A 3D Navier-Stokes solver to investigate Water-On-Deck events within a Domain-Decomposition strategy

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The present analysis is a part of a research activity aimed to develop a numerical method reliable and efficient for seakeeping problems with water-on-deck occurrence. Highlighting the need for efficient solutions, the Domain-Decomposition (DD) algorithm was chosen. A two-dimensional DD strategy has already been developed and assessed by comparison against experimental data and other numerical results for fluid dynamic problems similar to the one of interest. Its details can be found for instance in Colicchio *et al.* (2006) and Greco *et al.* (2007) and have been documented also at previous workshops. A preliminary 3D analysis was obtained combining a weakly-nonlinear potential flow solver for the external seakeeping problem with an in-deck shallow-water approximation to handle the water-on-deck events (see *i.e.* Greco *et al.* 2009). This has the advantage of being very efficient but has limitation in terms of validity because the nonlinearities involved in the water-ship interactions are accounted for only partially. Just to mention, the water run-up is not properly described when high-speed jets are formed and the plunging-wave phase, which usually characterizes the initial stages of the water shipping, is not captured.

The present study is an initial step toward a fully 3D more-general DD solver. The focus is on head sea waves and vessel without forward motion, which are of interest for FPSOs ships used as oil platforms. On the basis of previous 2D and 3D physical and numerical studies, surface tension and turbulence effects are neglected. Within the DD, a linear Boundary Element Method (BEM) will be used to describe the seakeeping problem in the whole fluid domain but for an inner sea region containing the upstream portion of the vessel and its deck. There a Navier-Stokes (NS) single-phase (water) solver will be adopted to predict the water-ship interactions and the subsequent water-on-deck occurrence. This means that nonlinear effects are fully handled in the NS domain. The seakeeping solver furnishes the initial conditions to the field solver, as well as the boundary conditions in terms of free-surface elevation, pressure and velocity along control surfaces, and ship motions along the wetted part of the vessel inside the inner region. Here the focus is on the description of the 3D NS solver developed and on the assessment of its numerical stability and reliability when boundary conditions, similar to those enforced within the DD, are applied.

Domain-Decomposition: linear wave theory and Navier-Stokes solvers. In a first stage, the research studies aim to weakly couple a linear potential solver with a fully non linear Navier-Stokes (N-S) solver, with information exchange only from the potential solver to the N-S solver and not *vice versa*. To make sure that numerical errors in the potential

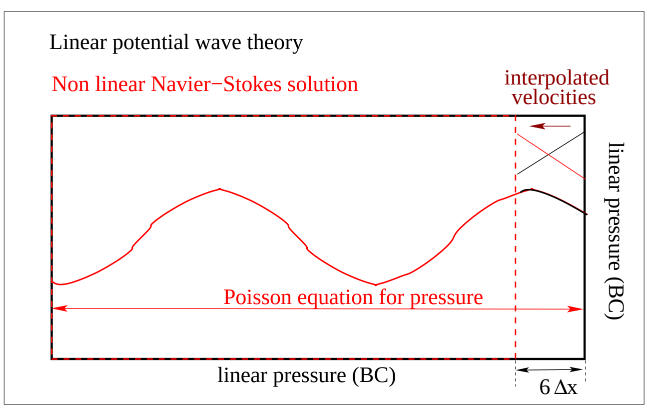

Figure 1: Definition of the domains of solution.

flow-calculations do not affect the coupling, the N-S solver is weakly coupled with a linear analytical potential solution. This kind of coupling is not less compelling than the final objective of this study as the linear and non linear solutions have a fundamental inconsistency close to the free surface, because the former assumes that the free surface is a small perturbation of the plane $z = 0$ and both pressure and velocity are obtained assuming valid this assumption. The non linear N-S solver instead has to deal with actual deformation of the interface and, therefore, needs the information in points where the potential solutin is not exactly defined as the crest and the throat of the wave. This requires a particular care to be taken if the two domains shared boundaries are crossed by a free surface. To ensure that oscillations and errors in those regions are limited, an overlapping domain will be used rather than a surface of contact (as seen in Colicchio *et al.* 2006).

Figure 1 shows an example of two kinds of boundaries. The bottom of the rectangle, not crossed by a free surface, is a simple surface of contact, *i.e.* where velocity and pressure from the potential solution are used as $C(0)$ boundary conditions. The right boundary, where the waves come in, is enlarged through an overlapping, to allow a softer interfacing between inconsistent solutions. The linear pressure is assigned at a distance $\beta\Delta x$ away from the real boundary of the N-S domain so that the oscillations, caused by the inconsistency, can be damped in the solution of the Poisson equation on the actual boundary of the N-S. Velocity and free surface elevation are provided from the linear solution in the superposition region. In particular, the potential free surface will be used as actual wave elevation there, while a linear combination of the N-S and potential velocity will give suitable boundary condition to the N-S domain. The length of the superposition region is chosen equal to $6\Delta x$, where Δx is the mesh size close to the boundary. This choice ensures, besides the damping of the pressure oscillations, also an adequate definition of the interface to calculate the distance function in the narrow band at the interface boundary (Colicchio 2004).

