Computers & Fluids XX (201X) XX–XX

Contents lists available at ScienceDirect

Computers & Fluids

journal homepage: www.elsevier.com/locate/compfluid

Gas cavity-body interactions: efficient numerical solution

Giuseppina Colicchio[a,b], Marilena Greco [a,b,c], Odd M. Faltinsen [b,c], Maurizio Brocchini [d,*]

[a] CNR-INSEAN, Italian Ship Model Basin, Roma – Italy
[b] CeSOS and AMOS, NTNU, Trondheim – Norway
[c] Dept. of Marine Technology, NTNU, Trondheim – Norway
[d] DICEA, Università Politecnica delle Marche, Ancona, Italy

ARTICLE INFO

Article history:

Keywords:
Gas cavity-fluid-structure interaction
Acoustic phase
Hyperbolic equations
Domain Decomposition

ABSTRACT

The paper investigates the interactions occurring between a gas cavity, the surrounding liquid and the nearby structures. In more detail, focus is in the characterization of the various dynamical phases (e.g. “acoustic phase” and “gas bubble phase”) and in the design of a modelling approach aimed at minimizing the computational efforts needed to analyse the cases of gas cavities spatially close to the target structure. Hence, a Domain Decomposition (DD) strategy is proposed which enables efficient computations. Hyperbolic flow equations govern the flow evolution and, while the inner domain 1D solution is calculated by means of an HLL scheme for the fluxes and a 1st order time stepping, the outer domain 3D solution is achieved on the basis of a MUSCL scheme coupled with a 3rd order Runge-Kutta time stepping. Various comparative tests, based on use of the full-scale experimental data by Smith (1975), have been used to test the DD strategy. A simplified approach is, finally, proposed to be used for the complex case of multiple cavity explosions. Use of the approach reveals that the worst load scenario for the target structure occurs when all cavities explode simultaneously.

1. Introduction

The study of the interactions between a gas cavity, the surrounding liquid and the nearby structures in the acoustic regime is very appealing because it involves several physical phenomena and it is of practical interest in different contexts: from underwater explosions, to medical applications, to erosion of propellers.

In [1], the implosion of micro-bubbles close to human tissues has been studied with reference to ultrasounds used to remove calculi in human bodies. In [2], it is shown that the cavitational bubble collapse can cause a shock wave associated with erosion damage on solid surfaces in hydraulic machinery.

Although there are many practical studies on micro-bubble explosions, most of the results are for military purposes (e.g. underwater explosions of mines close to ships and offshore structures). There, it is necessary both to predict structural effects and improve the design of the structures. To this purpose, physical tests were performed over the years and theories were developed [3].

* Corresponding author. Tel: +39-071-2204522; Tel: +39-071-2204528; E-mail: m.brocchini@univpm.it

Because of this abundance of information, the first application of the validation of the present work is carried on underwater explosions.

All the above described problems are characterized by: 1) bubble oscillations with the generation and/or interaction with acoustic waves, 2) interaction of the acoustic waves with the surrounding structures, 3) reflection of the waves and 4) their interaction with the bubble. All these phenomena evolve within the so-called "acoustic phase", because compressibility is important for both water and gas phases.

The study, here summarized, covers most of the points described above, some other results connected with the dynamics of the "acoustic phase" are reported in [4]. The following stage, where compressibility becomes unimportant for water and it is an issue only for the gaseous phase, is described in [5]. The generality of these features allows the proposed approach to be later extended to study the effect of multiple explosions close to a structure like those presented in [6].

The paper is organized as follows. Section 2 describes both the problem formulation and the Domain-Decomposition strategy. In Section 3 an approach is proposed for the simplification of the problem for the case of multiple explosions. The tools and procedure introduced in Sections 2 and 3 are, then, applied to a specific case of multiple explosions. Conclusive remarks and lines for future research are, finally, proposed.

2. The solution strategy: a time-space domain decomposition and preliminary validation

The complexity of the involved phenomena makes this study difficult: at least two fluids, with very different properties, have to be studied and there is also the description of the behavior of a structure under almost impact pressures.

