Development of a 3D Domain-Decomposition strategy for violent head-sea wave-vessel interactions: Challenges

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This research activity represents an additional step toward a three-dimensional Domain-Decomposition strategy for violent wave-ship interaction involving water-on-deck and slamming phenomena. The focus is on FPSO ships and on head-sea waves and vessel without forward speed. The compound solver under development aims to couple a global 3D linear seakeeping solver with an inner 3D single-phase (water) Navier-Stokes (NS) method in a region containing the forward portion of the vessel. The NS solver is characterized by a Projection method with a finite-difference scheme on an Eulerian grid. The Level-Set (LS) technique is applied to step in time the free surface and combined with point markers to enforce adequately the body-boundary condition within a hybrid Eulerian-Lagrangian approach. This requires a much finer discretization than the computational grid around the body to preserve its geometrical details in time. As time goes on, the markers move in a Lagrangian fashion and then the LS function is estimated on the Eulerian grid by interpolation from the markers locations. Previous efforts have been documented for instance in Greco *et al*. (2009)) and Colicchio *et al*. (2010). Here some of the challenges and the possible solutions for the development of the inner 3D NS solver are discussed. The stress is on the boundary conditions.

Free-surface and body boundary conditions When dealing with free-surface and moving bodies, an important source of numerical problems is the exchange of information across the involved interfaces. Wrong velocity predictions can propagate inside the water and destroy the solution in time. This is shown in figure 1 where a 2D ship cross-section moves sinusoidally in heave. The first time instant shown refers to downward body velocity, the last refers to sign change in the body velocity. The upward velocity leads to numerical errors in the velocity field when the flow solution is extended from the free surface outside the liquid domain (see solid velocity vectors), the physical behavior of the velocity field is recovered when the solution is extended from the water to the air/body (see dashed velocity vectors). The use of this

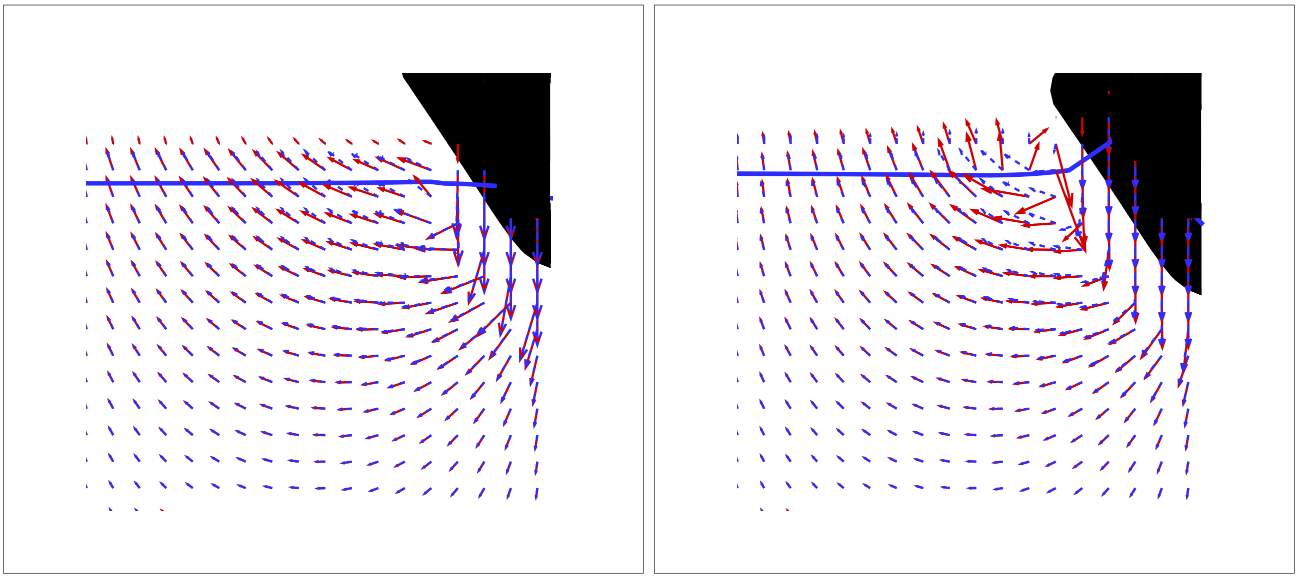

Figure 1: Radiation problem: NS free-surface and velocity vectors at a 2D-ship cross-section. Time increases from left to right. Solid-line solution: velocity extension from outside the water domain. Dashed-line solution: velocity extension from inside the water domain. NS discretization $\Delta x = \Delta z = 0.012L$. The section is forced to move sinusoidally in the vertical plane.

velocity extension involves also numerical errors that reduce with the grid size. Therefore this numerical recipe has been implemented in the solver.

