Validation of damaged ship hydrodynamics by a Domain Decomposition Approach using the Harmonic Polynomial Cell method and OpenFOAM

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1. Introduction

Flooding of ship compartments is a complex physical phenomenon involving exchange of floodwater, water dynamics inside damaged hull and vortex shedding near the damaged opening edges. Here a 2-dimensional (2D) domain decomposition (DD) strategy is proposed, where a Navier Stokes (NS) solver with Volume-of-Fluid (VOF) technique, handling the free-surface evolution, is coupled with a potential-flow solver. Differently from Greco et al. (2004) who used a Boundary Element Method in their water-on-deck study, here, the Harmonic Polynomial Cell (HPC) method, proposed by Shao and Faltinsen (2012, 2014) is adopted, which has been proved to be very efficient and accurate. The DD is compared against dedicated model tests and used to complement the physical analysis of the problem.

2. 2D Domain-Decomposition Strategy

In the present work, a 2D DD strategy is described, where the entire fluid domain is divided into two regions as shown in figure 1. In the inner domain region containing the damaged ship section, where viscous effects and vortex shedding might be important, a NS solver is used: the open-source Open Field Operation and Manipulation (OpenFOAM) C++ libraries. In particular, we use the interDyMFoam solver, which can solve multiphase flows and allows dynamic mesh morphing. SIMPLE method is used to transform NS equations into an algebraic system. The NS solver completely encloses the body and extends vertically from the computational top boundary in air to the bottom wall. The grid topology is constant but the cell shapes and sizes can change to compensate for body motion. The VOF technique is used for surface capturing. No slip condition is used at the body boundaries and the bottom wall. The time evolution is performed with the Euler implicit scheme. We have second-order accuracy in space and first order in time.

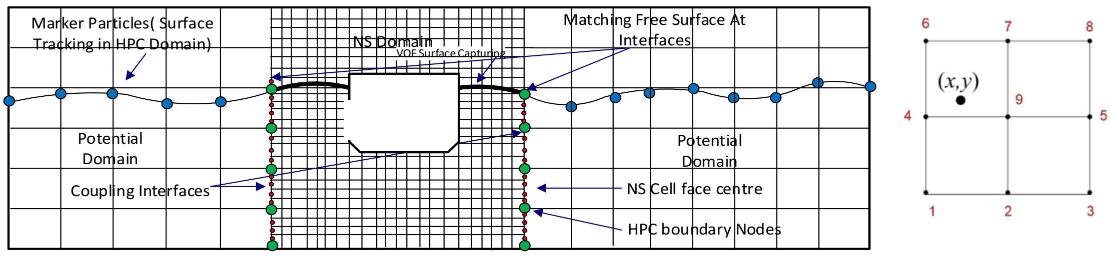

Figure 1: A sketch demonstrating the coupling domains and interfaces used in the proposed DD (left) and a local HPC cell (right)

