Application of a 2D BEM-Level Set Domain Decomposition to the Green-Water Problem

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A Domain-Decomposition strategy for the study of nonlinear air-water interface problems has been developed and presented to the last workshop (see Colicchio *et al*. 2004b). The method is based on the use of a Boundary Element Method (BEM) and a Navier-Stokes solver combined with a Level-Set technique to capture the interface evolution (NS-LS). Both solvers are accurate to the second order both in space and in time. The two solution techniques are applied to simulate the air-water evolution in different portions of the fluid domain. In particular, the NS-LS analyzes the regions that can be characterized by breaking and fragmentation of the interface, vortex shedding and air entrainment phenomena. The BEM is adopted in the rest of the domain of interest. Many practical problems in ship hydrodynamics exist where such kind of zonal approach can be adopted. An example is the water on deck caused by the vessel interaction with pre-existing waves. In this case the field solver is needed to describe all the stages of the water evolution onto the deck and near the vessel.

The challenge in a zonal method is the proper exchange of information between the two solvers across the common boundaries. This has been obtained enforcing an explicit coupling instead of using an iterative technique (see *i.e.* Quarteroni and Valli 1999). The details of the developed strategy are described in Colicchio *et al*. (2004a). These involve both a Domain-Decomposition step, where the data from one solver, say donator, are transfered to the other one, say receiver, and a Domain-Composition step, necessary to make the information from the donator consistent with the receiver. Due to these features, the resulting method has been named as Domain-Decomposition Domain-Composition strategy (DDDC).

Here the DDDC is applied to the water-on-deck problem on a two-dimensional rectangular-shaped structure kept fixed under the action of prescribed incoming waves. The case refers to the model tests described in Greco (2001). In the experiments both the water shipping on a bare deck and on a deck with a vertical superstructure were examined. For this problem, the fluid domain has been split in two regions, see sketch in figure 1. The BEM is used to generate the incoming waves and to damp out

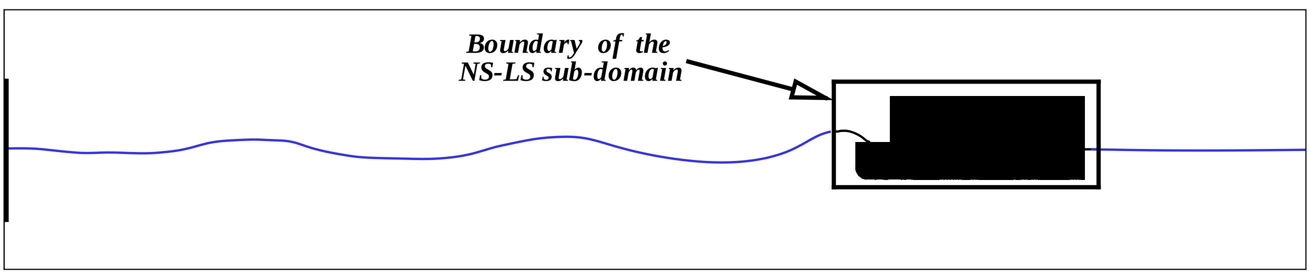

Figure 1: Domain-decomposition strategy applied to the water-on-deck problem. The incoming waves are generated by a flap wavemaker on the left and interact with a ship-like structure. This case refers to the model tests discussed in Greco (2001). The solid box delimits the fluid region described by the NS-LS method. The surrounding sub-domain is solved by the BEM. The horizontal size of the NS-LS region is about 0.08 times the domain extension.

those transmitted by the ship-like structure. The former is obtained by simulating a flap wavemaker moving according to the experimental time history. The latter is achieved by introducing a damping region downstream and stretching the panels. This is a mean to avoid unphysical reflections from the edge of the numerical domain. The NS-LS is applied to predict the wave-body interaction and therefore introduced in the fluid sub-domain containing the body. To make the solution more efficient, the BEM is used to simulate the flow evolution in the whole domain until a time instant $t = t^*$ very close to the occurrence of the water on deck. Then the NS-LS solution is initialized by taking the BEM information and making them consistent with the NS-LS method. From $t = t^*$ on, the domain decomposition is introduced.