The equation describing the flow is:

$$\frac{\partial \mathbf{U}}{\partial t}+\frac{\partial \mathbf{F}_x}{\partial x}+\frac{\partial \mathbf{F}_y}{\partial y}+\frac{\partial \mathbf{F}_z}{\partial z}=0 \qquad (1)$$

with $\boldsymbol{U}=[\rho, \rho u, \rho v, \rho w, E]^T$, $\boldsymbol{F}_x=[\rho u, \rho u^2+p, \rho uv, \rho uw, (E+p)u]^T$, $\boldsymbol{F}_y=[\rho v, \rho uv, \rho v^2+p, \rho vw, (E+p)v]^T$, $\boldsymbol{F}_z=[\rho w, \rho uw, \rho wv, \rho w^2+p, (E+p)w]^T$. Here u, v, w are the velocity components, p the pressure, ρ is the fluid density and E the total energy $\rho[e+(u^2+v^2+w^2)/2]$.

These equations are completed by the equation of state (EOS) for the specific internal energy e. Here this is assumed of the form $\rho e = f_f(\rho)p+g_f(\rho)$, with the functions f_f and g_f depending on the fluid properties. In particular, the Jones-Wilkins-Lee EOS is used for the gas [7] and an isentropic Tait relation for the water [3] i.e.

$$f_g=\frac{1}{\omega} \quad g_g=\frac{1}{\omega}\left[-A_g\left(1-\frac{\omega\rho_g}{R_1\rho_{0g}}\right)e^{-R_1\rho_{0g}/\rho}-B_g\left(1-\frac{\omega\rho_g}{R_2\rho_{0g}}\right)e^{-R_2\rho_{0g}/\rho}\right]$$

$$f_w=\frac{1}{\gamma_w} \quad g_w=\frac{(B_w-A_w)\gamma_w}{\gamma_w-1} \qquad (2)$$

where the subscripts g and w stand for gas and water, respectively, ρ_{0g} is the initial gas density, γ_w is the ratio of specific heats for water, while R_1, R_2, B_g, A_g, and ω depend on the explosion features. The dynamics of the structure is modeled like that of an orthotropic plate:

$$\bar{m}\ddot{w}+D_x\frac{\partial^4 w}{\partial x^4}+2B\frac{\partial^4 w}{\partial x^2\partial y^2}+D_y\frac{\partial^4 w}{\partial y^4}=p(x,t) \qquad (3)$$

where $\bar{m}$, D_x, D_y and B are characteristics of the structure and p is the pressure loading.

The aim of the present work is to study the effect of multiple explosions which take place at different times and positions with respect to the structure in analysis. A fully 3D coupled fluid-structure interaction solver, being time consuming, would limit the extent of the statistical analysis. For this reason, first the problem of a single exploding bubble is analyzed; the physical features of the problem are highlighted together with the possible simplification of the analysis, and then multiple explosions are taken into account.

However, even the study of a single explosion can be time consuming and, to make the study as efficient as possible, several numerical techniques are used, eventually combined within a more general solution strategy.

In particular, two types of coupling have been performed: a) 1D-3D solutions for the analysis of the fluid phase and b) 1D solution-structural analysis for the study of the fluid-structure interaction. In both cases, we assume that the explosion occurs very far from other boundaries and that the hydrostatic pressure does not affect the explosion phenomenon, leading to a radial symmetry of the bubble evolution.

A compressible 1D solver along the radial direction r is, then, used to simulate the flow evolution until the first shock wave from the explosion becomes close to the rigid boundary of interest. This can be done because the problem equations are hyperbolic and the downstream flow is quiescent, therefore, the presence of the structure does not affect the fluid upstream of the shock wave.

