Numerical Simulation of Heavy Water Shipping

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Background and Motivation

Rough-sea conditions can result in shipping of water on the deck of vessels. In particular, our ongoing investigation is focused on the bow-deck wetness in head-sea conditions for a moored ship, i.e. without forward speed. Though in practice three–dimensional effects matter, two–dimensional investigations are undertaken to gain basic insights, before developing more realistic three-dimensional approaches.

In previous Workshops, a combined numerical-experimental analysis has been presented. In particular, a potential flow model has been assumed and a Mixed Eulerian-Lagrangian method has been adopted to solve the unsteady interaction between the body and the free surface. The Boundary Element Method (BEM) has been used as numerical solver. In the experiments, a two-dimensional nearly-rectangular ship model has been placed in a narrow wave flume, and the first water-on-deck event due to incoming waves generated by a flap wavemaker has been investigated. The model is fixed and resembles the centerplane of a ship. Comparisons confirmed the validity of the adopted flow model and the efficiency of the BEM in capturing the water shipping from a global point of view as well as in predicting some local features, such as the initial pressure along a superstructure under the impact of the shipped water.

On the other hand, important limits of the model and research challenges have been evidenced:

A) **Initial plunging wave, air cushioning and bubbly flow** In the experiments, the water shipping has been observed to start always in the form of a water front plunging onto the deck. This stage is localized both in space and in time, and it is responsible for water impact with the deck near the bow. A cavity, entrapping air, is formed and stretched during the flow evolution, and finally collapsing into bubbles (see figure 1). From a simplified analysis based on a combined use of experimental and numerical means, we found that the collapse of the air cavity may imply a substantial increase of the pressure which can be responsible for deck damages.

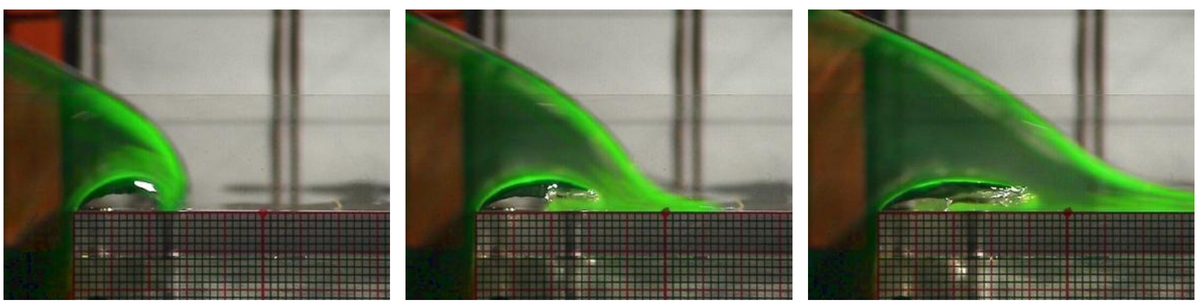

Figure 1: Two-dimensional water-on-deck experiments. Water impact with the deck and cavity formation during the initial stages of the water shipping.

The initial plunging has been numerically captured by enforcing a 'continuous' Kutta-like condition at the edge of the deck (*cf.* [1]), with a good agreement between numerics and experiments. Surface-tension effects have been numerically discussed in [2]. The short-time post-impact phase would require a matching with a high-speed local solution, as well as the incorporation of a proper model to account for the air compression in the cavity. This stage has not been numerically investigated. The final collapse of the air cavity into bubbles cannot be handle by the BEM.

B) **Late water overturning and wave breaking** Later on, the flow of the shipped water resembles a dam breaking-type flow (*cf.* [3]). Once the water reaches a superstructure, a second impact takes place with the developing of a fluid jet rising the wall. Initially, flow accelerations dominate the pressure exerted on the structure. Later on, the gravity matters and finally determines the water run down. This backward fluid motion is characterized by water overturning and plunging onto the underlying water still flowing towards the superstructure (see figure 2). This phenomenon is responsible for a second sharp increase of the pressure acting on the structure, with a secondary peak of the same order of magnitude as the first one related to the initial water impact, [1]. Since post-breaking cannot be handled by a BEM, this second stage has not been numerically analyzed.

