Nonlinear air-water interface problems through a BEM-Level set domain decomposition

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Several water flow problems of practical interest are characterized by fluid regions where the flow evolution is efficiently described by the potential theory, and other regions where this model is not valid. For instance, confined fluid areas can experience large air-water interface deformations followed by wave breaking and fragmentation phenomena. Limited water portions can be characterized by substantial vorticity generation due to water-water or water-structure interaction. In these cases the surrounding fluid domains can be slightly affected by such events.

The ship hydrodynamic field is full of similar circumstances. The water-on-deck problem represents an example. In this case, compact masses of water enter the ship deck and the subsequent motion can result in important loads for the deck superstructures. On a long time scale, water breaking, air entrainement and vorticity generation are expected to occur. The later water-off-deck phase will cause the re-entering of water in the sea surrounding the vessel. As a result, near the vessel the free surface cannot be modeled as a smooth surface. Both the water shipping event and the final water-entry phase can involve substantial induced water loads on the vessel and large movements of the ship. Therefore related phenomena are of great interest for ship hydrodynamics, both from the operability and safety points of view.

Due to the large free-surface deformations involved, a nonlinear analysis is needed. Before breaking and/or vortex shedding events, potential flow theory can capture accurately and with computational efficiency the involved flow evolution and predict connected loads and motions. After that, in the water regions where such phenomena occur and develop, this model has to be substituted by more general methods suitable to track the free surface deformations after the breaking, to handle the flow vorticity introduced in the fluid domain and to model the entrapped air.

The present research activity is aimed to develop a numerical method able to simulate such ship flows and to adapt itself to the specific analyzed problem for an efficient and suitable solution. This has been done by considering a domain-decomposition strategy (see *i.e.* Quarteroni and Valli 1999, Campana and Iafrati 2001) .
In previous studies (see *i.e.* Greco *et al*. 2002) this approach has been investigated by using a Boundary Element Method (BEM) in the fluid region where no breaking of the free surface occurs, and a field method in the rest of the fluid domain. The latter solves the Navier-Stokes equations and captures the free surface deformations through a single-phase Volume-of-Fluid method (VOF). Such study analyzed the use of different coupling strategies. Besides its versatility and robustness, the used method

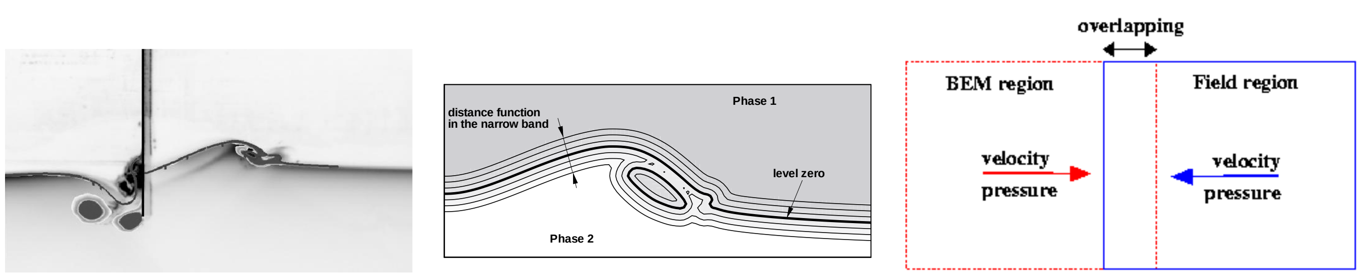

Figure 1: Left: experiments of an advancing vertical plate. Level-set results are compared with experiments (background, Colicchio *et al.*, 2003). Center: definition of the air-water interface within the Level-set technique. Right: coupling strategy within the domain-decomposition approach referred to as procedure *b* in Greco *et al.* (2002).

showed limitations. The applied field method is correct to the first order both in space and time. So it becomes unreliable for large time scale phenomena where accuracy is an important target. The VOF method is very good in preserving the fluid mass, but it presents problems when reconstructing the free surface. Generally the presence of air affects the water behavior when high deformations of the interface occur. In particular, in case of sufficiently large regions of entrapped air, the air cushioning may change substantially the surrounding pressure field and therefore the related induced loads on close enough structures.