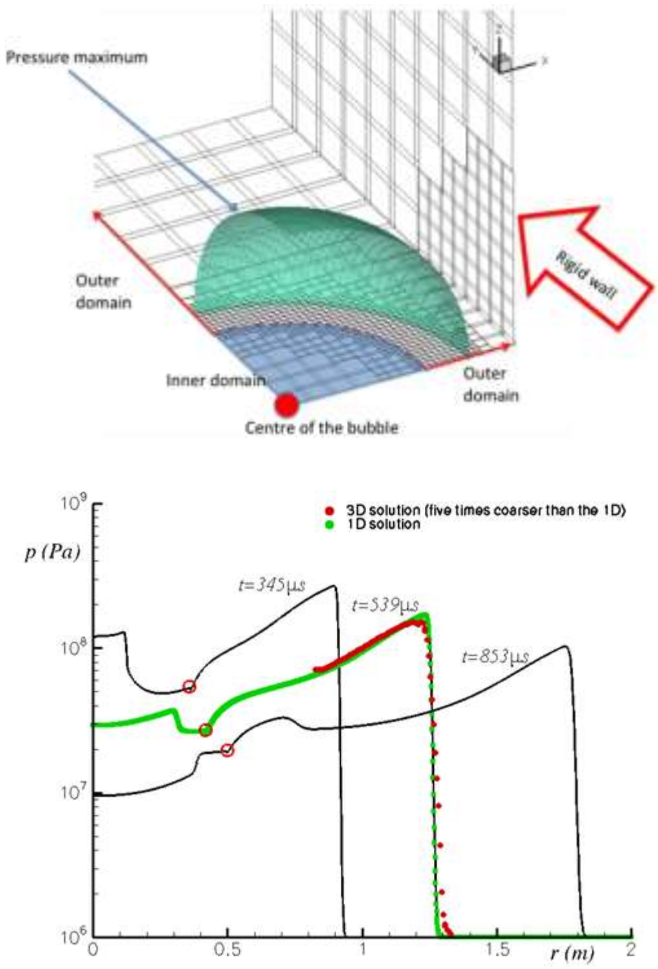

Fig. 1. Top: example of the domain of solution. The inner domain with the bubble is analyzed with a 1D approximation of equations (1) and the outer flow with a 3D solution. The black lines represent the edges of the blocks in which the domain is decomposed, they become finer with increasing pressure values. Bottom: comparison of the 1D and 3D pressure solutions for the underwater explosion of [9]. The red large circles give the position of the gas-water interface.

As the shock wave becomes close to the body, in case a), a time-space Domain-Decomposition (DD hereinafter) strategy is switched on, where a compressible 3D solver is initialized by the simplified 1D solution in an inner region affected by the body and used to investigate the fluid-body interactions. The 1D solution is still applied far from the structure and provides the boundary conditions to the 3D solver along a control surface bounding the inner domain as described in the top panel of Figure 1.

This implies a one-way coupling between the solvers and limits this kind of decomposition up to the instant the reflected waves reach the inner region. Even with the DD approach the 3D solution can be very time consuming, hence an Adaptive Mesh Refinement (AMR) has been introduced to make the solution faster.

The algorithm described in [8] is used to refine the mesh size where large pressure gradients take place, as shown in the top panel of Figure 1. The bottom panel of the same figure documents the comparison between 1D and 3D/1D coupled pressure profiles along the ray of the explosion in the case described in [9]; even though the meshes are rather different for the two solvers, the position and the intensity of the shock wave are quite well captured by the DD strategy.

The 1D/3D solution is then able to describe the reflection of the acoustic waves generated by the explosion on the boundary of the domain as shown in Figure 2, where an isosurface of density $r=1061 kg/m^3$ is shown, as well as the pressure contour on the mid section of the domain.

