

Underwater explosions near marine structures: a Dynamic Fluid-Structure Domain-Decomposition strategy

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Historically underwater explosions (UEs) have been investigated for their huge military relevance, but they remain an important issue also for civil marine applications. As an example, UEs can occur near or on oil-gas plants due to severe environmental conditions or human errors and this has substantial consequences for the production. Preliminary information about time scales of the phenomenon and knowledge about possible strategies on how to limit the consequences of its interaction with close-by structures is crucial to make the proper decisions. A numerical investigation would in general require a 3D compressible (at least) two-phase hydro-dynamic solver strongly coupled with a suitable model of the involved structure. Because the CPU-time requirements are still too high for reliable and feasible predictions, a Domain Decomposition (DD) strategy has been proposed by Colicchio *et al.* (2013) and Colicchio *et al.* (2014) and applied to a fully coupled fluid-structure analysis by Colicchio *et al.* (2015). Here, the DD is further extended as Dynamic DD (DDD) to overcome limits of applicability in time. The dynamic strategy proposed is not limited to UEs problems and to the two coupled solvers involved. When examining the UE interaction with a marine structure, like a surface ship, one can distinguish basically two stages: the first one, with important compressible effects and local fluid-structure interactions; the second one, with global consequences for the structure, possibly involving large deformations and damages as well as free-surface waves generation. The present research focuses on the first stage but the proposed DDD strategy can be adopted also for the second stage.

Basic hybrid method Unless the underwater explosion occurs very close to a boundary, gravity effects can be neglected and the UE features a radial symmetry with the formation of a spherical gas bubble, rapidly expanding and eventually oscillating. The initial acoustic phase and the later cavity phase are relevant for structures not far from the initial explosion. Based on this, the developed DD solves the problem through a weak coupling between a 1D radial blast solver (solver 1) and a 3D compressible flow solver (solver 2). Solver 1 is a first-order finite-difference (FD) scheme in space and time based on the Harten-Lax-Van Leer (HLL) approximate Riemann solver while solver 2 is a FD method with second order accuracy in space and third order in time treating the fluxes with a Harten-Lax-van Leer contact (HLLC) Riemann solver. Solver 2 is used to examine the UE interaction with a marine structure modelled either as rigid or as a deformable 3D plate assuming small deformations and orthotropic plate theory (see *e.g.* Faltinsen 1999). An Adaptive Mesh Refinement (AMR) limits the computational time by reducing dynamically the local cells size only when the flow gradients overcome a threshold value. The basic DD identifies instead statically the 1D and 3D sub-domains, *i.e.* at the beginning of the simulation.

Left plot of figure 1 shows the evolution of the structure UE-induced pressure assuming a numerical UE equivalent to the experiments by Hung *et al.* (2005) used for validation of the method (see Colicchio *et al.* 2014). The explosion

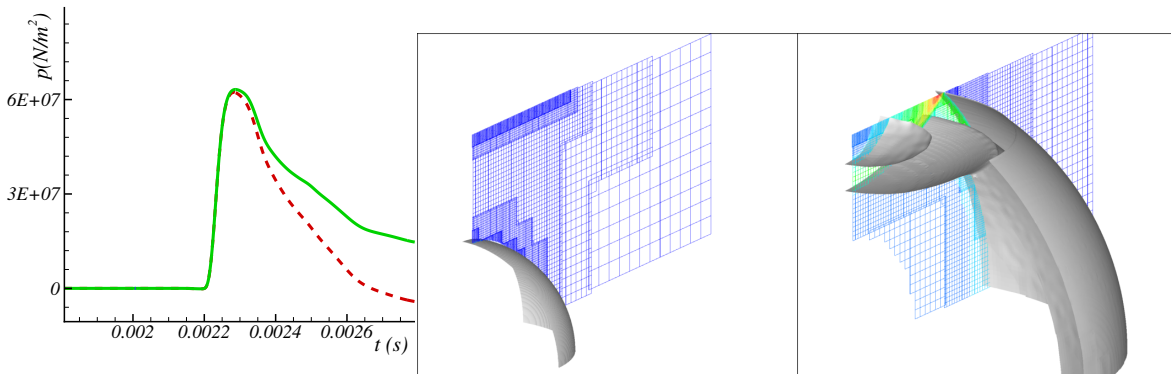


Figure 1: Basic hybrid method (see Colicchio *et al.* 2014). Left: pressure, relative to the water ambient pressure $\simeq 0.1$ MPa, at the center of the plate from approximate (green solid lines) and full (red dashed lines) FSI. Center and right: development of radial asymmetric features. The slice shows also a hole where the radial 1D solution is used and highlights the dynamic mesh refinement provided by the AMR strategy.