In the outer region, where potential theory describes the flow evolution adequately, we implemented a HPC method. This is a field solver for potential flow problems. The velocity potential at point (x,y) inside the generic cell in the right of figure 1 is represented as a sum of harmonic polynomials that satisfy the Laplace equation, i.e, $\phi(x,z) = \sum_{i=1}^{8}\sum_{j=1}^{8} c_{j,i} f_j(x,z)\phi_i$. The unknown coefficients $c_{j,i}$ are found enforcing the boundary conditions of the studied problem. All harmonic polynomials up to third order and one fourth-order (first eight polynomials) are included which leads to a spatial accuracy of velocity potential between third and fourth order. Here we adopt an extended version of the original HPC, whose details can be found in Ma et al. (2017). In brief, we use Eulerian structured squared grids. This helps us to calculate coefficients for center nodes of HPC cells just once at the beginning of time-dependent problems, with substantial computational savings. Semi-langrangian markers restricted to move along vertical gridlines are used for free-surface tracking. Nonlinear free-surface kinematic and dynamic boundary conditions are implemented on the surface markers, no penetration condition at the bottom and a damping zone at the far field to dissipate radiated waves. The time evolution is performed with the second order Runge-Kutta (RK2) scheme. Within the DD, the grid strategy used in the NS and HPC domains contributes in limiting the computational costs as the grid topology must be built only at the initial time step. The two domains are coupled at the left and right vertical interfaces as shown in figure 1. We need to maintain continuity of pressure, velocity and free surface calculated from the two solvers across the coupling interfaces spatially and temporally. Pressure and velocity are calculated from HPC solver and passed to OpenFOAM as input boundary conditions. Velocity calculated from OpenFOAM is then passed as input to HPC solver in the form of a Neumann condition. A volume fraction of 0.5 is used to identify the free surface in the NS solver and the free surface is matched at the boundary with HPC marker lying on the domain boundaries. The slope of the free surface at the interface also needs to be matched. Figure 2 demonstrates graphically the time stepping procedure used in the DD. The starting solver is the domain where initial disturbance takes place. In the DD application in section 3, it coincides with the NS solver, while for wave-body interaction problems it would coincide with the HPC solver. In the rare case of initial perturbation in both domains, then an initial iteration process must be carried out to make the flow conditions at common interfaces consistent for the two solvers. Each solver is stepped in time independently and boundary conditions are passed from one solver to the other alternately. For example, in case of forced heave motions described in section 3, NS solver will provide initial conditions at n^{th} time step to HPC domain. Both solvers then march in time independently. The boundary conditions obtained from HPC domain solution at $(n+1)^{th}$ step are passed to the NS domain and serve as corrected boundary conditions for the NS solver for next time step. DD helps in limiting size of NS domain. A smaller inner domain helps us to use a finer grid leading to better flow features resolution in the NS solver as demonstrated in Colicchio et al. (2006). They demonstrated finer grids in the NS solver help in obtaining better flow capturing using three different grid sizes. The grid size for the HPC domain can be much coarser than for the NS solver since it has a higher spatial accuracy. It should be noted that the NS solver requires input values of pressure and velocity at the cell centers whereas the HPC solver takes the velocity conditions at the cell nodes. Therefore, third order interpolation schemes are used to interpolate velocity and pressure values back and forth between the two solvers from nodes to cell centers and vice versa. The solution from this algorithm has been successfully assessed against a solution with enlarged NS-domain. Colicchio et al. (2006) developed a DD using BEM and NS with level set coupling for nonlinear air-water interface flows. They used an overlapping region where solutions from the two domains overlap instead of a sharp interface. This makes the coupling between domains more flexible and can be more stable. For forced motions, since the radiated waves propagate outwards, a single interface works well but an overlapping domain is in development for a damaged section in waves.

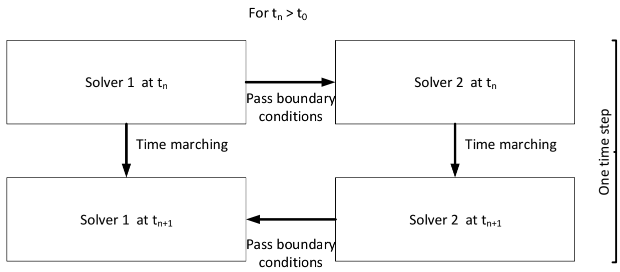

Figure 2: Time stepping used for the numerical DD

3. Application to a damaged ship section

The proposed DD is used here to study forced heave motions for a damaged 2D section. In this case, the primary aim of the outer domain is to propagate the radiated waves outwards and therefore a coarser grid can be used for the HPC domain. The NS domain should be large enough so that the vorticity reflected at the domain boundaries diffuses before reaching the body boundaries. A set of forced heave motion experiments on a damaged barge midship section were carried out in a wave flume at NTNU to investigate local and global consequences on the hydrodynamic loads, with respect to an intact ship. The details of the model section are given in table 1.The experiments were set up to obtain 2D flow features. Here only selected cases are examined; in particular added mass, damping values and flooding behavior inside the damaged section from the numerical method are validated against experimental results for the physical parameters given in table 1. Dimensions of the two domain regions used are shown in figure 3. 75000 cells are used within the NS solver with $\Delta x = 0.02B$ and $\Delta z = 0.02B$. For the HPC solver $\Delta x = 0.1B$ and $\Delta z = 0.1B$ with 80802 nodes for both right and left HPC zones. Smaller cells in the NS domain help in obtaining a sharper air-water interface, with limited VOF smearing and better free-surface resolution.