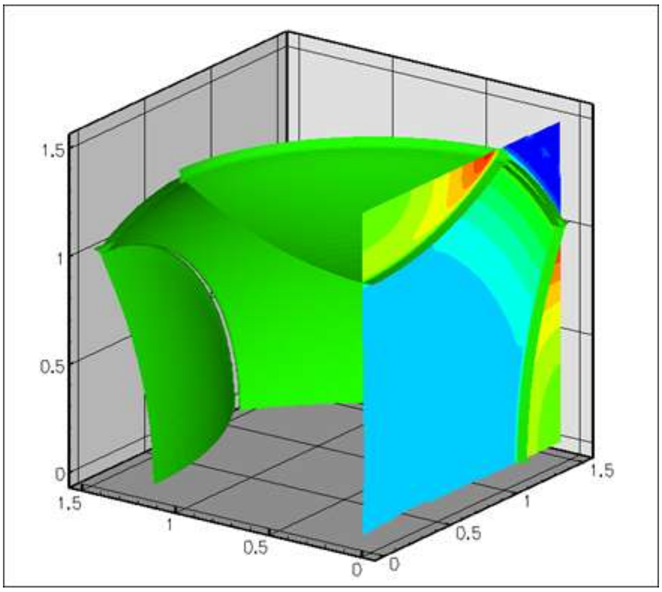

Fig. 2. Reflection of the compression wave from an explosion onto solid boundaries. An eight of the domain is shown.

In case b), the analysis of the interaction of the shock wave with the structure has been first studied in a simplified way, i.e. assuming that the radial incoming waves are simply reflected back from the moving structure so that the loading pressure can be written as

$$p(x,t) = 2P_i(x,t) - \frac{\rho c \dot{w}}{\cos\theta} - \text{added mass} \quad (4)$$

where the first two terms on the right hand side are compressible contributions and the last one an incompressible term. The results of this coupling are illustrated in detail in [10].

Figure 3 shows the effect of the almost-impulsive pressure peak on the inception of the free vibration of an orthotropic plate, similarly to what described in [10].

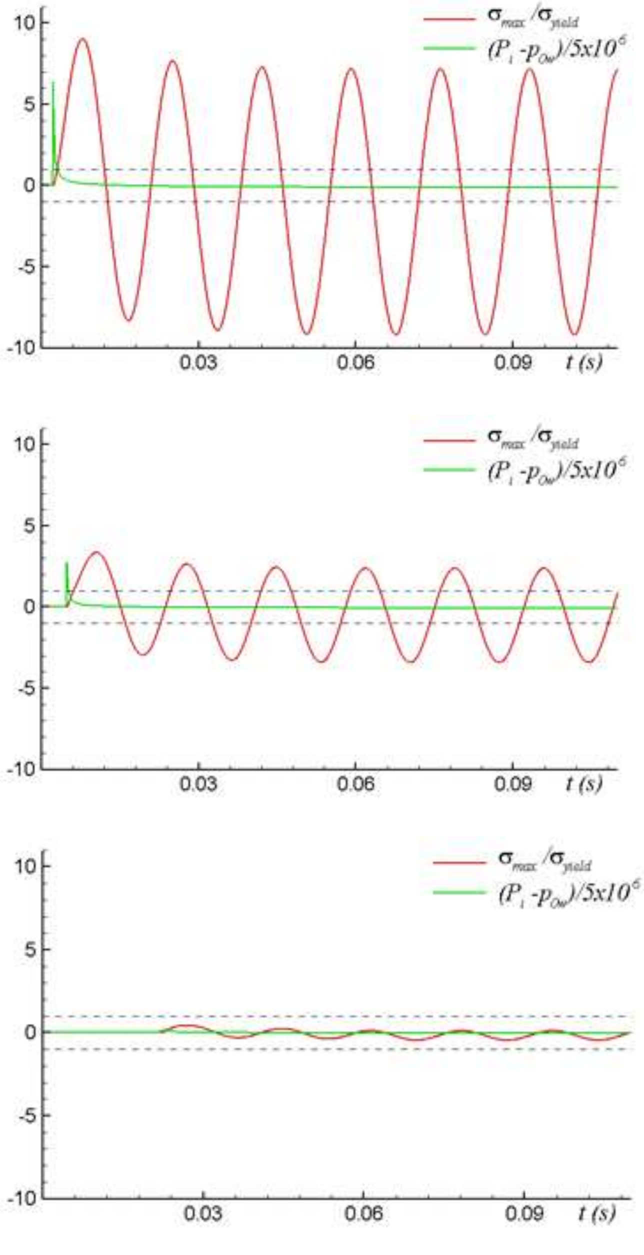

Fig. 3. Effect of the distance on the maximum stresses on the plate (distance increases from top to bottom (*r=4m, 8m, 35m*).