Figure 2 shows the first water-on-deck event caused experimentally by prescribed regular incoming waves $\lambda = 40f$ long and with a crest-to-trough height $H = 0.08\lambda$, $f = 0.05$ m being the ship freeboard. In this case no superstructure was placed along the deck. The solid lines reported in the right of each plot represent the configurations of the DDDC air-water interface at the corresponding time instants. The numerical simulation was performed with a grid size $\Delta x = \Delta z \simeq 0.04f$, implying 20000 computational nodes in the air-water domain. In the examined case, the water shipping starts at $t = t_{\rm wod} \simeq 110.46\sqrt{f/g}$, and the domain decomposition is switched on at $t^* = 109.98\sqrt{f/g}$. At this time instant the fluid across the air-water interface in the NS-LS sub-domain has a velocity almost normal to such surface. Therefore the velocity field given by the BEM is already smooth and almost divergence free across the air-water interface and has not to be particularly manipulated for the NS-LS solver. This is confirmed by figure 3 giving the pressure and velocity fields before and after the domain-composition step. Small corrections can be observed just in the close vicinity of the deck edge to smooth adequately the BEM data.

The comparison with the model tests (see figure 2) appears rather satisfactory, both in the initial plunging wave phase and in the later evolution of the dam-breaking like flow along the deck. Some localized differences can be detected in the deformation and

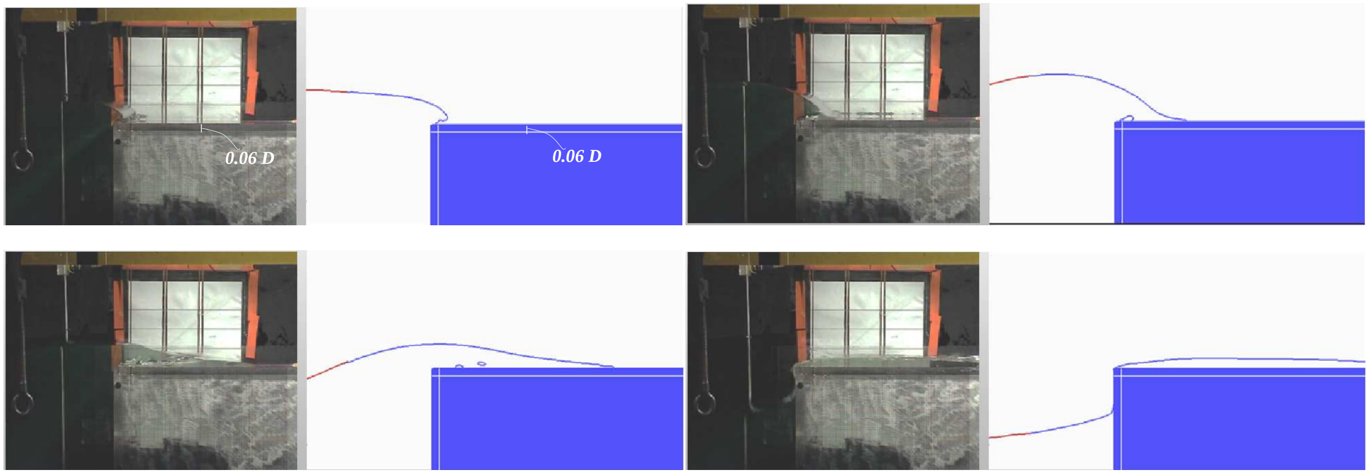

Figure 2: Flow evolution during the first water-on-deck caused by prescribed regular incident waves $\lambda = 40f$ long and with a crest-to-trough height $H = 0.08\lambda$, $f = 0.05$ m being the ship freeboard. No superstructure has been placed along the ship deck. Left of each plot: experimental results by Greco (2001). Right of each plot: snapshots of the numerical DDDC air-water interface. The time increases from left to right and from top to bottom and corresponds, respectively, to: $t - t_{\mathrm{wod}} \simeq 1.6, 2.8, 4.88$ $7.28\sqrt{f/g}$. $D = 3.96f$ is the ship draft. $t_{\mathrm{wod}} \simeq 110.46\sqrt{f/g}$ is the time of the water-on-deck occurrence.