Boundary conditions of the inner solver An overlapping region is used near the boundary of the inner domain and the boundary conditions are enforced in terms of free-surface elevation, fluid velocity and pressure. More in detail, in the upstream and lateral sides the linear free-surface elevation is given to the NS solver, the velocity is obtained as a linear interpolation bridging from the NS solution to the outer potential linear solution, the pressure is estimated solving the Poisson equation. No overlapping is necessary on the bottom boundary, where the velocity and pressure are locally given by the linear solution. A special care is needed at the downstream boundary portion where the body crosses the communication region. Here, both an inflow condition and an outflow condition have been checked. The former is similar to what is done at the upstream and side boundaries, the latter means that the velocity is obtained extrapolating from the inner NS solution while the pressure is enforced as the linear solution for two cells near the boundary. Here the diffraction

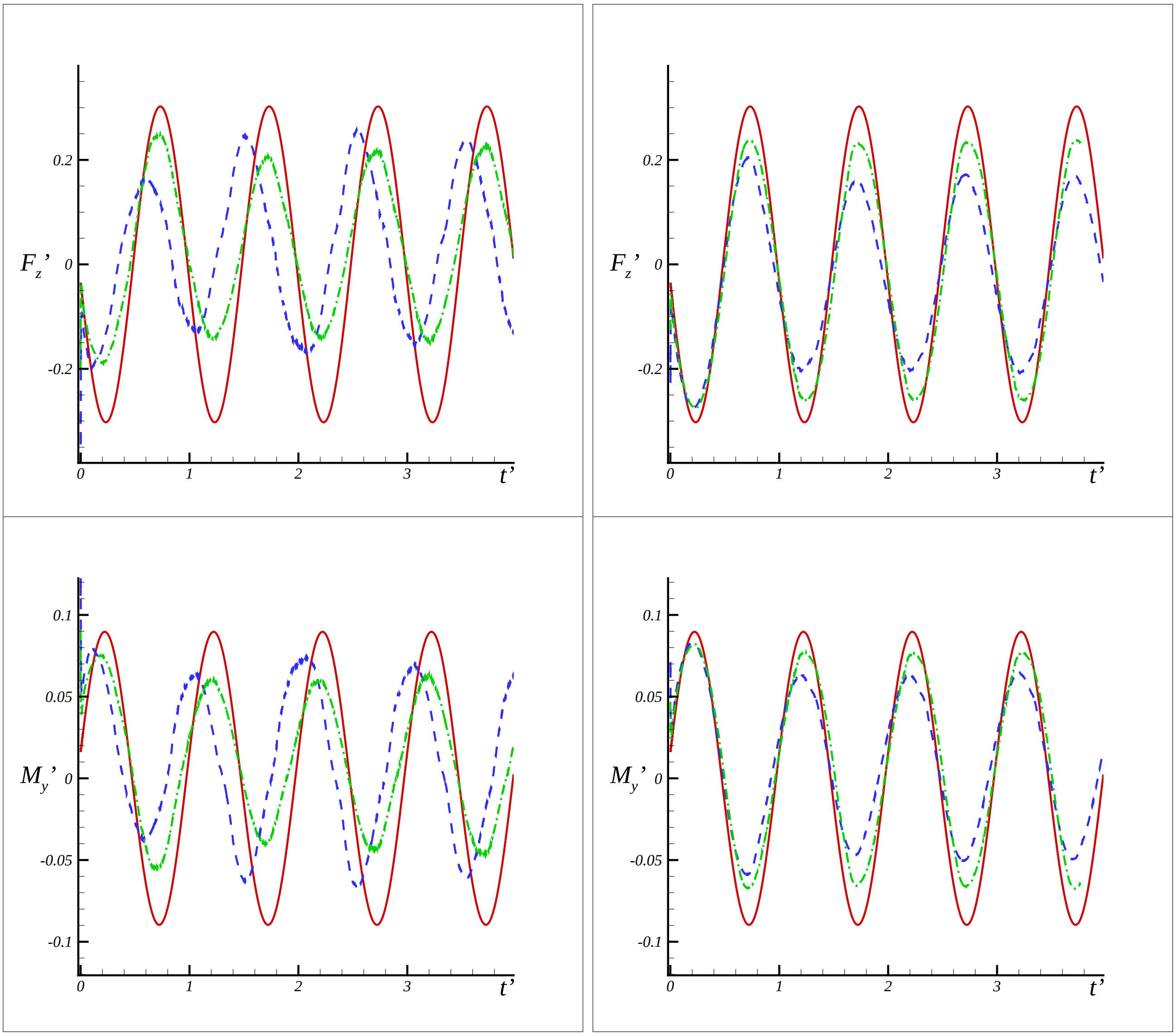

Figure 2: Diffraction problem. Top: nondimensional vertical force $F'_z = F_z/(\rho g L B A)$; bottom: nondimensional pitch moment $M'_y = M_y/(\rho g L^2 B A)$. In each plot: solid line = linear solution, dashed line = NS solution with inflow condition downstream, dashed-dot line = NS solution with outflow condition downstream. Top: NS discretization $\Delta x = \Delta y = \Delta z = 0.012L$. Bottom: NS discretization $\Delta x = \Delta y = \Delta z = 0.006L$. Incident waves long $\lambda \simeq 1.25L$ and steep $kA = 0.05$. L= ship length, B= ship beam, ρ water density and g= gravity acceleration.

problem is used to compare inflow and outflow boundary conditions, because in this way the numerical consequences are not hidden by the body motions and related flow. The results discussed in the following refer to a patrol ship described in Greco *et al*. (2009). The global results using these two boundary conditions are given in figure 2 in terms of diffraction vertical force and pitch moment for the case with incident wavelength-to-ship length ratio $\lambda/L \simeq 1.25$ and small incident wave steepness $kA = 0.05$ for two NS discretizations $\Delta x = \Delta y = \Delta z = 0.012L$ and $0.006L$, respectively. The coarsest discretization corresponds to a hull represented only by 4 cells in the largest draft and 5 cells in the largest beam semi section. Moreover such a course discretization does not allow to model at all the ship bulwark. The finer used grid is also not fully adequate to describe the deck protection (see figures 3 and 4). The NS results are compared with the corresponding load linear solutions. Despite being more natural, the enforcement of the inflow condition leads to worse numerical load solutions for both grid discretizations, for the coarse mesh there is even a phase error which is avoided by refining the grid. The outflow condition appears more reliable and provides convergent results. The two boundary conditions are compared in terms of local variables through figures 3 and 4. Both the boundary conditions cause a phase