The maximum stresses generated by this vibration vary with the distance of the explosion. If it takes place further than 35m, the maximum stress does not exceed the yield stress, this means that deformations are only elastic, if the distance is around 8m the deformation can occur in the plastic regime, if it takes place closer, a plastic deformation of the plate surely occurs with an eventual rupture of the plate. In case of a small plastic deformation, the maximum displacement has been taken to be the plastic deformation of the plate and compared with other numerical and experimental findings from [11] (see Figure 4).

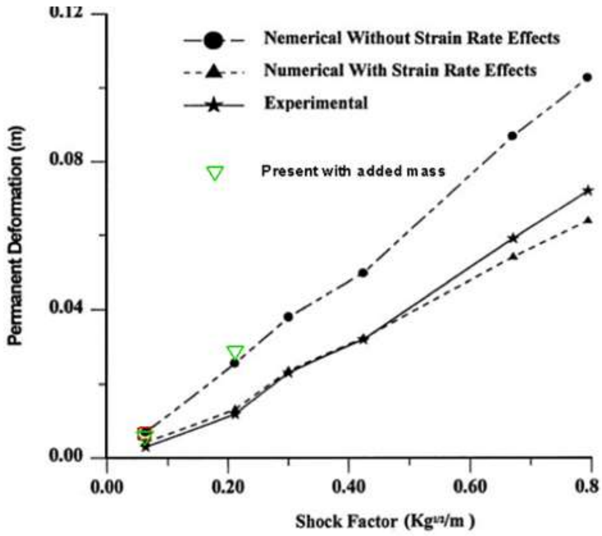

Fig. 4. Comparison of the permanent deformation with other numerical and experimental results from [11].

For small plastic deformations, the agreement is promising, although the approach is much simplified. As the explosion becomes more intense the discrepancy is larger and it is due to having neglected the nonlinear strain rate effect, as shown in the other numerical data.

3. Simplification of the problem in case of multiple explosions

Once the tools for the analysis have been validated, they can be used to identify possible simplifications of the problem in case of multiple explosions.

First, the areas where the superposition principle could be valid are estimated by using the 1D/3D coupled solver to check if: 1) the acoustic waves generated by multiple explosions interact by simply superimposing each other, 2) the contribution of the acoustic waves generated by a small displacement of the boundary can be accounted for as a simple superposition to the acoustic wave existing in the case of a fixed boundary.

To simplify the analysis, hereinafter the explosion described in [9] is taken as the benchmark for all the examples. For this case, we can make variables dimensionless by characteristic fluid dynamic quantities. In particular, lengths are made dimensionless by $L_0=c\ T_{bubble}$ where $T_{bubble}=0.135s$ is the period of oscillation of the bubble and $c=1450m/s$ is the sound speed in water.

Figure 5 shows the effect of the superposition of two acoustic waves (top panel) generated by two simultaneous explosions taking place $0.02L_0$ apart. In the bottom panel the red solid line represents the full solution and the blue dashed line gives the superposition of the curves shown in top panel: the pressure contours are practically superposed and the differences are due more to the different discretization deriving from the AMR technique than to nonlinear effects.