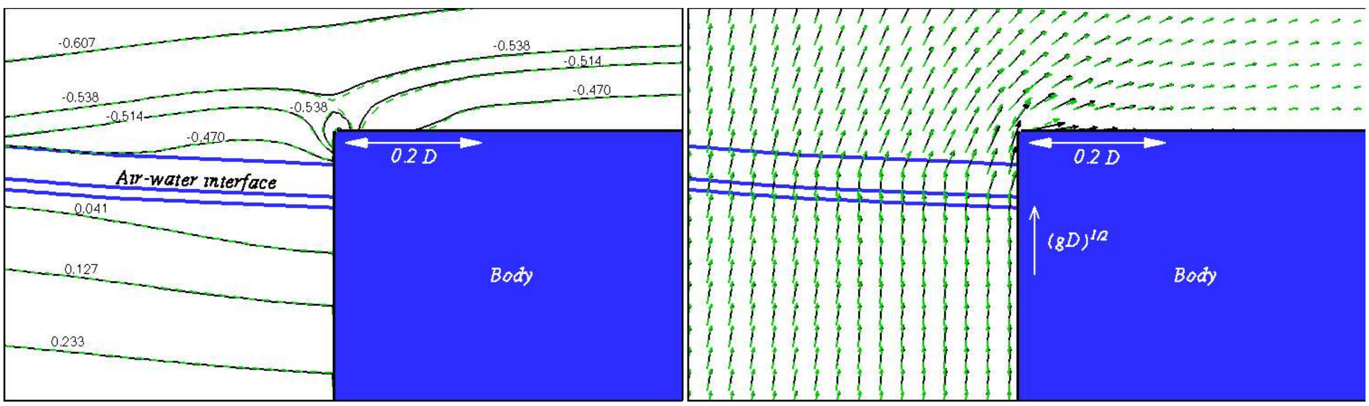

Figure 3: Flow evolution during the first water-on-deck caused by prescribed regular incident waves with $\lambda = 40f$, $H = 0.08\lambda$ and $f = 0.05$ m. Pressure contour levels (left) and velocity field (right). Solid lines and vectors: Domain-Decomposition step, information from the BEM solver. Dashed lines and vectors: Domain-Composition step, information given to the NS-LS solver. Thick solid lines: fluid region across the air-water interface with density variation. Time instant $t = 109.98\sqrt{f/g}$ from the starting of the wavemaker motion. The spatial scale and the reference vector are given in terms of the ship draft $D = 3.96f$. The pressure levels are made nondimensional by using $\rho g D$.

final collapse of the air-cavity entrapped near the bow after the initial impact of the shipped water with the deck. The disagreement is partially explained by the use of a quite coarse grid with respect to the cavity size. The initial cavity configuration contains approximately 20 cells of the used mesh (cf. figure 4). Another possible reason of the differences is connected with the

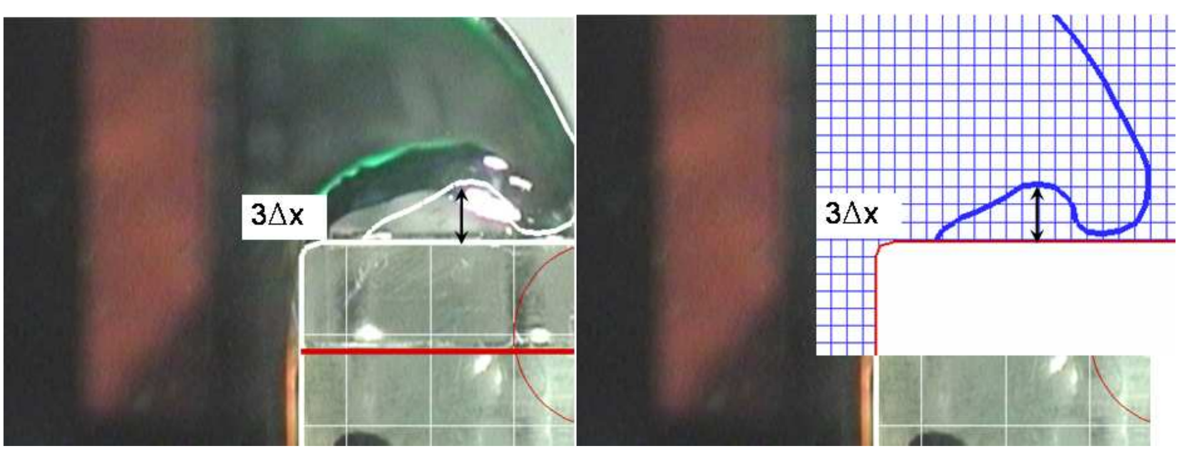

Figure 4: First water-on-deck caused by prescribed regular incident waves with $\lambda = 40f$, $H = 0.08\lambda$ and $f = 0.05$ m. Initial plunging phase. The shown grid represents the numerical mesh used in the DDDC simulations. $\Delta x = \Delta z \simeq 0.04f$.