Figure 2: Two-dimensional water-on-deck experiments. Water overturning and breaking after the water impact with a superstructure during the later stages of the water on deck.

Domain Decomposition

The modeling of the free-surface fragmentation eventually featured both in stage A and in stage B requires new numerical means. In the literature, several field methods have been proposed to handle flows with free-surface breaking fragmentation which are not treatable by the BEM. Also, viscous effects cannot be recovered easily by BEM. On the other hand, the latter is more efficient and accurate than field methods to describe free-surface flows.

On this ground, we combine both types of solvers within a Domain Decomposition (DD) approach, [4]. The BEM is used to describe most of the fluid-flow domain, far enough from the body, while the field method can capture the flow evolution near the bow and onto the deck.

Our implementation of the field method is rather standard. The fluid-motion equations are discretized on a staggered cartesian grid, and solved for the primitive variables velocity and pressure. Viscous and surface tension effects are modeled, though those terms are switched off in the present analysis. Consistently, the free-slip condition along rigid boundaries and the pressure continuity across the water-air interface are enforced. The free-surface evolution is modeled by a Volume-of-Fluid (VOF) technique, where the interface is reconstructed by means of the passive scalar field $f(\boldsymbol{P}, t) \in [0, 1]$ representing the local water-volume fraction. Details for the numerical algorithm can be found in [5].

Within the domain decomposition approach, BEM and VOF regions are connected by a transmission boundary, through which the two sub-domains exchange information. In particular, the velocity distribution computed by the BEM is used in the boundary conditions for the field method. The latter returns the pressure distribution which is used, through the Bernoulli equation, to update the velocity potential enforced along the transmission boundary. In the numerical implementation the time step is governed by the stability constrains of the VOF solver, more stringent than those requested by the flow evolution in the BEM region, where a standard fourth-order Runge-Kutta method is used.

As a preliminary study to verify the domain decomposition algorithm, we consider the break of a dam (height h) and study the fluid motion along a dry deck. The initial length of the reservoir of water is l. A sketch of the problem and of the domain decomposition is given in the left plot of figure 3. The VOF region is rectangular shaped and its boundary

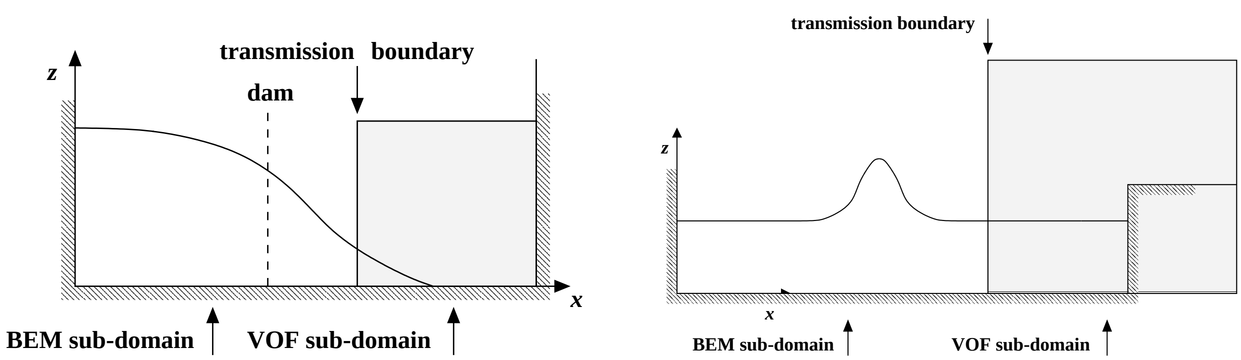

Figure 3: Definition of BEM and VOF regions for the problem of dam breaking followed by the impact with a vertical wall (left), and for the problem of water on deck in shallow water conditions (right).