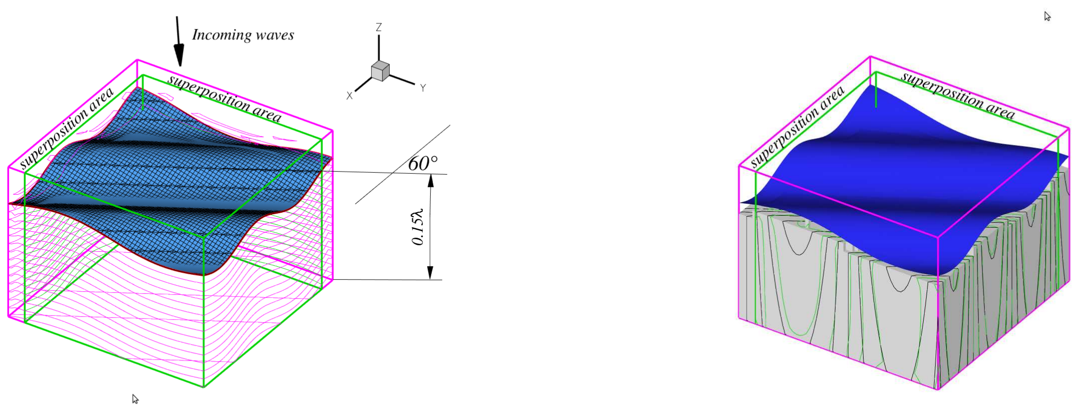

Figure 2: Left: Comparison between theoretical (meshed in black) and numerical free surface (blue shaded) after two wave periods. Pressure contours are plotted on the side of the domain. Right: Comparison between theoretical (black) and numerical (green) contour plots of x-component of the velocity.

The results of this coupling is shown in figure 2 where an Airy wave with steepness $ka = 0.03$ enters the N-S domain with an angle $\theta = 60^o$. Two of the vertical boundaries, in the wave side, are characterized by the presence of a superposition region, while the bottom is a simple contact surface. The other two vertical boundaries present outflow boundary conditions. On the left of the figure, the numerical free surface (blue shade) after two periods is compared with the Airy theory (black mesh). They are very close and the discrepancies can be attributed to well known non-linearities that develope during the evolution, as at through of the wave. The same figure shows the oscillations that arise in the pressure field at the potential side of the overlapping region (pink contour lines). On the right side there is the comparison of the contour plots of the x component of the velocity. Once again the results are very similar and the discrepancies are due to small non linearities besides inconsistencies on the bottom where the highest differences can be highlighted.

Body motion. The description of the body that is used in the 3D solution has already been described in Colicchio *et al.* (2006). A level set function captures the surface of the body, pressure and velocity are imposed on the body surface making use of this function. This prevents a regrid or a deformation of the mesh at each time step for a moving body, saving computational time. As long as the body is smooth, the convection of the level set function with the body velocity can be very straightforward and requires very low computational time. If the body is characterized by very fine details, it is very likely that they will be lost in the Eulerian advection. To avoid this problem a hybrid method, similar to the one proposed in Enright *et al.* (2002), will be used here. The level set function around the body at the initial position is described on a uniform mesh four times finer than the minimum mesh size in the computational grid. The signed distance from the body is calculated geometrically on that mesh in a band six times larger than the maximum mesh size of the computational grid. The cell centres in that band become a set of particles that preserves the level set function around the body. In the time evolution, they are moved in a Lagrangian fashion, preserving all the details of the body geometry and

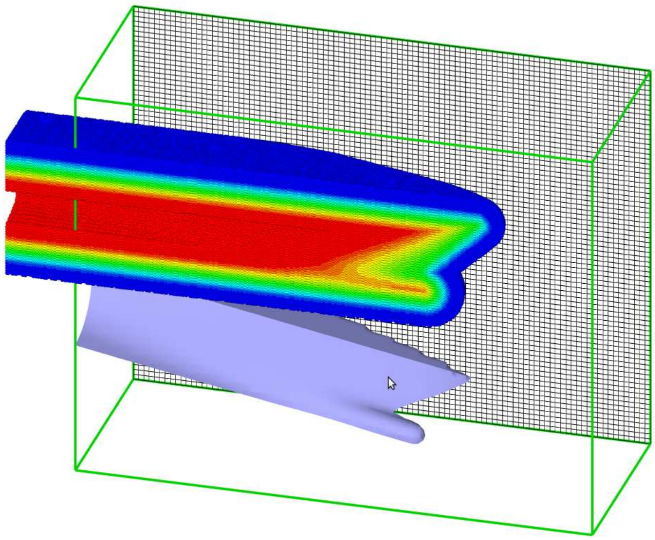

Figure 3: Example of hybrid tracking of the body position. A set of particles, labelled with their distance function from the hull surface are advected on the grid.

the Eulerian level set function is calculated as their interpolation in the cell centres. A fast tracking of the particles can be achieved taking advantage of the local topology, for example considering that the particles will not move to cells further then $\alpha\Delta\boldsymbol{x}$ (with $\alpha < 1$) from their previous position and the intialization of the level-set function can be performed just in a subset of cells that they cross.