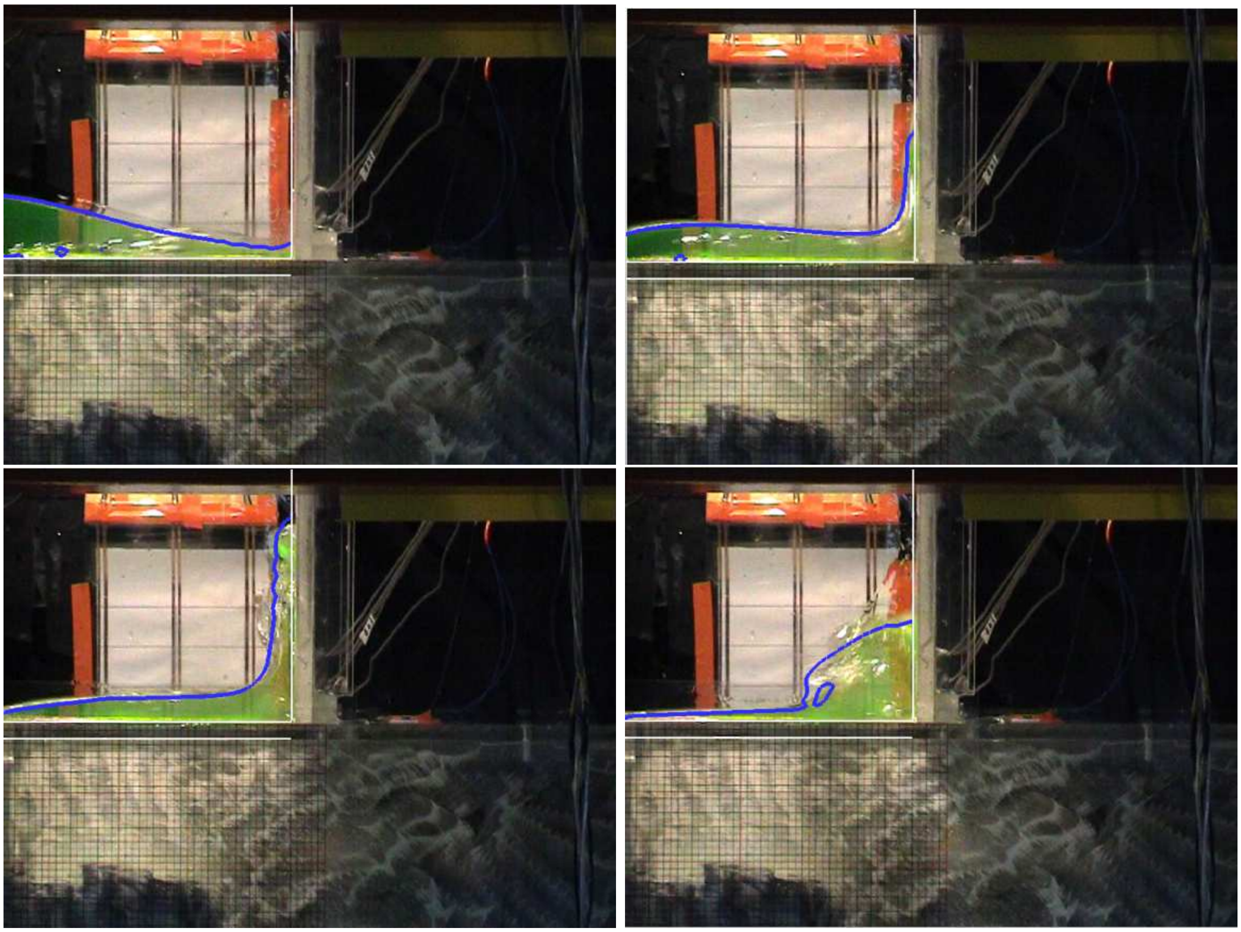

Figure 5: Flow evolution during the first water-on-deck caused by prescribed regular incident waves with $\lambda = 40f$, $H = 0.08\lambda$ and $f = 0.05$ m. A vertical superstructure has been placed along the deck, $4.55f$ from the bow. Experimental pictures by Greco (2001) and DDDC air-water interface configurations (solid lines). The time increases from left to right and from top to bottom and corresponds, respectively, to: $t - t_{\text{wod}} \simeq 4.89, 6.01, 7.13$ and $9.37\sqrt{f/g}$. $t_{\text{wod}} \simeq 110.46\sqrt{f/g}$ is the time of the water-on-deck occurrence.

compressibility of the air entrapped experimentally, which is not modeled in the numerics.

Figure 5 shows the interaction of the shipped water with a vertical superstructure along the deck. Also in this case the global agreement between model tests and DDDC evolution is quite good. The main differences are related to the later stages of the phenomenon, particularly when the water falls down along the vertical wall. These could be explained by three-dimensional flow instabilities excited during the water run up on the structure, as suggested by this sequence of experimental pictures and clearly confirmed by other views of the model tests. The full comparison (not reported here) showed that, despite the numerical resolution is not sufficient to capture adequately the initial cavity entrainment, the bubbles caused by the cavity collapse follow correctly the evolution of the physical ones.

The numerical simulation identifies three stages of the water shipping relevant for the loads on the deck structures. These are shown in figure 6 by means of the pressure contour levels in the air-water domain on the ship, and are related to three impact events, respectively, (i) the initial water impact with the deck and the subsequent air entrapment, (ii) the water impact with the vertical wall, and (iii) the later impact of the backward plunging jet