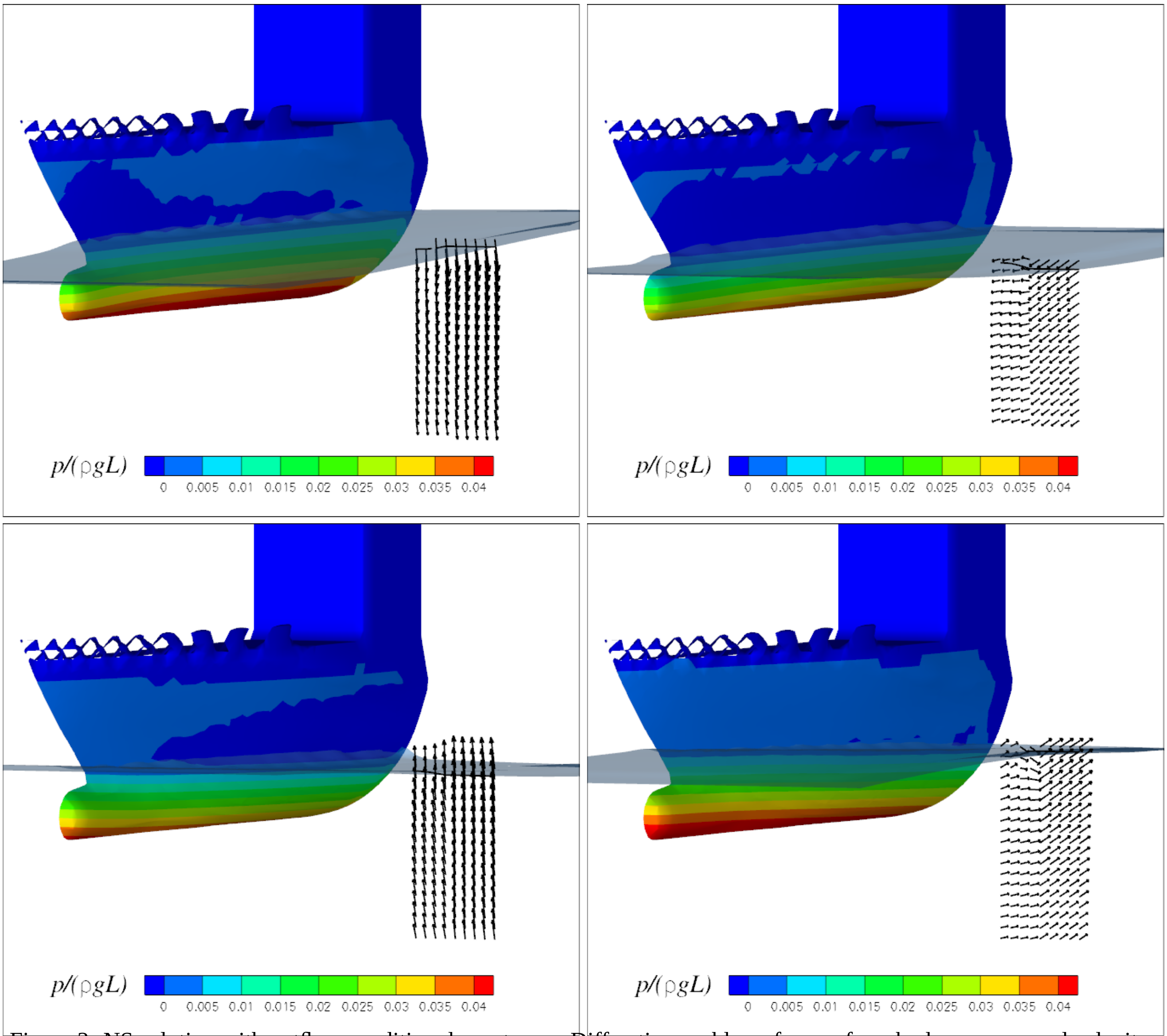

Figure 3: NS solution with outflow condition downstream. Diffraction problem: free surface, body pressure and velocity vectors at the longitudinal distance $x = 0.468L$ upstream the center of the hull. The position of the free surface at the section with $x = 0.468L$ is indicated by the solid line. Time increases from left to right and from top and bottom with $t_0 = 2.84T$, $t_0 + 0.25T$, $t_0 + 0.5T$ and $t_0 + 0.75T$, with T the incident-wave period. NS discretization $\Delta x = \Delta y = \Delta z = 0.006L$. Incident waves long $\lambda \simeq 1.25L$ and steep $kA = 0.05$. L= ship length, ρ water density and g= gravity acceleration.

shift in the velocity on the side of the overlapping region. This can also be seen in the slight difference of the free-surface elevation in that same region. The free surface and body pressure highlight the limitations of using an inflow condition downstream: an overpressure develops on the body because of the slight phase shift between the two solvers velocities. For this reason, the outflow condition has been implemented in the solver. Further steps in the solver evolution will be discussed at the workshop.

