Fluid-Structure Interaction in Cavitation Erosion

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Abstract

This numerical work focuses on the collapse of a single air bubble close to a deformable wall generated by the impact of an incident high-pressure wave. A CFD code was fully coupled to a FEM solid code in order to compute the bubble collapse and the subsequent plastic deformation in the material. The CFD code FSI4CAV was developed from the numerical model of Johnsen et al. [1]. A mobile mesh capability was added in order to account for the displacement of the fluid-structure interface. This has been done through the implementation of an ALE (Arbitrary Lagrangian Eulerian) method. The solid response to the bubble collapse was computed with the FEM software CAST3M [2] assuming an elastic-plastic constitutive law for the material. The communication between the two codes is achieved through the MPI library. The paper presents a detailed analysis of the two-dimensional bubble collapse dynamics and the corresponding solid behaviour. The damping of the impact pressure with respect to a perfectly rigid wall was computed as well as the plastic deformation developed in the material. The comparison of the simulation results with a non-coupled approach where the pressure applied to the solid is computed from CFD simulations definitely shows the importance of including the fluid-structure interaction into the simulation of cavitation erosion.

Keywords: Fluid-Structure Interaction, Cavitation, Numerical Coupling

Introduction

The prediction of cavitation erosion by numerical techniques is still a challenge for industrial applications. It faces several major difficulties including the prediction of the impact loads induced by the collapse of vapor structures (known as the erosive potential or aggressiveness of the cavitating flow) and the simulation of the response of a solid wall to these successive impact loads.

On the fluid side, recent progress has been made to predict cavitation aggressiveness in terms of impact load spectra [3] and in terms of erosion risks [4-6]. A fully compressible model is required with a high temporal resolution in order to capture the shock waves emitted during bubble collapse.

On the solid side, the response of a solid specimen to a single impact load and the prediction of the subsequent cavitation pit has been studied by several investigators such as [7] and [8]. However the dynamic response to multiple impact loads and the prediction of crack initiation and propagation and the resulting mass loss is one remaining challenge that requires developing a relevant damage model for the material under consideration.

Another challenge to be addressed is the damping effect on the amplitude of impact loads due to the wall deformation. This requires simulations of the fluid-structure interaction. Very few studies have been devoted to fluid-structure interaction in cavitation erosion. Chahine et al. investigated the case of the Rayleigh collapse of a bubble touching an elastic-plastic metallic wall [9] and confirmed the existence of a significant damping effect of the pressure peak applied to the wall. These authors predicted the fluid-solid interface displacement at each time step from the solid code but did not implement sub-iterations within the time step to correct this displacement and account for its feedback on the fluid flow during the time step.

The present work consists in developing a complete fluid-structure model which will be applied to the case of a single bubble collapsing close to an elastic-plastic specimen made of Aluminum. The bubble collapse is triggered by a plane shock wave. The bubble is assumed to be composed by air; no phase change is computed. The simulations are carried out in two dimensions assuming a plane strain state in the domain. After a short presentation of the computational strategy, the collapse of a single bubble close to a deformable aluminum medium is analyzed. Fluid-structure coupling

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is based on a two-way approach for which not only the wall deformation is affected by the flow, but the flow, and particularly the impact load, are also affected by the wall deformation, resulting in damping at the interface. This two-way approach is compared to a one-way approach, that assumes no feedback of the solid deformation on the flow, and that is thus obtained by simply applying, as a boundary condition, the pressure load obtained from a fluid-only simulation to a solid-only simulation.

Numerical approach

A CFD code for compressible fluid simulations was coupled to a FEM code for solid mechanics simulations. The CFD code is based on the code developed by Johnsen et al. [1]. This code is based on the 5-equations model: conservation of mass, momentum and energy with an additional conservation equation for the mass fraction of air and an equation of state valid for both liquid and gas. The stiffened gas equation of state was used with the same parameters as used by Beig [10]. To allow the displacement of the fluid-structure interface, the original Eulerian description in a fixed mesh was changed into an Eulerian description in a moving-deforming mesh using the Arbitrary Lagrangian Eulerian (ALE) method. The fluid mesh could therefore perfectly accommodate the deformation of the interface.