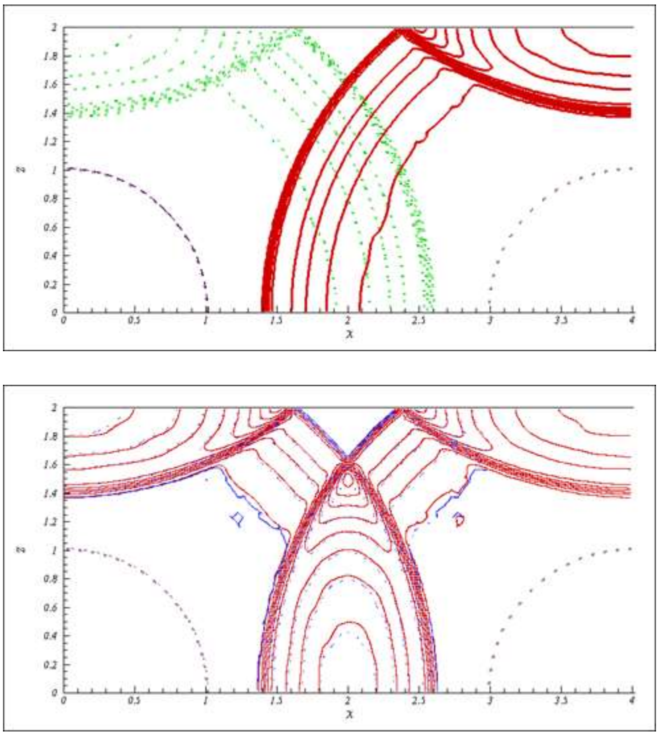

Fig. 5. Pressure contours generated by two explosions. Top: pressure field generated by each separate explosion. Bottom: pressure field calculated as the sum of those in the left panel (blue dashed line) and as solution of the two simultaneous explosions (red solid line).

Figure 6 examines the interaction of a moving boundary with an acoustic wave (generated by an explosion at $0.01L_0$ from the solid boundary). The green dashed line is the pressure field generated by an explosion reflection on a wall moving with velocity w_b. The effect of the wall motion can be modelled simply superimposing the pressure $\rho c w_b$ to the pressure field generated by the reflection of the acoustic wave on a fixed boundary. The result is plotted with the red solid line in the figure..

The differences in the pressure field are very limited, this meaning that the effect of the incidence angle θ of the incoming wave relative to the wall normal direction (factor $1/cos(\theta)$ in equation (4)) can be disregarded in the acoustic damping.

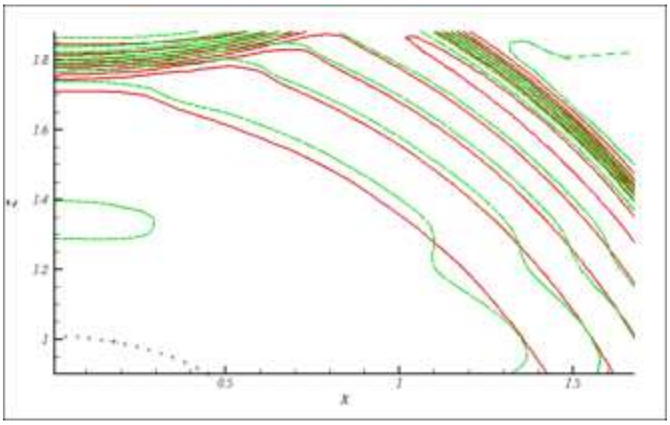

Fig. 6. Pressure contours generated by the reflection of acoustic waves on a moving wall (green dashed line) and on a fixed wall and shifted by $\rho c w_b$.

In these examples, the maximum Mach number in water is of the order of *0.1*, this means that compressibility effects are limited, similarly for the nonlinear interaction of the waves.

The above result enables a simplified description of multiple explosions, i.e. by simply superimposing their effects and further simplifying equation (4) as:

$$p(x,t) = 2\sum_{ex} P_{i,ex}(x,t) - \rho c\dot{w} - \text{added mass} \quad (5)$$

where the sum is made on the number of explosions (“ex”).

4. Applications to multiple explosions

Using the superposition principle described in the previous paragraph we analyze the problem of two explosions taking place *4m* ($0.02L_0$) apart and *4m* ($0.02L_0$) below an orthotropic plate, with dimensions *6.09m×3.05m* and elastic characteristics described in [10], as shown in Figure 7.