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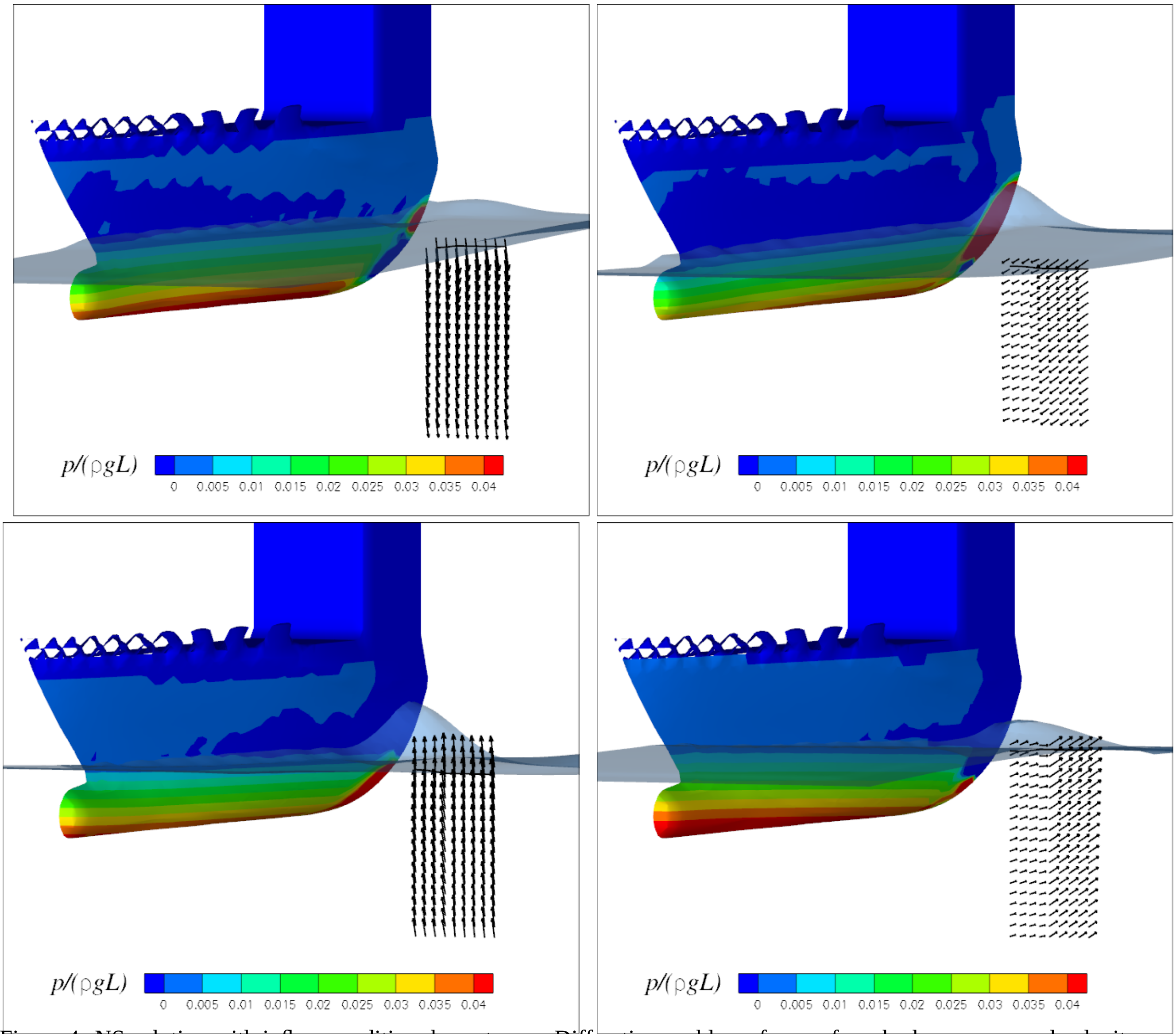

Figure 4: NS solution with inflow condition downstream. Diffraction problem: free surface, body pressure and velocity vectors at the longitudinal distance $x = 0.468L$ upstream the center of the hull. The position of the free surface at the section with $x = 0.468L$ is indicated by the solid line. Time increases from left to right and from top and bottom with $t_0 = 2.84T$, $t_0 + 0.25T$, $t_0 + 0.5T$ and $t_0 + 0.75T$, with T the incident-wave period. NS discretization $\Delta x = \Delta y = \Delta z = 0.006L$. Incident waves long $\lambda \simeq 1.25L$ and steep $kA = 0.05$. L= ship length, ρ water density and g= gravity acceleration.

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