The latter aspects pushed toward an alternative domain-decomposition method whose field counterpart is more suitable to handle the above tasks. The alternative is characterized by the coupling between the BEM and a Navier-Stokes solver using a Level-set technique (Colicchio *et al*. 2003) to capture the air-water interface. Both boundary and field solvers are accurate to the second order in time. Since the field solver handles two-phase flows, the air problem is also simulated in the BEM sub-domain. Both methods have been extensively verified and validated by investigating problems of naval interest. Systematic water-on-deck studies in terms of wave and ship parameters have been carried out by using the BEM method and reported for instance in Greco (2001). Level-set ability of analyzing the phenomena of interest has also been deeply investigated and demonstrated (see *i.e.*Colicchio *et al*. 2003). To the purpose, left plot of figure 1 shows a snapshot of the flow pattern around an advancing vertical plate (black straight line). The plot shows the comparison of the numerical method with experiments for the same case (background image in the figure) and demonstrates the capability of the Level-set in capturing the air-water interface (solid line), the vorticity evolution (contour-lines) and the air entrainement.

The coupling we want to handle is challenging since it has to deal with cases where (1) the air-water interface interests the overlapping and (2) can be highly deformed across such region. In this context a substantial issue is represented by the Level-set variables of interest (pressure, density, velocity) smoothed across the interface, which is modeled as a varying density layer with finite thickness (see center sketch in figure 1). Differently, in the BEM zone the interface is a line and therefore the involved variable gradients can be quite large. Additional information about velocity and pressure distributions around the transmission boundary are required to carry on a proper variable smoothing consistently with the Level-set approach. The challenge of properly connecting such different behaviors is balanced by a more powerful and efficient instrument for analyzing the wave-ship interactions. The developed method can be more correctly referred to as a Domain Decomposition-Domain Composition method (DDDC), indicating with this the strategic phases characterizing the coupling: (a) the problem is decomposed in two (many) sub-zones where the two solvers are alternatively used, and (b) at the overlapping the information is given from one solver, say source, to the other, say receiver, after having made the information consistent with the receiver features. Therefore, if the Level-set is the receiver, the exchanged data are preliminary smoothed across the interface layer, while if the BEM is the receiver the data are sharpened recovering the interface as a line. The coupling strategy used in the present study is the one sketched in the right plot of figure 1. This strategy was identified as suitable to cope with strong coupling between the sub-zones by our BEM-VOF domain-decomposition study. In this case, the fluid domain is split in two (many) overlapped zones, each one studied by the more suitable solver. At the overlapping, both interacting solvers are applied and velocity and pressure information are exchanged from one region to the other through the corresponding boundary limiting the overlapping. Additional information is required by the Level-set method with respect to the VOF. For instance, not only the interface location at the transmission boundary must be given but also its local normal vector.

As first attempt to prove the validity of present domain-decomposition strategy, here the dam-breaking problem and the later impact of the water with a vertical rigid wall downstream the initial dam are analyzed (see sketch in figure 2). The related flow

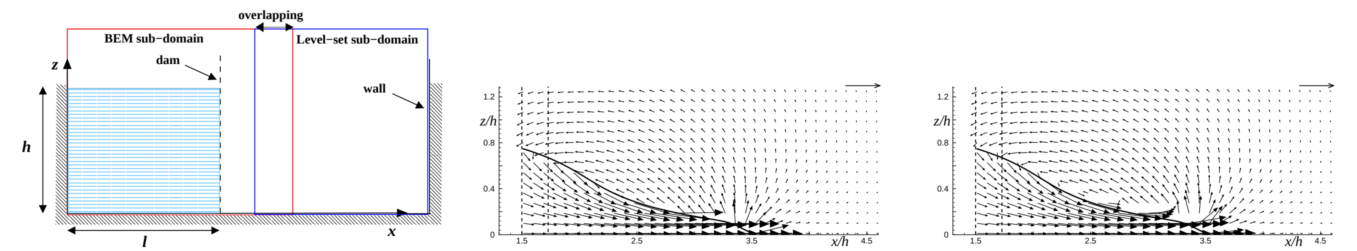

Figure 2: Dam-breaking *plus* water-wall impact problem. Left: definition of the problem and of the parameters used. Center: velocity field in the Level-set sub-domain at $t = 1.35\sqrt{h/g}$ as initialized by the BEM solution. Right: velocity field in the Level-set sub-domain at $t = 1.35\sqrt{h/g}$ as resulting after a smoothing process. The reference vector in the center and right plots has length $\sqrt{hg}$.

