in [19] to minimize the effect of unphysical oscillations in the estimation of slamming forces for rigid wedges. A coupled Lagrangian and Eulerian formulation is considered also in [21] to analyze rigid and flexible wedges with a focus on jet flows near the edges of the wetted hull and structural failure. In [25], a CFD approach based on a finite element analysis is implemented to estimate the stress field on the fluid–structure interface of an elastic wedge slamming with constant velocity. An implementation of the boundary element method is proposed in [27] to investigate slamming of a flexible cylindrical shell. A domain-decomposition strategy to study the bottom slamming of a very large floating structures is presented in [20], and further advancements and comparison against experimental findings are presented in [31].

This work represents a first attempt of modeling the fluid–structure interaction in hull slamming with a combined lattice Boltzmann-finite element method. The lattice Boltzmann method (LBM) is used to study the fluid flow for a viscous weakly-compressible fluid. This method is a fluid simulation technique based on a set of particles streaming and colliding in a discrete space–time universe and moving on a lattice mesh through fixed velocity vectors [32–35]. Due to its intrinsically mesoscopic nature, it has several advantages as compared to other conventional CFD methods, which are based on the conservation laws of the macroscopic properties. Specifically, the distinctive features of the LBM are the conceptual and practical simplicity of the numerical scheme and the computational efficiency in simulating flows with complex geometries. Moreover, the pressure field and the stress tensor are locally available and the non-localities are linear, because advection proceeds along constant straight lines defined by the particle discrete speeds. In the last two decades, the LBM has been successfully employed for the simulation of several phenomena of technical interest, including aerodynamics, multiphase flows, microflows, wave propagation, and soft matter systems [36–42]. In addition, the LBM has been recently applied to the study of fluid–structure interactions [43–49] and in the framework of immersed boundary approaches [50–55].

In the proposed method, the structure is modeled using the classical linear Euler–Bernoulli beam theory, and Hermitian and linear basis functions are used for finite element discretization in space. The structural dynamics is analyzed using the time discontinuous Galerkin (TDG) procedure presented in [56–59]. The LBM and TDG scheme are coupled through a staggered-explicit coupling strategy, adopting the same time sequence for both solvers. As the LBM is constructed on a regular fixed Cartesian lattice, the solid boundary does not lie on the nodes and moves “immersed” in the fluid domain. This removes the computationally demanding need of generating body-fitted moving meshes and makes the proposed method a “non-boundary-fitted” technique. Following the approach presented in [60–62], we use a high-order no-slip wall boundary condition formulation and solid motion is performed through an enhancement of the refill procedure proposed in [43].

The paper is organized as follows: first, the numerical model is described, with a review on the lattice Boltzmann method and the adopted boundary condition for the analysis of fluid–structure interactions. Therein, we also describe the finite element method for structural solution. Then, numerical results are presented for three different structural characteristics: a rigid wedge, two rigid beams connected through a spring, and a deformable wedge. The results are compared to analytical and experimental data in the literature to demonstrate the accuracy of the proposed methodology.

2. Numerical model

We study the response of an elastic frame that impacts the free surface of an otherwise quiescent viscous weakly-compressible fluid. We focus on 2D geometries and we consider small displacements of the elastic structure. In addition, we neglect the effect of gravitational forces and surface tension on the dynamics of the fluid free surface, which is described as a traction-free boundary. Gravitational forces are retained in the structural analysis especially to estimate impact speed in drop-tests.

2.1. The fluid: lattice Boltzmann method

The fluid analysis is based on the lattice Boltzmann equation (LBE), which is a minimal form of the Boltzmann kinetic equation, that has been proven to be quite successful for the quantitative description of a broad class of complex flow phenomena [33]. Since the LBE is amply described in the literature [34,35,38], here, we revisit only the basic concepts behind its formulation. The LBE reads as follows:

$$f_i(\mathbf{x}+\mathbf{c}_i\Delta t, t+\Delta t) - f_i(\mathbf{x},t) = -\frac{1}{\tau}(f_i(\mathbf{x},t) - f_i^{eq}(\mathbf{x},t))\Delta t, \quad i = 1,\ldots,m, \tag{1}$$

where the particle distribution function $f_i(\mathbf{x},t)$ corresponds to the probability of finding a fluid particle at site $\mathbf{x}$, at time t, and moving at velocity $\mathbf{c}_i$. In addition, $\Delta t = \Delta x/\|\mathbf{c}_i\|$ is the lattice time step and Δx the lattice grid spacing. In Eq. (1), it is assumed that, at each site, particles can only move along a finite number of directions m. The left-hand side of Eq. (1) describes the molecular free-streaming, whereas the right-hand side represents the BGK inter-particle collisions described through relaxation towards local Maxwellian equilibrium f_i^{eq}, on a time-scale τ, called relaxation parameter [63]. In the present work, 2D simulations are performed and particle velocity space discretization is done through the D2Q9 nine-speed model, $m = 9$. The equilibrium distribution functions read as follows:

$$f_i^{eq}(\mathbf{x},t) = w_i \times \frac{\rho(\mathbf{x},t)}{\rho_f}\left(1 + \frac{\mathbf{c}_i\cdot\mathbf{v}(\mathbf{x},t)}{c_s^2} + \frac{(\mathbf{c}_i\cdot\mathbf{v}(\mathbf{x},t))^2}{2c_s^4} - \frac{\|\mathbf{v}(\mathbf{x},t)\|^2}{2c_s^2}\right), \tag{2}$$