An example of this technique is given in figure 3, where the set of particles advecting the distance function are shown at their initial position. The body rotates as well as the particles and the interpolation of their values on the cell centres gives the body-distance isosurface shown in gray.

In this case, during the rotation, the use of a larger set of particles than the one necessary at $t = 0$ allows also the introduction of new sections of the body in the computational domain without any problem. This is particularly important for our problems of interest: only the front part of the ship will be studied with the N-S solver, and it will move with the motion prescribed by the potential flow solution, including pitch and sway motions which are more challenging as described below.

Check of the outflow conditions. The example of the waves, shown before, has outlined that the used outflow conditions were robust enough to cause only very small reflections of the wave from the computational boundaries. To make sure that this is valid also when a body crosses the outflow section, the case of a portion of hull in a current is studied here. Only 40% of the front part of the ship is inside the computational domain, as shown in figure 4. The above view of the figure shows the flow deformation around the hull, at an intermediate stage. This view does not seem to show any side-effect of the abrupt outflow condition, but the bottom view with the dynamic pressure contour plots highlights an extreme drop of the free surface at the exit and, above all, some pressure oscillations in the exit section. A similar behaviour is amplified when the body starts to move. Then, it is necessary to use a modified outflow condition that, at least, is driven by more precise out-, or even in-, flow velocities. This can be done when the solver is fully coupled with the potential solution, that gives an estimate of the local entry/exit velocity.

Such kind of coupling will be shown at the workshop as well as the application to the water on deck problem.

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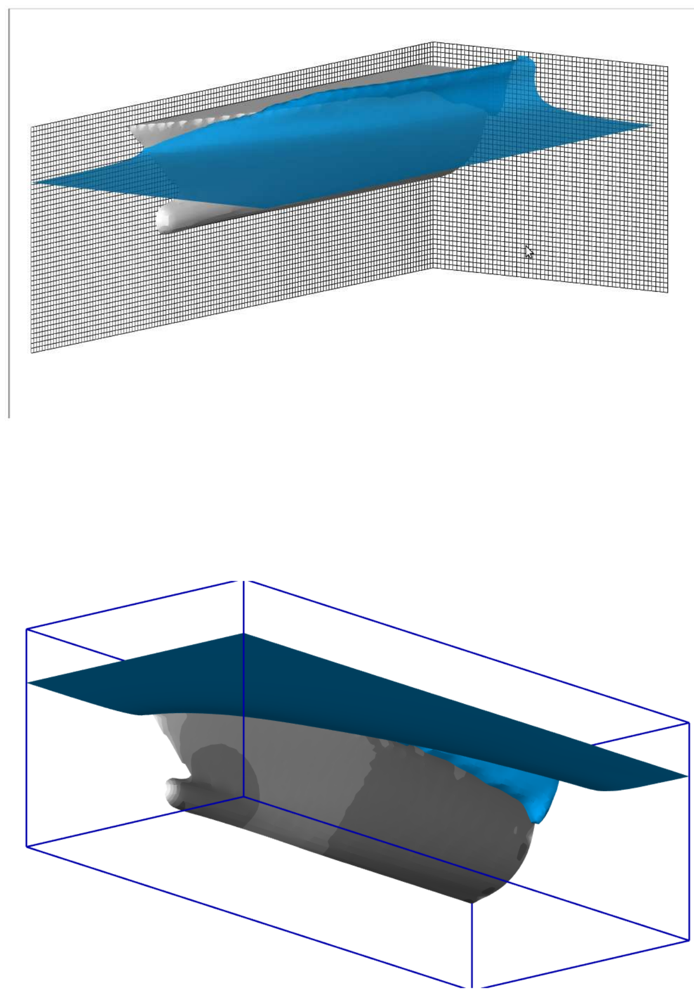

Figure 4: Free surface and dynamic pressure contour plots around the bow of the hull.

References

COLICCHIO, G. (2004). Violent disturvance and fragmentation of free sruface. *PhD Thesis, University of Southampton, Uk*.

COLICCHIO, G., M. GRECO, AND O. M. FALTINSEN (2006). A BEM-level set domain-decomposition strategy for non-linear and fragmented interfacial flows. *J. for Num. Meth. in Eng. 67*(10), 1385–1419.

ENRIGHT, D., R. FEDKIW, J. FERZIGER, AND I. MITCHELL (2002). A hybrid particle level-set method for improved interface capturing. *J. of Computational Physics 183*, 83–116.

GRECO, M., B. BOUSCASSE, G. COLICCHIO, AND C. LUGNI (2009). Weakly-nonlinear seakeeping model: regular/irregular wave interaction with a ship without/with forward speed. In 24^{rd} *Int. Workshop of Water Waves and Floating Bodies*, Zelenogorsk, Russia.

GRECO, M., G. COLICCHIO, AND O. M. FALTINSEN (2007). Shipping of Water on a Two-dimensional Structure. Part 2. *J. of Fluid Mech. 581*, 371–399.