with the underlying water. The pressure rises due to such phenomena can be dangerous, respectively, for the deck portion near the bow, the vertical wall, and an intermediate deck area between the bow and the superstructure. The water-shipping severity will affect the extension and location of the ship regions interested by high pressure levels, as well as the time durations and peak values of the loads. For the water-on-deck event analyzed here, the largest values have been recorded during the air-cavity evolution phase, the smallest pressures are those connected with the impact of the backward-plunging jet. The water impact with the vertical wall causes pressure levels slightly lower than phase (i) and is characterized by two peaks: the first in time related to the initial water impact, the second one caused by the water run-down along the structure under the gravity action. The numerical time histories of the pressure at two locations on the wall indicate that these peaks are of the same order of magnitude, as shown in figure 7. The lines with symbols also reported in the plots are the corresponding model test data. The agreement between the results is rather good despite the difficulties involved in the experimental and numerical pressure measures and the three-dimensional instabilities occurring during the model tests.

No pressure devices have been placed along the deck during the model tests, therefore no experimental data are available to confirm the numerical results for phases (i) and (iii). However, the relevance of air-cushioning during the initial plunging phase can be investigated also numerically. In particular, by modeling the air in the cavity as an ideal gas subjected to an adiabatic process. Since the air affects the water evolution only in the fluid portions with large deformations and fragmentations of the air-water interface and with air entrapment, the increase of computational costs due to the presence of a compressible phase can