is characterized by the interface (left side), the 'deck' (bottom side), and two other rigid portions (right and top sides). As already mentioned, the velocity computed by the BEM is enforced along the transmission boundary, while a free-slip condition is imposed along the remaining portions of the boundary. At time $t = 0$, the dam breaks and the fluid flows along the deck. At the beginning, the VOF region does not contain water and the field computations start only at a time $t^* > 0$, after the water front passed the transmission boundary. The BEM solution is used to initialize velocity, pressure and f everywhere within the VOF sub-domain. From t^* on, the BEM sub-domain will be limited in the rightward extent by the transmission boundary. Since a Lagrangian algorithm is used in the BEM sub-domain, the free-surface points entering the VOF sub-domain are eliminated. When needed, new free-surface points are introduced in the BEM domain by using cubic-spline interpolation procedures. Figure 4 gives the free-surface configuration for $t = 1.25\sqrt{h/g}$ after the dam break (left plot), and the water-front propagation along the deck (right plot) in the case of $l = h$. The DD solution (circles, transmission boundary at $1.5h$ from the dam) is compared with the full BEM (lines) and the full VOF (squares) solutions. The three solutions agree quite well both from a global (free-surface snapshot) and from a local (water-front

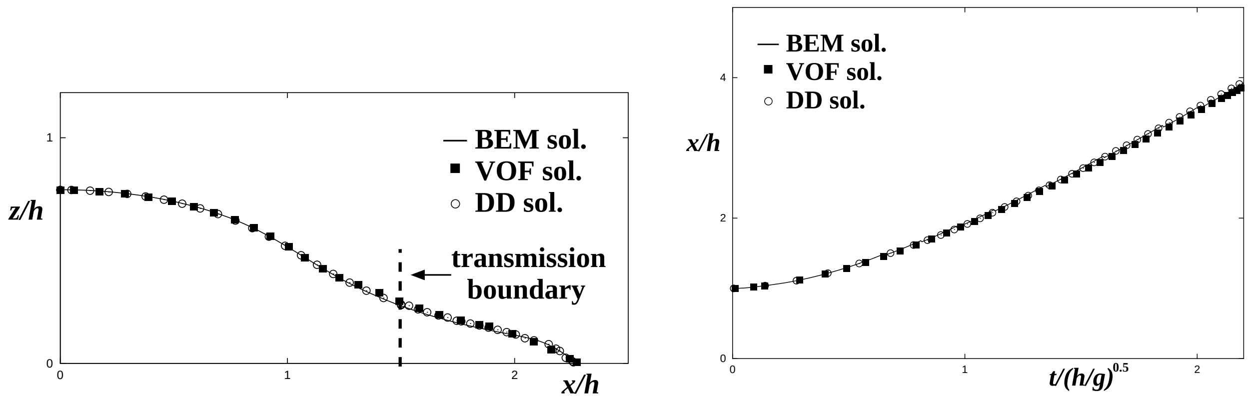

Figure 4: Dam-Breaking problem. Left: free surface configuration at $t = 1.25\sqrt{h/g}$. Right: water-front evolution. DD results (circles, transmission boundary at $1.5h$ from the dam) are compared with BEM (lines) and VOF solutions (squares). The height and length of the reservoir of water delimited by the initial dam are both h.

propagation) point of view. In more detail, the water-front evolution obtained by the full VOF appears a bit slower than the others, and in less agreement with the BEM solution than the DD simulation. This is reasonable since the latter was initialized by the BEM solution. The comparison gives reasonable verification both of the VOF solver and of the DD approach.