takes place at $4m$ from a parallelepipedal structure with flexible bottom. The gas cavity has initial radius $r_0 = 0.16m$,

density $\rho_0 = 1630.0 \text{ Kg/m}^3$ and pressure $p_0 = 8.381 \cdot 10^9 \text{ Pa}$. The results refer to weak and strong fluid-structure interaction (FSI) strategies and highlight the relevance of a strong coupling for a proper detection of cavitation phenomena near the structure. During the interaction, due to the wave reflection from the body, radial asymmetries develop in the flow as shown in the center and right of figure 1. When they reach DB, the basic DD must be stopped. This limitation is overcome by the DDD.

Dynamic domain decomposition strategy Very few works exist in literature with dynamic evolution of the boundaries between solvers in DD strategies. An example can be found in the work by Sriram *et al.* (2014), where an Improved Meshless Local Petrov Galerkin method and a finite element method are strongly coupled to model breaking and non breaking waves. Colicchio *et al.* (2015) use a DDD strategy to strongly couple a Finite Difference Navier-Stokes (FD-NS) solver with a Lattice Boltzmann Method (LBM) to follow the flow evolution downstream a cylinder.

Here, the DDD is applied as a weak (one-way) coupling. The fact that the information travels only from the 1D to the 3D sub-domain makes more challenging the identification of the boundary and its tracking in time. One must stress that, even if as time goes on the solver-1 zone reduces in favor of the more expensive solver-2 region, the developed DDD is very advantageous compared with using the full 3D solver for the whole evolution. This is because: (1) at the beginning the 3D domain is very limited and the evolution of UE effects can be accurately and efficiently described by the radial solver; (2) later on the 3D domain enlarges but the flow features can be captured with less refined grid than at the initial stage. To explain the DDD strategy the same UE as described above is examined but it is assumed to occur at the centre of a closed cubic rigid tank with size 6m and filled with water. At the initial stage of the evolution, solver 1 can be used almost everywhere while the 3D features are modelled only near the tank sides (see left side of figure 2) using solver 2. The 3D domain is dynamically divided into AMR blocks, each with, say, n_x , n_y and n_z cells in x , y and z

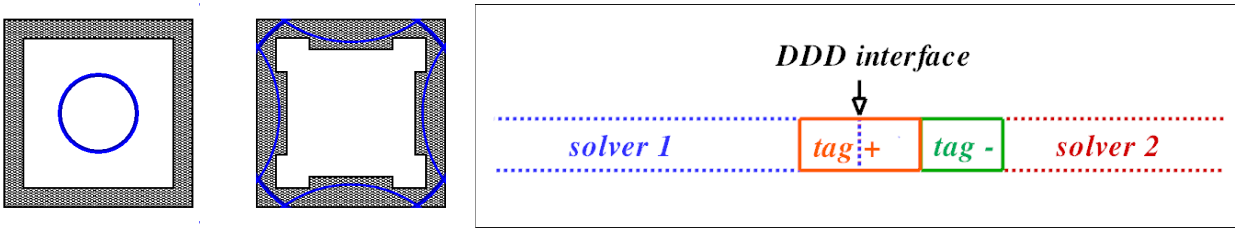


Figure 2: Left and center: central section of the 3D domain with the initial decomposition (left) and the decomposition after the reflection from solid boundaries (center). The 3D algorithm is used in the grey shaded area, the 1D solver in the white area. The blue line represents the evolution of the compression wave generated by the explosion. Right: domain subdivision along the local normal direction at the DDD boundary with the definition of the auxiliary zones with tag + and -.

directions. Moreover, when the compression wave from the explosion is reflected by the tank walls, the DDD boundary (DB) modifies dynamically enlarging in time the area computed by solver 2, as shown in the center of figure 2 which refers to a later time instant. This is obtained through the following algorithm.