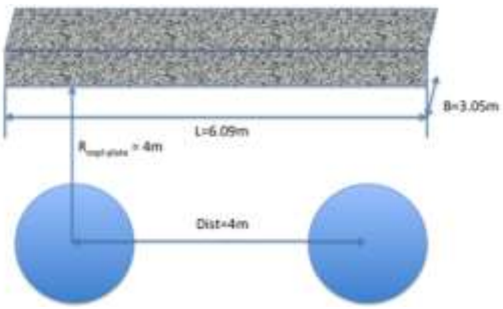

Fig. 7. Sketch of the double bubble explosion below a plate.

The second bubble explodes with a delay Δt from the first. Figure 8 shows the effect of the delay, made dimensionless with the first natural period of oscillation of the plate $T_{structure}=0.0172s$, on both the displacement and velocity of displacement of the plate.

In the free vibration regime (when the transient effect of the acoustic wave is exhausted), the amplitude of oscillation of the displacement and of the velocity of oscillation of the plate, depend on the delay between the explosions, in particular if the compression wave of the second explosion reaches the plate in correspondence with a minimum of the velocity (plate deforming towards the bubbles) the amplitudes of oscillation are minima, conversely if the second explosion arrives when the velocity is maximum (plate deforming away from the bubbles) the superposition is constructive and the amplitudes of oscillation are increased.

Because of the periodic nature of the oscillation, also the curves of the top panel of Figure 8 present a period $T_{structure}$. Nonetheless, the largest amplitudes of oscillations are due to simultaneous explosions.

The effect on the maximum velocity of displacement and on the maximum displacement is not periodic, the maxima are at zero delays, and reduce very fast when the explosions are shifted apart in time. In particular, the maximum value quickly tends to the value related to the single explosion.

This means that assuming all the explosions to take place simultaneously leads to the worst scenario for the structure.

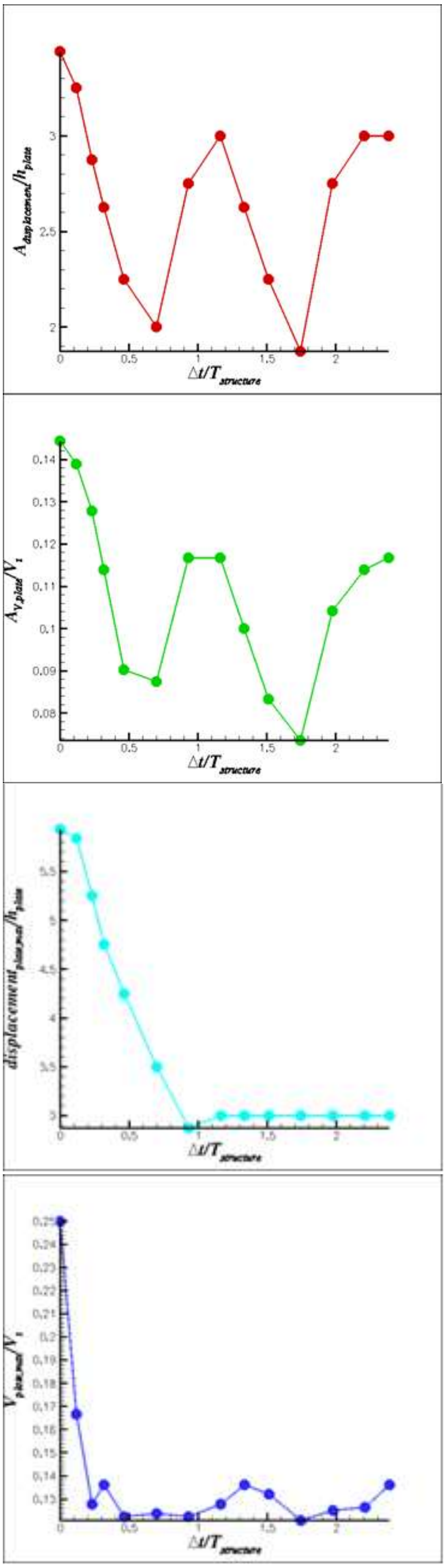

Fig. 8. From top to bottom: amplitude of the plate displacement in free oscillation, amplitude of the plate velocity in free oscillation, maximum displacement of the plate, maximum velocity of the plate versus the delay between two explosions.