behaves similarly to the water flowing along the ship deck and hitting a superstructure, during a water shipping event. A two-dimensional dam limits a reservoir of water high h and long $l = 2h$, and suddenly breaks at time $t = 0$. A flat 'deck' is assumed, initially dry downstream the dam and limited by a vertical rigid wall at $3.366667h$ from the reservoir. The boundary conditions required by the field method are completed assuming a horizontal roof at $2.2h$ from the deck. This means that a box-shaped domain is modeled numerically. The domain decomposition is switched on after $t = 1.35\sqrt{h/g}$ from the dam release, before that the BEM is used to simulate the air-water flows in the whole domain. When the DDDC is started the Level-set variables are initialized by the BEM solution. This is numerically challenging due to the mentioned different features of the air-water interface according to the BEM and Level-set techniques. Center and right plots of figure 2 show the velocity field in the Level-set sub-domain, respectively, as given by the BEM and as resulting after the smoothing process. The latter is necessary within the composition and the initialization phases for the Level-set method.

The DDDC solution at $t = 2.2\sqrt{h/g}$ is given in the left and right plots of figure 3 in terms of the velocity and pressure fields, respectively. Two different locations of the overlapping portion are considered. In the top plots the transmission boundary is upstream the initial dam location (run 1), in the bottom ones it is downstream (run 2). In the former case, the water level near the coupling area is initially high and reduces as time goes on. In the latter one, the water level at the overlapping is quite small from the beginning. The two conditions correspond to quite different tasks from the numerical point of view. Run 2 implies results more sensitive to the specific numerical choices and therefore is more challenging since the water level in this case is comparable to the thickness of air-water interface used by the Level-set. Moreover the overlapping region is located in an area characterized by high recirculation. So the solution is very much dependent on the ability to model properly the exchange of information between the two sub-domains. The two numerical simulations show the validity of the used coupling strategy both in the case of flow information traveling from the BEM to the Level-set (here interesting the water flow) and conversely (here interesting the air flow). Differences in the velocity gradients are visible at the interface in the overlapping region for the case with smaller water level at the overlapping. They are related to the composition step of the numerical strategy and die out as soon as we are deeply inside each fluid. In run 2 also the pressure contours are not exactly superimposed in the transmission area, but the possibility to continue the simulation (see figure 4) without an iterative time scheme shows the robustness of the strategy implemented.