The solid deformation is computed by the FEM implicit code CAST3M developed by Commissariat à l'Energie Atomique et aux Energies Alternatives [2]. The equation of motion of the solid is solved in a dynamic way to allow wave propagation in the solid. The elastic-plastic behavior of the solid was modeled by a Ludwig-type power law connecting the Von Mises stress σ and equivalent tensile strain ε:

$$\sigma = \sigma_Y + K(\varepsilon - \varepsilon_Y)^n \qquad Y \text{ index corresponds to yield strength.} \tag{1}$$

In this first approach, the strain rate effect was not included in the model. Continuity of normal load and normal velocity is enforced at the fluid-solid interface. At each time step, each code transfers data to the other one thanks to an MPI interface. Convergence between mesh velocity at the interface in the fluid code and interface velocity calculated by the solid code is ensured at each time step by a convergence loop, implying sub-iterations at each time step.

Analysis of single bubble collapse close to an aluminum specimen

We now present the results of a typical simulation of the collapse of a 2D air bubble in water, close to a deformable wall. Air and water are initially at atmospheric pressure and a plane shock wave propagating in water towards the wall is supposed to make the bubble collapse. The amplitude of the incident shock wave is 120 MPa, the initial bubble radius is $R_0 = 50$ μm and the bubble center is initially two radii away from the solid. The solid domain is made of aluminum with a density of 2700 kg.m^{-3} and a Young modulus E of 70 GPa. Yield strength σ_Y is 500 MPa and the coefficients for the Ludwig law (Eq. 1) are K= 396 MPa and n= 0.3

We focus the following discussion on three distinct moments of the dynamic evolution:

- the impact of the incident shock wave on the fluid/solid interface.
- the impact of the shock wave due to bubble collapse on the interface.
- the generation of plasticity in the solid.

Figure 1 shows the density and pressure fields in the fluid as well as the stress component σ_{xx} and the corresponding plastic deformation ε_{xx} in the solid at various times. The reference time t_{ref} corresponds to the impact of the incident shock wave on the side of the bubble interface farther away from the wall.