We now consider the more complex case of the water impact occurring when a vertical wall is placed downstream the dam. The studied case is the same discussed in [6]. In particular, the reservoir of water has a length $l = 2h$ and the wall

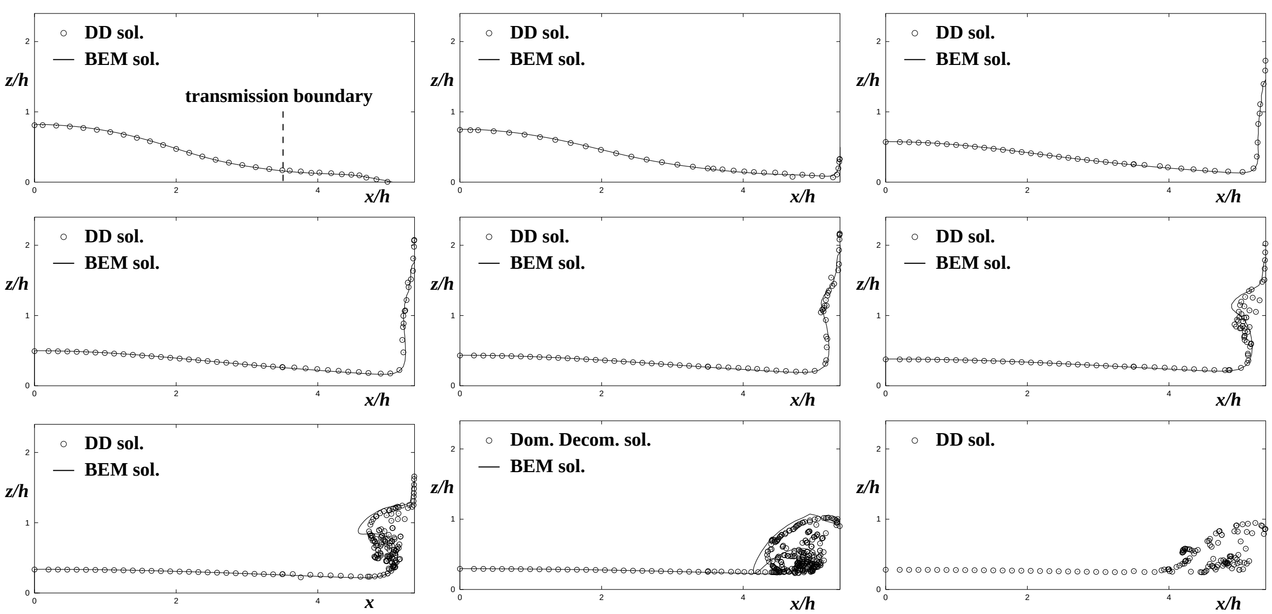

Figure 5: Dam-Breaking problem ($l = 2h$) and impact with a vertical wall at $3.366h$ far from the dam. Free surface configurations at $t = 2.2, 2.6, 3.6, 4.1, 4.6, 5.1, 5.6, 6.2$ and $6.4\sqrt{h/g}$. Time increases from left to right and from top to bottom. DD results (circles) are compared with BEM results (lines).

is placed at $3.366h$ from the initial dam. In the DD simulation the transmission boundary is taken at $1.3h$ from the dam. Snapshots of the free-surface evolution are given in figure 5, where the DD solution (circles) is compared with full BEM simulation (lines). The time increases from left to right and from top to bottom ($t = 2.2, 2.6, 3.6, 4.1, 4.6, 5.1, 5.6, 6.2$ and $6.4\sqrt{h/g}$). As we can see the overall agreement between the two results is promising. The initial impact and the water rise up along the vertical wall are well captured by the DD approach. The results of the two methods start to diverge in the late stages, during the water run down, when the backward plunging is formed, finally hitting the underlying water. In particular, in case of the DD solution, the impact phenomenon occurs earlier and closer to the vertical wall.

From our water-on-deck experiments, the late water overturning and wave breaking determine a second pressure peak on the structure hit by the water. We can expect that the different shape of the plunging water and the different impact position will result in different predictions of the pressure peak on the vertical wall. However, we cannot quantify this before we have studied the continuation of the BEM result with a field method. The sensitivity of the pressure field to the details of the flow field has not been investigated, so far. The last time instant shown in sequence 5 refers to the post-impact phase that cannot be handled by the BEM, so only DD results are given.