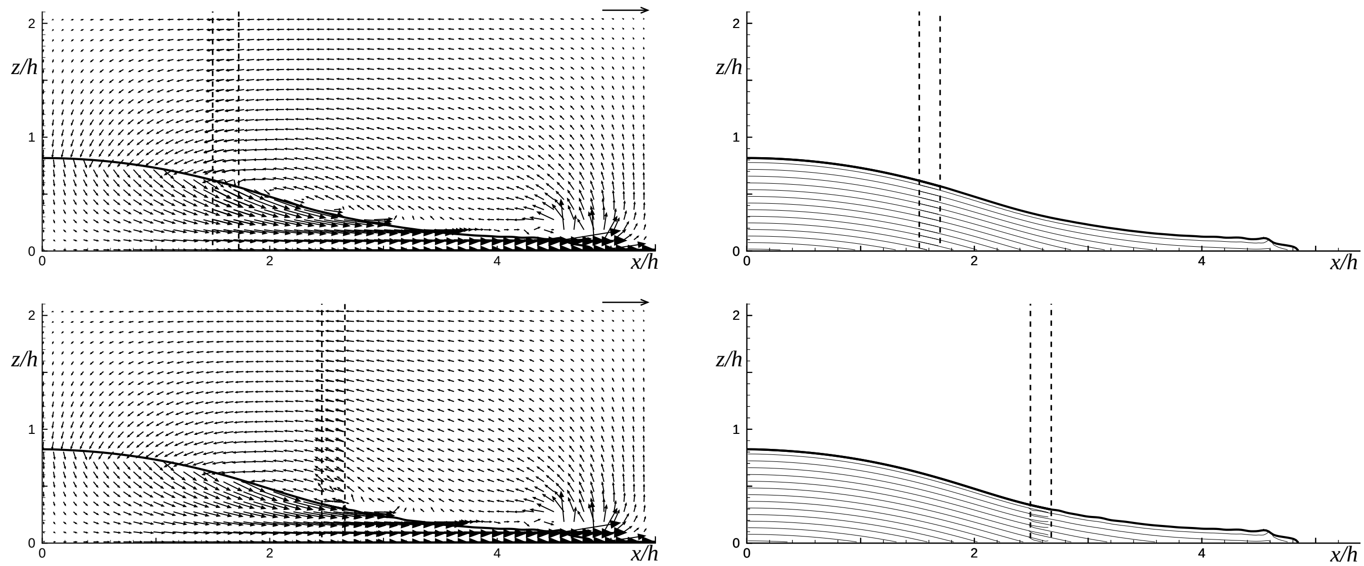

Figure 3: Dam-breaking *plus* water-wall impact problem. DDDC solution after $t = 2.2\sqrt{h/g}$ from the breaking of the dam for the air-water interface (thick-solid line), the velocity field (left plot) and the pressure field (right plot). The reference vector in the left plots has length $\sqrt{hg}$. Two overlapping locations are used, respectively, upstream (top plots) and downstream (bottom plots) the initial dam.

Figure 4 gives the air-water interface evolution for the the full BEM (dotted lines), the full Level-set (dashed lines) and the DDDC results for run 2 (solid lines). As we can see the agreement is satisfactory, both before the impact with the downstream vertical wall, and during the water rise-up and run-down phases along the structure. The last plot shows the air-water interface

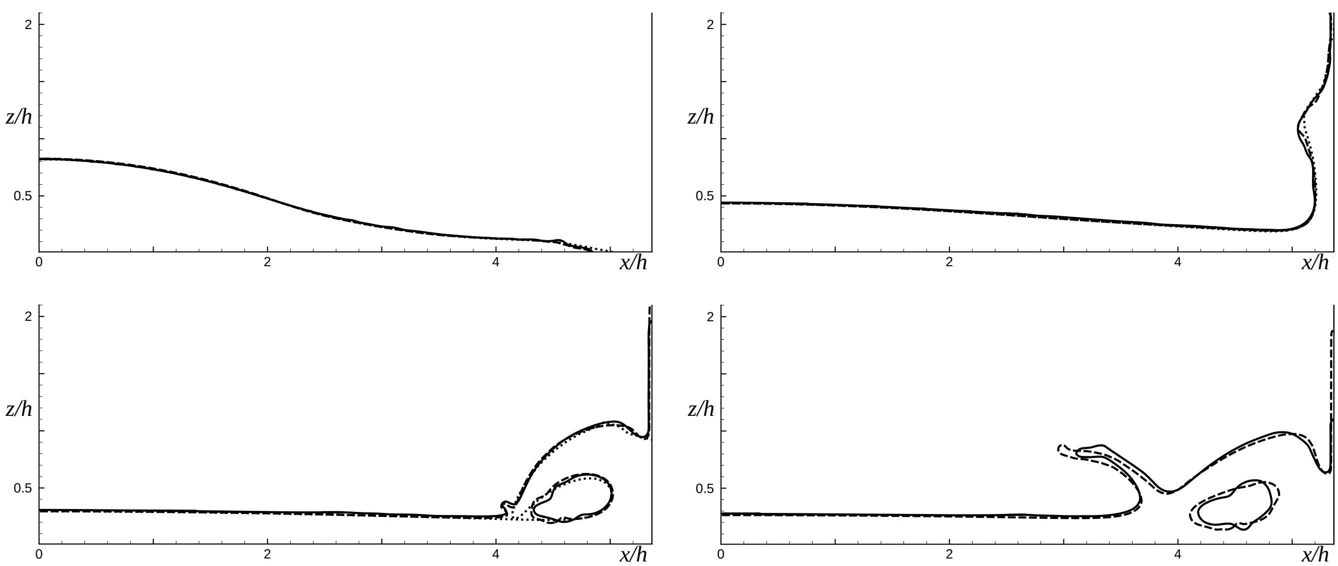

Figure 4: Dam-breaking *plus* water-wall impact problem: air-water interface evolution. Dotted lines: full BEM, dashed lines: full Level-set, solid lines: DDDC method. Time increases from left to right and from top to bottom. Shown time instants: $t \simeq 2.2, 4.6, 6.2$ and $6.8\sqrt{h/g}$.