Length (L)	0.57 m
Breadth (B)	0.5 m
Depth of model (D)	0.3 m
Side damage Length (d)	0.4 m
Side damage height (h_d)	0.08 m
Forced heave amplitude (z_a)	5 mm
Filling depths (h)	8 cm & 14 cm

Table 1. Model section dimensions and experimental parameters

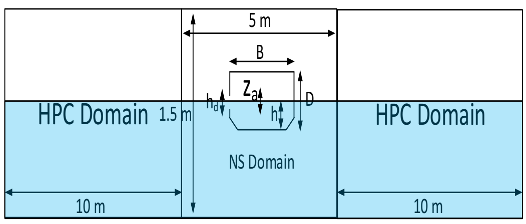

Figure 3: Sketch with dimensions of the two domains and symbols used in table 1

Figure 4 demonstrates that the agreement of numerical added mass and damping coefficients with the experiment values is satisfactory overall but for some minor differences. On the experimental side, error may be introduced due to the glass walls in the flume, three-dimensionality in the experiments and minor measurement errors. For the numerical scheme an in-depth convergence study is ongoing. For the used discretization, errors can be due to improper discretization near the free surface causing poor accuracy for VOF capturing. Some error may also be introduced due to difference in spatial discretization schemes in the two domains. Added mass coefficients for a damaged section are very high compared to those for an intact section especially at small frequencies, which is captured in both experiments and the numerical scheme. This is because at low frequencies the added mass is inertia dominated and large mass of water exchange takes place slowly causing large forces in the vertical direction. The damping is also higher than for an intact section at small frequencies with a secondary peak near the first sloshing resonance frequency.

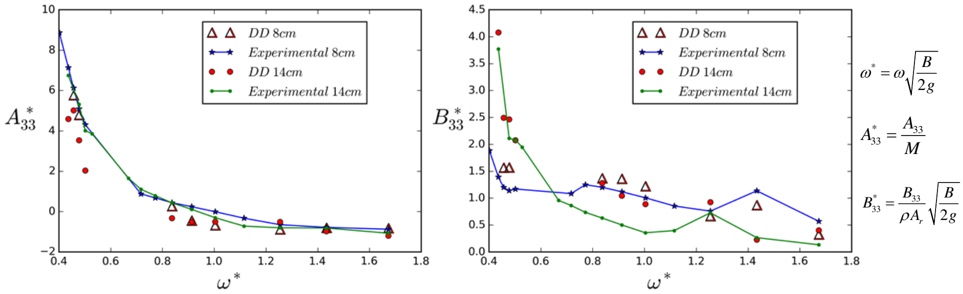

Figure 4: Non-dimensional experimental and numerical added mass (left) and damping (right) coefficients for 5 mm heave amplitude at two filling levels as a function of normalized frequency (A_r is the submerged area of section, M is mass of section)

In case of damaged ship flooding, sloshing and piston mode resonance can be excited. This has been documented adequately by experiment data and videos. Similar behavior is observed in numerical simulations. Figures 5 and 6 demonstrate the behavior of wave systems inside and outside the damaged section. Good agreement is observed for the flow behavior inside and outside the section for both filling levels and two different forcing frequencies. The numerical images are not at the same scale as the images from the physical tests since the resolution of the images in the two cases is different. At 8 cm filling depth, wave systems are associated with shallow water depth conditions in the damaged compartment. As seen in figure 5, for both numerical simulation and experiments, an incoming wave is generated at the opening, which meets with the reflected wave from the wall. This causes a large wave elevation near the middle of the tank and then finally splashes down. This can be an important scenario for loads on internal structures in the case of real ships. We also see that at higher filling depth (14 cm) linear sloshing is excited in the tank. Forced heave motion cannot excite sloshing within linear theory for a closed tank. Therefore, the excitation mechanism is of a nonlinear nature. Figure 6 shows the second mode of sloshing excited in both experiments and numerical simulations.

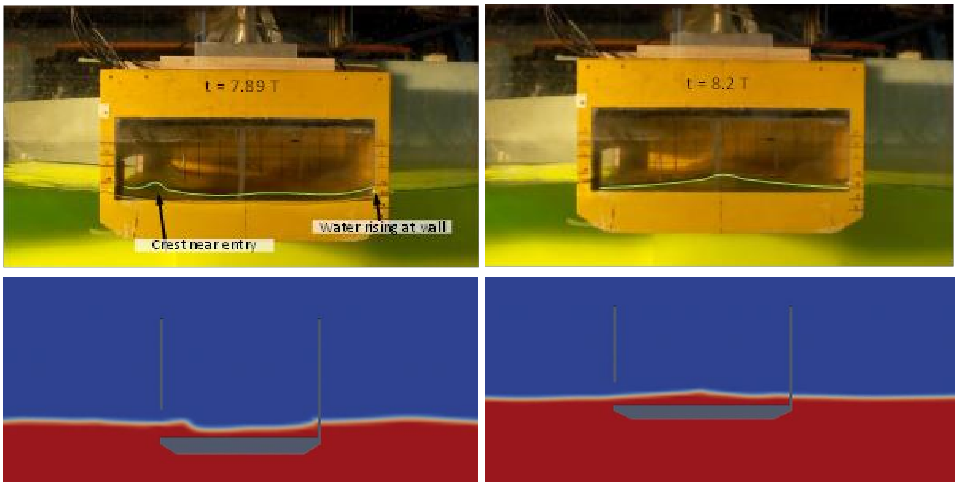

Figure 5: Snapshots of numerical simulations (bottom) along with experimental images (top) at same time instants for a filling level of 8 cm and forcing frequency ω* = 1.67 (in the top plots, T=forcing period)