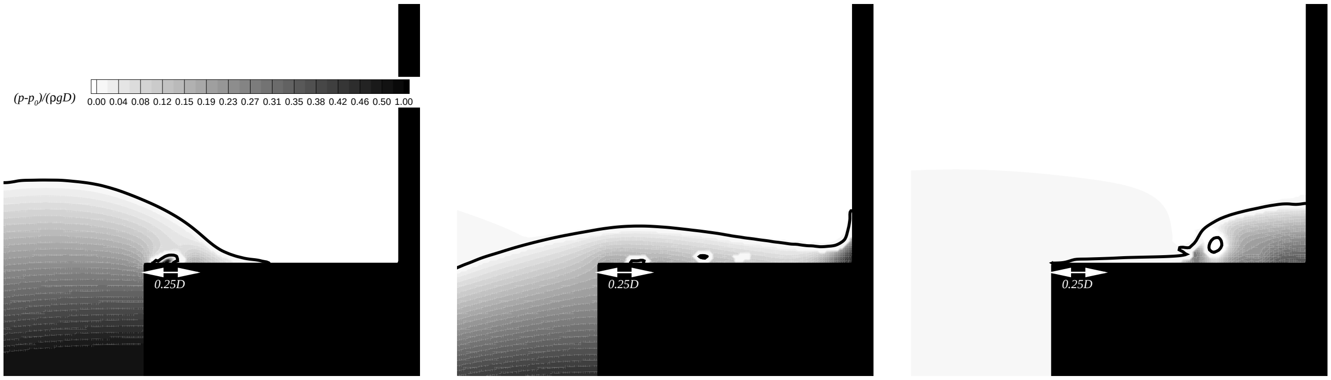

Figure 6: Relevant green-water loads on the deck structures during the first water-on-deck caused by prescribed regular incident waves with $\lambda = 40f$, $H = 0.08\lambda$ and $f = 0.05$ m. Pressure contour levels from the DDDC simulation. Left: air entrapment during the initial plunging phase, $t - t_{\rm wod} \simeq 2.79\sqrt{f/g}$. Center: water impact with the vertical wall, $t - t_{\rm wod} \simeq 5.18\sqrt{f/g}$. Right: impact of the backward plunging jet with the underlying water, $t - t_{\rm wod} \simeq 9.54\sqrt{f/g}$. $D = 3.96f$ is the ship draft. $t_{\rm wod} \simeq 110.46\sqrt{f/g}$ is the time of the water-on-deck occurrence.

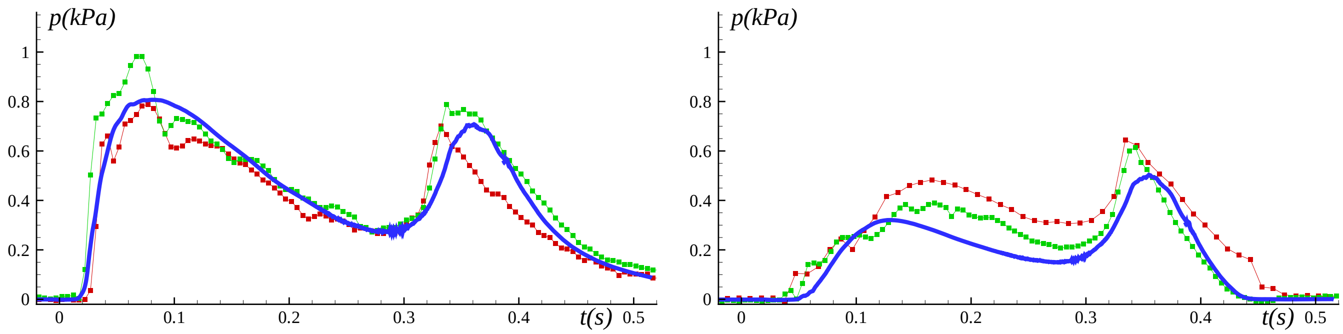

Figure 7: Pressure evolution at the wall locations $0.24f$ (left) and $0.64f$ (right) above the deck, with $f = 0.05$ m the ship freeboard. The water-on-deck has been caused by prescribed regular incident waves $\lambda = 40f$ long and with a crest-to-trough height $H = 0.08\lambda$. Lines with symbols: experiments by Greco (2001), two runs are shown for each pressure sensor. Solid lines: DDDC results. Here $t = 0$ s the time instant of the initial water-wall impact.

be counteracted by describing numerically the air flow only where necessary. This requires to handle water regions surrounded by (a) void, where the air-water interface is not particularly deformed, (b) incompressible air, where the air-water interface is highly deformed, and (c) compressible air, in the entrapped cavities. The solver should also account for the possible variation in time of the sizes and locations of such regions. To do this dynamically a proper algorithm has to be developed.

In the case analyzed here, the vortex shedding phenomenon, for instance from the downstream edge of the body, was rather slow and the resulting vortical structures remained inside the NS-LS sub-domain for the time interval investigated. Things would be different for a freely-floating body. This would require a dynamic enlargement of the field-solver region as a compromise between efficiency and effectiveness of the numerical solution.

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