However, here the effect of the reflected wave on the initial bubble is not taken into account, its study will be the object of the future research.

5. Conclusions and lines for future research

A Domain Decomposition (DD) strategy is proposed, which enables efficient computations for the interactions between an exploding gas cavity, the surrounding fluid and target solid structures.

Validations tests, based on use of the full-scale experimental data by Smith (1975), have been performed and show that the DD strategy well reproduces the solution over the entire domain.

A simplified approach is, finally, proposed to be used for the complex case of multiple cavity explosions. Use of the approach reveals that the worst load scenario for the target structure occurs when all cavities explode simultaneously.

The proposed solution procedure well reproduces many of the dynamical features of the phenomenon under investigation, but significant improvements are still possible and advisable for a correct reproduction of the gas cavity-fluid-structure interaction. In particular, we are currently working along the following lines of research:

- Full coupling of the 3D local flow solutions with the structural solution. This will enable feedbacks of structural dynamics on the flow;
- Modelling of the interaction of the waves reflected by the structure with the gas cavity. This will lead to a dynamical evolution of the boundaries between the 1D and 3D solution domains;
- Give proper account of cavitation phenomena. This will permit realistic computations such that large negative pressures at the structure will force phase changes.

Acknowledgements

This research activity is partially funded by the Centre for Autonomous Marine Operations and Systems (AMOS), NTNU, Norway, and partially by the Flagship Project RITMARE - The Italian Research for the Sea - coordinated by the Italian National Research Council and funded by the Italian Ministry of Education, University and Research within the National Research Program 2011-2013.

References

[1] Lingeman J., Mcateer, J. Gnessin M., Evan A. Shock wave lithotripsy: advances in technology and technique. Nature Reviews Urology 2009; 6: 660–670.

[2] Dular M., Coutier-Delgosha O. Numerical modelling of cavitation erosion Int. J. Num. Meth. Fluids 2009; 61(12): 1388-1410.

[3] Cole R.H. Underwater Explosions. Princeton, New Jersey: Princeton University Press; 1948.

[4] Colicchio G., Greco M., Faltinsen O.M. A numerical strategy for gas cavity-body interactions from acoustic to incompressible liquid phases, IWWWFB, France; 2013.

[5] Colicchio G., Greco M., Faltinsen O.M. Domain-Decomposition Strategy for Marine Applications with Cavities Entrapments, J. Fluids Struct. 2011; 27(4): 567-585.

[6] Hajizadeh A., Farhangmehr V., Ohl S.W., Khoo B.C., Shervani-Tabar M.T. Characterization of the interaction of two oscillating bubbles near a thin elastic membrane, Exp. Fluids 2012; 53:1723–1735.

[7] Dobratz B.M., Crawford P.C. LLNL Explosives Handbook Properties of Chemical Explosives and Explosive Simulants. Lawrence Livermore National Laboratory; 1985.

[8] Olson K.M. PARAMESH: A Parallel Adaptive Grid Tool", in Parallel Computational Fluid Dynamics 2005: Theory and Applications. Proc. Parallel CFD Conference, College Park, MD, U.S.A., eds. A. Deane, A. Ecer, G. Brenner, D. Emerson, J. McDonough, J. Periaux, N. Satofuka, and D. Tromeur-Dervout (Elsevier); 2006.

[9] Smith R. AUSM(ALE): A Geometrically Conservative Arbitrary Lagrangian Eulerian Flux Splitting Scheme. J. Comput. Phys. 1999; 150: 268–286.

[10] Greco M., Colicchio G., Faltinsen O.M. A domain-decomposition strategy for a compressible multiphase flow interacting with a structure, Int. J. Num. Meth. Engng. (submitted); 2013.

[11] Ramajeyathilagam, K., Vendhan, C. P., Rao, V. B. Non-linear transient dynamic response of rectangular plates under shock loading. Int. J. Impact Eng. 2000; 24: 999–1015.