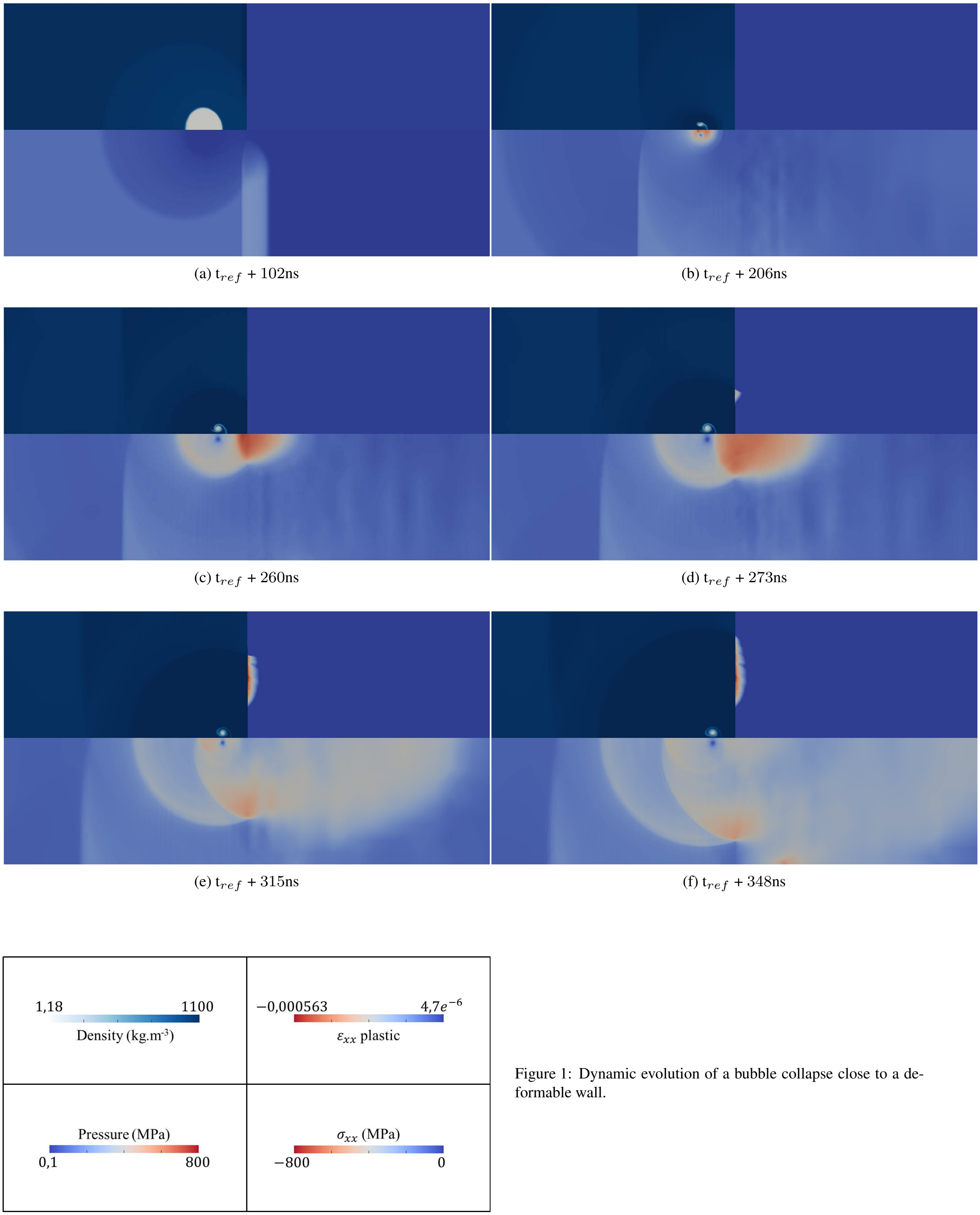

Figure 1: Dynamic evolution of a bubble collapse close to a deformable wall.

At t_{ref} + 102ns, the incident shock wave hits the wall. The wave is partially transmitted in the solid and partially reflected in the fluid. The pressure exerted on the interface is the sum of the amplitudes of the incident and reflected waves. Due to the conservation of the normal stress at the interface, the liquid pressure on the interface (bottom-left in figure 1a) is equal to the normal stress σ_{xx} in the solid at the interface (bottom-right in figure 1a). The pressure on the wall at the region facing the bubble center is smaller than elsewhere on the wall because of the screening effect of the bubble. The amplitude of the initial shock wave is too small to induce any plastic deformation in the solid (top-right in figure 1a). In the case of a rigid wall, the amplitude of the pressure peak would be twice the amplitude of the incident shock wave, i.e. 240MPa. This pressure peak is below the material yield strength of 500MPa. Note that for a compliant wall like polymers, this value could be much smaller due the damping effect of the wall displacement.

At t_{ref} + 206ns (figure 1b), water under pressure deforms the side of the bubble interface farther from the wall and initiates a microjet. When the microjet pierces the bubble (i.e. when the two-dimensional bubble is split into two parts), a radially outward-propagating shock wave is produced. When this shock wave reaches the wall, a pressure peak of 744MPa is produced. The amplitude of the shock wave generated by the bubble collapse is significantly larger than that of the incident shock wave, and is capable of inducing plastic deformation in the material.

Figure 1c shows the different fields just after the impact of the bubble-induced shock wave on the wall (t_{ref} + 260ns). Continuity between the liquid pressure and the normal stress σ_{xx} at the liquid / solid interface can be appreciated on this figure. Figure 1c also shows that the waves travel faster in the solid than in the liquid. A small, roughly circular residual air bubble is visible in figure 1c (top-left), which corresponds to pressurized air. There is still no plastic deformation in the solid (top-right in figure 1c).

After hitting the interface, the shock wave is transmitted into the solid. It will also spread along the fluid-solid interface. On the interface, a pressure peak is observed locally, which corresponds to the passage of the wave front. Regarding the solid, this pressure peak results in a high amplitude loading, applied to the surface of the material.