Let us move along the local normal direction of the DDD boundary and assume that we have the zones for solver 1 and 2 in the left and right of the boundary, respectively (see in the right of figure 2). Across DB an overlapping region exists (tag +) where the solution smoothly goes from the solver-1 to solver-2 values through a weighting law based on the position relative to DB. This means that both solvers are used to analyze the problem in the region with tag +. Actually, within the weak coupling, solver 1 models the fluid in a wider domain than the tank and as the tank walls were not there. This prediction is used to initialize the solution in solver 2 sub-domain and to provide information to it in time through the DDD boundary. This implies that only solver 2 can enlarge on regions of domain previously described by solver 1. To assess when this has to happen, a solver-2 region near and until the overlapping is defined at the beginning and updated in time to compare the solutions from the two solvers (tag -). Every n time steps, with n chosen as a compromise between solution accuracy and efficiency, a three-step check is performed: (1) blocks with tags - and + are searched. Each block with tag - becomes a solver-2 block if $|\bar{\rho}_{3D} - \bar{\rho}_{1D}| / (\bar{\rho}_{3D} + \bar{\rho}_{1D}) > 0.05$, with $\bar{\rho}_{3D}$, $\bar{\rho}_{1D}$ and $\bar{\rho}_{3D} - \bar{\rho}_{1D}$ the block mean values of the density ρ from the 3D and 1D solvers and their difference. Each block with tag + is labelled as a solver-1 block and listed for a second check; (2) listed blocks with solver-2 neighbors receive the tag - otherwise are stored for a third check; (3) listed blocks with neighbors with tag - receive the tag +. At this stage the regions with pure 1D and 3D solutions and their overlapping are identified and the problem can be stepped in time accordingly. This check is performed on the AMR blocks because at cell level would be much more expensive.

DDD application to a 1D case The 1D version of the dynamic hybrid solver is used to study the collapsing bubble labelled as case 1.A by Wardlaw (1998) with centre in $x = 0m$ and assuming a wall at $x = 3.1m$ for solver 2 and much longer domain for solver 1. When the compression wave from the bubble is reflected from the wall the DDD should move the DB to allow solver 2 to follow the backward motion of the shock. Figure 3 shows the evolution of the wave front calculated both with solver 1 everywhere and with the DDD. At the initial time shown the shock front propagates from

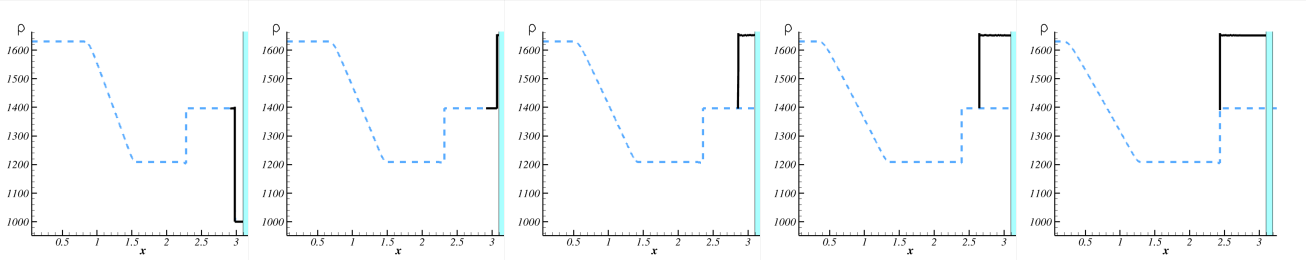


Figure 3: 1D solution in dashed line and DDD solution in solid line for the case of a 1D problem at $t=0.288-0.328-0.368-0.408-0.448\mu s$.

one domain to the other without any problem and the two results are superimposed. When the wave front reaches the wall, the DDD sees a reflection of the shock wave that moves backwards, the solution is able to capture this behaviour with the solver-2 domain enlarging from the third time instant shown on.

This study highlighted that within a DDD strategy the overlapping region across DB must be wider than for a static DD to ensure a smooth transition of the solution: when using a thickness four times the local mesh size Δx , as for the basic hybrid method proposed by Greco *et al.* (2014), the continuous variation of the DB position and the approaching of the reflected wave cause local discrepancies between the solvers that can lead to unphysical solution oscillations at DB. The smoothing thickness should be at least $10\Delta x$. In the present study a cosine law, say I_x , was identified as suitable interpolation function with parameters the distance from DB, the number of cells per block, n_{xb} , and a coefficient eps .

DDD application to a 3D case The 1D smoothing law for the overlapping region has been extended to 3D problems as the product of three cosine functions, *i.e.* $I = I_x I_y I_z$. Different values of eps can be suitably selected for each direction so to reduce the anisotropy of I . Here $eps=1$ is set for each direction and $n_{xb}=n_{yb}=n_{zb}$ is used for each block. The resulting DDD is applied to the UE in the cubic rigid tank defined above. Figure 4 shows the development in time of the solver-2 region. The 3D computation starts only when the compression wave approaches the boundaries of the domain