At higher time periods, piston mode can occur as shown by numerical results in figure 7. A large change of mass occurs inside the compartment at this resonance causing important vortex shedding from the opening edge. From the figure, we see a distribution of vortices near the section and the height of the water inside the tank (h) demonstrates a large change in water mass. This causes large forces in vertical direction leading to high added mass at smaller frequencies. Therefore, it is important to use a NS solver for the inner region, however, these vortices diffuse quickly and in the outer domain the waves are propagated efficiently by the HPC solver. Also, at higher frequencies and 8 cm filling depth the free surface inside the damaged tank can be highly nonlinear with some occurrence of wave-breaking and therefore, a NS solver is better suited for this region.

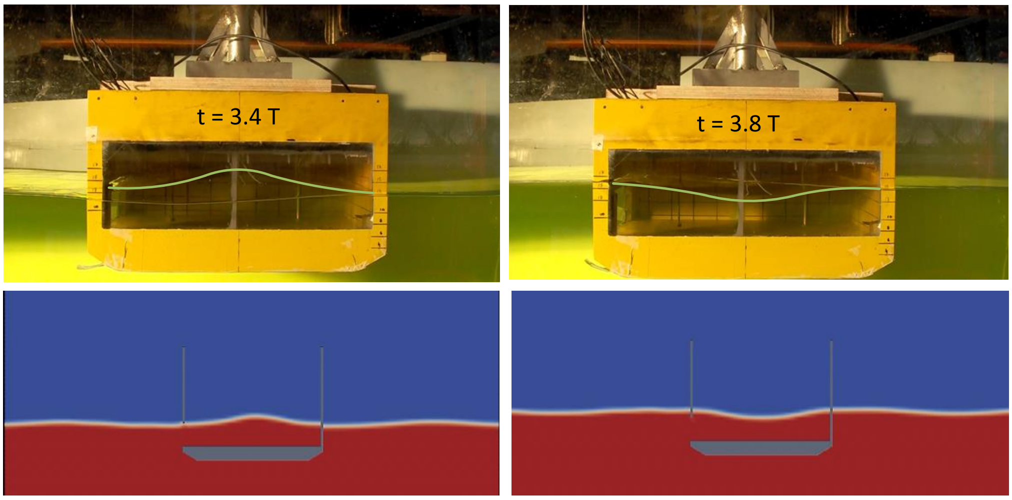

Figure 6: Snapshots of numerical simulations (bottom) along with experimental images (top) at same time instants for a filling level of 14 cm and forcing frequency ω* = 1.67 (in the top plots, T=forcing period)

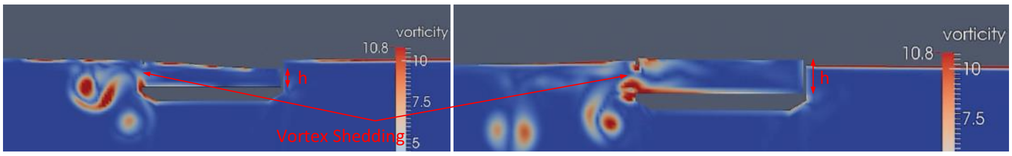

Figure 7: Numerical Vorticity (Hz) in the inner domain for a filling level of 14 cm and forcing frequency ω* = 0.48

4. Conclusions

A 2D DD strategy is developed between a NS-VOF OpenFOAM solver and the potential-flow HPC method. Here, a damaged midship section in forced heave motion has been examined. Good agreement is observed for the proposed DD with experimental results. This is an ongoing work and will be extended to simulate behavior of a freely floating damaged section in beam-sea waves. The HPC solver will be used for wave generation, propagation and dissipation. The results for this analysis will be presented at the workshop. Challenges and limitations using this DD will also be presented.

Acknowledgements
This work has been carried out at the Centre for Autonomous Marine Operations and Systems (NTNU AMOS) and supported by the Research Council of Norway through the Centre of Excellence funding scheme, Project number 223254- AMOS.

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