At t_{ref} + 315ns, the shock wave has traveled along the wall over a distance of the order of $3R_0$. Figure 1d to 1f shows that the upper limit of the plastic zone corresponds to the front of the shock wave. The plastic zone starts developing at a distance of about $1.2R_0$ from the bubble axis at time t_{ref} + 273ns (figure 1d) and progressively grows at the same speed as the wave propagates along the wall. At every instant, the plastic front in the material and the shock wave front in the fluid coincide on the wall. The growth stage of the plastic zone ends at instant t_{ref} + 348ns (figure 1f) and its maximum length is about $3R_0$. After some oscillations due to wave propagation, the deformed wall takes the form of a standard erosion pit with maximum depth on the bubble axis.

1-way/2-way comparison

In the previous section, a two-way simulation of a single bubble collapse close to a wall was presented. The two-way simulation takes into account the effect of the solid deformation on the fluid. In order to quantify this effect, the two-way simulation is compared to a one-way simulation corresponding to the solid-only simulation with the pressure load from a fluid-only simulation applied as a boundary condition. Three parameters are considered for this comparison: the amplitude of the pressure peak, the pit depth on the bubble axis and the area of the generated plastic surface. In our case, there is no damping of the wave in the solid so the wave can propagate endlessly. The interface is moving during the whole simulation without coming to rest since the incident shock wave was assumed to be a step function and not a pulse of limited width. So to define the pit depth, we consider the difference between the highest and the lowest points of the interface.

	Pressure Peak (MPa)	Pit depth (nm)	Plastic surface (mm^2)
1-way	827.4	112.2	3.13 10^{-3}
2-way	744,7	62.4	1.52 10^{-3}

Table 1: Comparison between 1-way and 2-way simulation.

Table 1 shows that the deformation of the wall damps the pressure peak by about 9.9% in comparison to a rigid wall.

In the simplified case of a plane shock wave impacting a purely elastic material, the damping coefficient depends upon the ratio α of the acoustic impedance of the solid to that of the liquid and is given by $\frac{1}{\alpha+1}$ [11]. In the present case, this equation gives a damping coefficient of 11.1% when estimating the speed of sound in the solid by $\sqrt{\frac{E}{\rho}}$. The computed value of the damping coefficient obtained by the present FSI simulation (9.9%) is relatively close to this rough estimate.

This decrease in the loading of the interface induces a drastic decrease in the generated plastic surface and in the resulting pit depth, that are roughly divided by two for the case studied. These results illustrate the importance of including the fluid-structure interaction in the simulation of cavitation erosion.

Conclusion

In this paper, fluid-structure interaction was investigated numerically in the case of a 2D air bubble collapsing close to an elastic-plastic aluminum specimen with a yield strength of 500MPa. The collapse was generated by an incident shock wave with amplitude of 120MPa traveling towards the bubble and the wall. To perform the simulation, a two-way coupling was achieved between the 2D compressible fluid code FSI4CAV originally developed by Johnsen et al. and the solid solver CAST3M. Coupling was performed by the use of MPI library.

The main steps in the process of bubble collapse and wall deformation are the following. The bubble starts collapsing when its interface is impacted by the incident wave. A microjet penetrating the bubble and moving towards the wall develops during the collapse stage. When the microjet pierces the bubble, a circular shock wave of large amplitude is generated. When this wave impacts the deformable wall, a pressure peak of amplitude 744 MPa is measured on the wall. This induces plasticity in the solid which modifies the interface profiles into a shape similar to a typical experimental pit.

This simulation based on a two-way coupling was compared to the case of a one-way coupling that assumes that the loading on the wall would be the same as on a perfectly rigid wall. It was shown that the amplitude of the impact load is damped by 9.9% due to the wall deformation. In the present case, the damping effect induces a drastic change in the extent of the plastic region together with a significant reduction in pit depth.

In conclusion, this work shows that a one-way approach that neglects the feedback of the wall deformation on the fluid dynamics may not be sufficient to accurately predict impact loads and plastic deformations. It may be critically important to take into account wall deformation and to develop a two-way approach in order to accurately simulate the processes involved in cavitation erosion.

Acknowledgements

This work has been partially supported by the LabEx Tec 21 (Investissements d'Avenir - grant agreement n^{o}ANR-11-LABX-0030) and ONR grant N00014-12-1-0751.

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