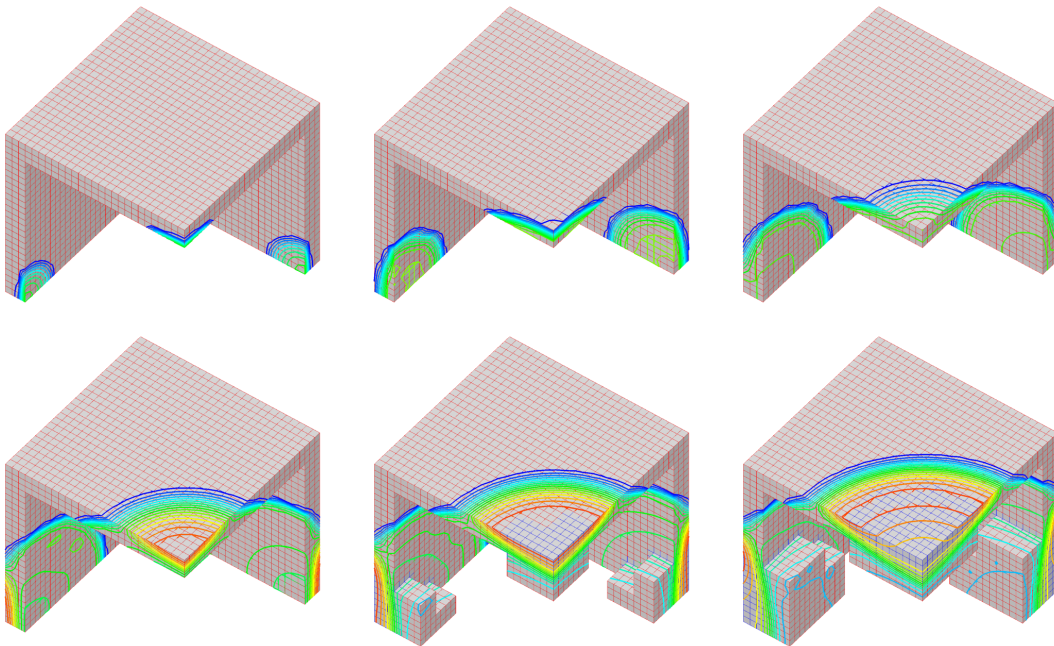


Figure 4: DDD for the UE interaction with the wall: blocks of the solver-2 domain. The mesh colour represents the tag of the block, red stands for - and blue for solver 2. Time increases from left to right and from top to bottom.

(see left upper panel). All the boundary blocks have tag -, so the comparison of the 3D solution against the 1D radial value is carried on there. The difference between the two solutions overcomes the threshold limit when the reflected wave approaches the boundaries of some of the blocks with tag - (see central bottom panel). Then the solver-2 domain enlarges as radial asymmetric flow features grow in the computational domain. For this simple problem, the computational time with the DDD strategy is a fourth of the one with a comparable DD method.

The need for a DDD strategy becomes more stringent in the case of multiple explosions at generic location from the structure, with different charge and generic relative time lag. Left plot of figure 5 shows as an example two explosions occurring near a structure. This could be a realistic scenario inside a pipeline, with the view given in the cross-sectional plane. The individual UEs can be simulated with the radial solver as the other explosion and the structure were not there,

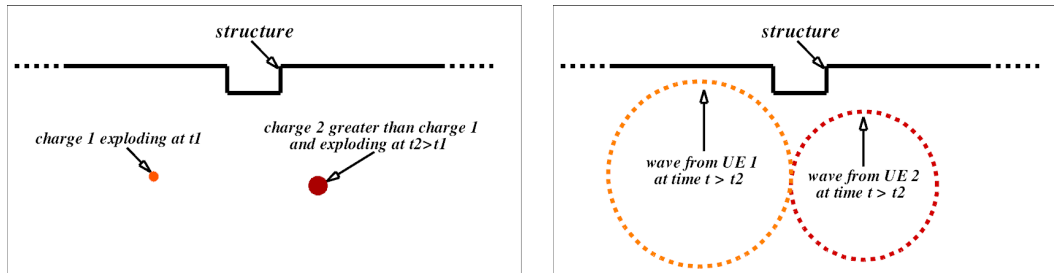


Figure 5: Scenario with two UEs near a structure: charge positions and relative time of explosion (left), and time instant of the interaction for the acoustic waves from the UEs (right).

with great saving of CPU time relative to a full 3D solution. Such strategy is suitable until the acoustic waves resulting from the UEs interact with each other. In the examined scenario, this occurs before the waves reach the structure (see in the right of the figure) and induces radial asymmetries requiring earlier the enlargement of the 3D sub-domain initially limited near the pipeline boundary.

The details of the solution method and its application for the physical investigation of multiple UE phenomena will be discussed at the Workshop.

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