configuration after the impact of the backward plunging wave with the underlying water has occurred, therefore the BEM solution is not available. Despite some local differences due to the not exact correspondence in terms of time and used mesh, the full Level-set and DDDC results show quite similar cavity deformation and water splash up. The horizontal force acting on the wall due to the water-structure interaction is given in the left plot of figure 5. The load reaches a first peak just after the initial water-wall impact ($t \simeq 2.36\sqrt{h/g}$). After short time the force starts to rise again until the occurrence of another important peak, associated with the backward plunging impact with the underlying water ($t \simeq 6.2\sqrt{h/g}$). A secondary peak between the two already mentioned can be detected from the plot. This is due to the water impact with the horizontal roof assumed at a vertical distance $2.2h$ from the deck in the computations. From the results, the DDDC curve compares well with the force predicted by the full Level-set method. The right of the same figure presents the numerical pressure evolution as measured along the vertical wall by the DDDC (thick-solid line), the full Level-set (dash-dotted line) and the full BEM (dotted line). More in detail the pressure has been recorded at a location $D = 0.1999h$ from the bottom. The pressure time history has a similar behavior as the horizontal force. The agreement among the curves is fairly satisfactory, also considering that this is a local result and therefore more sensitive to the specific discretization choices. In the same plot the experimental pressure by Zhou *et al.* (1999)

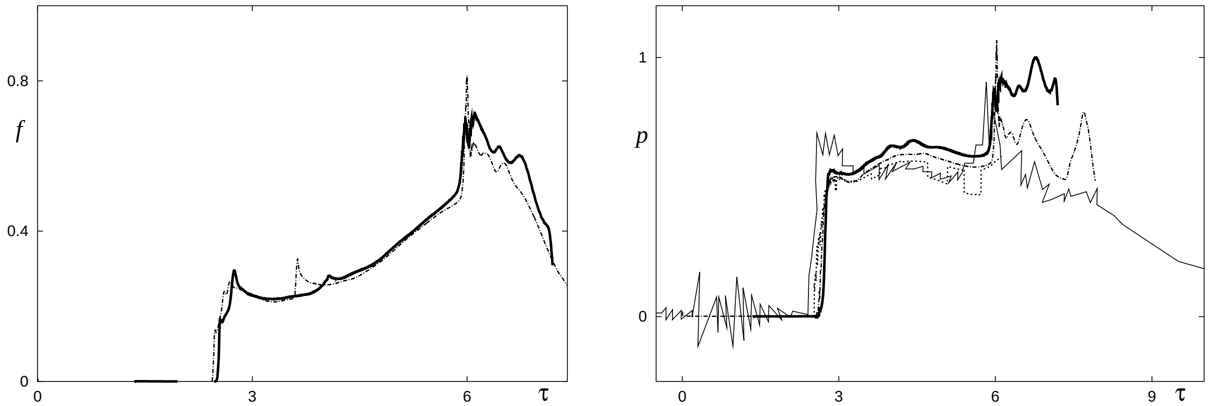

Figure 5: Dam-breaking *plus* water-wall impact problem: impact loads on the vertical wall. Left: horizontal force evolution by DDDC (thick-solid line) and full Level-set (dash-dotted line) methods. Right: pressure evolution at a location $D = 0.1999h$ from the bottom by DDDC (thick-solid line), full Level-set (dash-dotted line) and full BEM (dotted line) methods. The thin-solid line is the pressure time history measured by Zhou et al. (1999) at a pressure gauge centered at $0.2666h$ from the bottom and having D as lowest area point. $f = F/(\rho g h^2)$, $p = P/(\rho g h)$ and $\tau = t/\sqrt{h/g}$.

is superimposed. In the tests a circular pressure gauge centered at $0.2666h$ above the bottom and with lowest area point D was used. The reasons for comparing the numerical results with experimental data centered at a different location can be found *i.e.* in Greco (2001). The experimental results are consistent with the numerical ones although a different post-breaking behavior can be detected. At this stage the results are very sensitive to the cavity deformation and to the numerical choices and discretizations. This partially explains the differences detectable among the full Level-set, the tests and the DDDC data.

The details of the developed modeling will be described at the Workshop. The main numerical issues and challenges will be highlightened. The applicability of the method for the analysis of problems of hydrodynamic interest will be further discussed and proved.

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Discusser: R. Beck

In the comparison you showed between the pure Navier-Stokes solver and the domain decomposition method, what is the difference in computation run time?

Author's reply:

Obviously the time saving for the computations depends on the size of the Navier-Stokes sub-domain. For the case we considered, this resulted in the time necessary being halved. In addition, time has been further saved by the following the initial stage of the phenomenon through the full BEM.