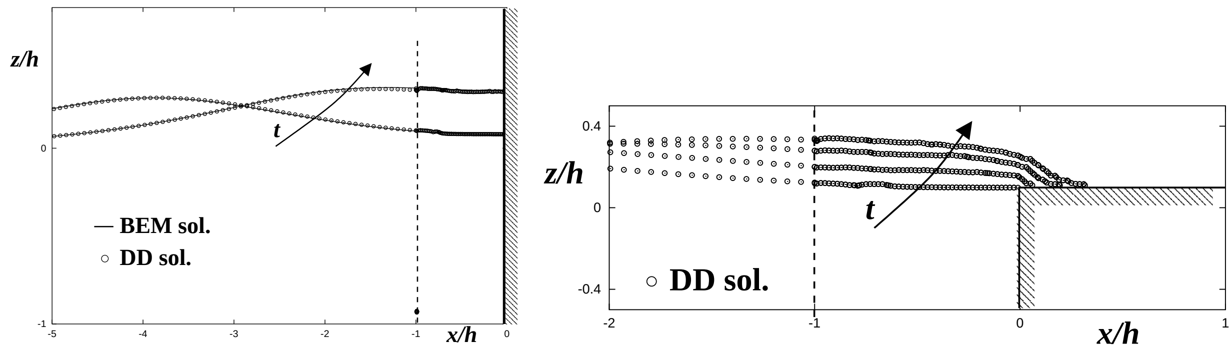

Figure 6: Left: Run-up of a solitary wave with amplitude $A = 0.3h$ along a vertical structure. Free-surface configurations at two time instants by BEM (lines) and DD (circles) methods. The vertical axis is enlarged with respect to the horizontal one. Right: Water-on-deck phenomenon in the case of $f = 0.1h$ due to a solitary wave with amplitude $A = 0.3h$. Free surface evolution by DD method.

We finally study a prototype problem closer to the shipping of water. In particular, we have studied the water shipping caused by a solitary wave on a rectangular structure with draft equal to the water depth h. In the DD simulations the VOF domain is rectangular shaped and the deck structure is seen as an internal rigid obstacle (see the right sketch in figure 3). The left plot of figure 6 shows two free-surface configurations during the water run-up along the vertical 'bow'. The amplitude of the incident solitary wave is $A = 0.3h$. The DD results (circles, transmission boundary placed at h from the bow) agree quite well with the full BEM results (lines). The right plot of the same figure gives the DD evolution during the water shipping, for a freeboard $f = 0.1h$. A special treatment of the flow field is not needed in the field method at the edge of the deck.This is different from the BEM implementation. The plunging-wave phase is the natural consequence of the flow evolution after the water exceeded the freeboard. In the considered example, due to the specific flow conditions, this phenomenon is rather small and it is not captured by the DD solver, for the adopted degree of resolution. The grid dependence of the solution will be further studied in the future.

We are presently developing the domain decomposition approach for dealing with more general two-dimensional 'ship' geometries, in particular with finite draft of the body in deep water, where arbitrary shapes of the transmission boundary have to be dealt with.

A physical discussion of the post-breaking stages will be reported at the Workshop, based on new numerical simulations and our experiments.

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Discussion Sheet

Abstract Title :	Numerical Simulation of Heavy Water Shipping		
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First Author :	Greco, M.		
Discusser :	D.Howell Peregrine		

Questions / Comments :

The air trapped by water falling on deck is very similar to examples we have studied of water overtopping a breakwater. See Walkden, Wood, Bruce & Peregrine (2001) Coastal Engng. 42 pp257-276 (also available from publication list on www.maths.bris.ac.uk/~madhp). We were very surprised at the high pressures within the air pocket. Note the time scales of the pressure records.

Author's Reply :
(If Available)

Author did not respond.