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Transient response of a plate–liquid system under an aerial detonation : Simulations and experiments

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ABSTRACT

This paper presents a mixed numerical approach to model the blast waves generated by the detonation of a spherical stoichiometric mixture of propane and oxygen, impacting a plate–liquid system. The problem is split into two parts. The first calculation part relies on the modeling of the blast load and its propagation. Over-pressure distribution, in this part, is presented and reveals a very good level of agreement with experimental results. The time and space scales of the blast load data must be compatible with the plate–liquid system. This compatibility is ensured by an appropriate spatio-temporal interpolation technique. This technique is presented and its effectiveness and accuracy are demonstrated. The second part consists in modeling the response of the coupled plate–liquid system under the numerical blast load model. Experiments at reduced scale are carried out in two configurations in order to assess the effectiveness of this mixed numerical approach. Convincing results are obtained and discussed.

1. Introduction

In this work we study the mechanical effect of an explosion in air over a flat plate resting on a quiescent fluid. The response of the plate–liquid system is determined by the fluid structure interaction which develops very rapidly owing to the blast wave of the explosion.

In practice, blast loads arise when solid or gas explosives detonate due to the ignition of high explosive materials. There is a real need to understand the effects of such loads on structures or on persons, for example, in the field of risk and industrial safety, risks prevention against terrorist attacks, or in military applications.

Conceptually, the explosion phenomenon can be broken down into the following phases: (i) the detonation process in the explosive medium, (ii) the shock propagation in the surrounding environment, (iii) the shock reflection by an obstacle wall, (iv) the response of the impacted structure and of the fluids and/or materials confined by the structure. These 4 phases correspond to 4 modeling steps involving multiphysical simulations: phase (i) is a reactive flow; phase (ii) deals with unsteady compressible fluid flow; phases (iii) and (iv) involve fluid structure interactions (FSI).

Blasts are created by underwater explosion (UNDEX) and in air explosions (INEX). The major difference between UNDEX and INEX is due to the dynamics of the gas core produced by the detonation of high explosives. In INEX the pressure of the gas core decreases (as the detonation products expand) until it reaches the atmospheric pressure. In UNDEX, the gas products form a bubble which experiences alternate expanding-contracting motions. In UNDEX problems, the issue of cavitation is unavoidable; it has been studied by Geers and Hunter [9], Sprague [31] and Galiev [8], among others. Cavitation must be considered at the gas–liquid and at the fluid–structure interfaces. Experimental techniques dedicated to cavitation studies are presented by Herbert et al. [13]. The modeling of UNDEX and INEX must describe the differing nature of the phenomena due to the differing properties of the media in which the explosion takes place.

Explosions in air and their effects on structures have been widely investigated. A review concerning various aspects of the response of blast loaded plates was published by Rajendran & Lee [28]. There are two major approaches for investigating blast effects on structures.

Firstly, studies address the explosion phenomenon and its coupling with the structure. Numerical methods are elaborated to describe the shockwave ignition and propagation. For example, the equations of the reactive flow can be solved using the Eulerian multimaterial formulation with a finite element discretization [1]. Thus, the interaction between the blast and the structure can be described within long durations after the beginning of the explosion [34]. However, these methodologies require a large amount of optimized numerical parameters as well as very long computational times. Consequently high frequency phenomena are difficult to capture accurately. Simplifications might be chosen, as done by Kambouchev et al. [16] who applied the rigid-body

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Notation

t: Time [s]
ρ_ℓ: Fluid mass density [kg.m^{-3}]
χ: Fluid bulk modulus [Pa^{-1}]
c_ℓ: Speed of acoustic waves in the liquid [m.s^{-1}]
ρ: Plate mass density [kg.m^{-3}]
E: Plate Young modulus [Pa]
ν: Plate Poisson's ratio(W/m^2)

h: Plate thickness [m]
I=h$^{3/12}$: Moment of inertia of the cross-section [m^4]
G=E/[2(1+ν)]: Shear modulus [Pa]
D=EI/(1-ν^2): Flexural modulus [Pa· m^4]
r$_{\text{plate}}$: Maximum radius on the plate [m]

assumption for the plate but, nevertheless, fully solved the FSI in a Lagrangian frame.

Secondly, only the mechanical response is sought without modeling the blast dynamics. Therefore, the loads are given as input functions such as decaying exponential, constant pulses, the parameters of which are tuned to match experimental data. Another kind of input data is the well-known US Army Technical Manual ConWep code providing empirical blast loading functions [25,21]. Here, the key point is to compute the response under such loads including finite transformations, see for example [19]. The simulations include user-defined materials (or "UMAT") Longère et al. [21] programmed in commercial codes, mainly ABAQUS, LSDYNA, EUROPLEXUS. Different structures can be studied, ranging from a "simple" plate, [15,25], or a sandwich panel [17] to very complex assembly such as a soldier helmet with composite and polymer materials [11] or laminated glass [20].

The aforementioned commercial codes are indispensable tools for solving dynamics problems, especially with blasts and FSI, in complex real systems (such as vehicles, planes, ships, plants) for which a long time and global response is sought, see for example studies on mine blast modeling [12]. However, as will be seen in this work, if very specialized aspects of the dynamic response are investigated, such as the *early response*, it might be more appropriate to develop fully controlled numerical codes which allow focusing the model on high frequency waves. In addition, fully controlled codes (or "white box") are better options than commercial codes for careful comparison with delicate and difficult experiments, as is the case in the present work.

The interaction of the impacted structure deformation with the blast must be taken into account if the solid wall experiences large displacements, which can interact significantly with the flow, [4]. Such load durations may exist if explosions occur in confined zones and generate planar blast waves (e.g. tunnels, closed rooms). On the contrary, a wall exposed to an aerial explosion is loaded by a moving pressure front. In this case, the first movements of the target are small in amplitude, unable to modify the shock reflection; large displacements may occur when the loading is over.

The explosive used in the present work creates a source-explosion. Therefore, the incident waves are spherical, and the wave reflections are due mainly to oblique incident waves. According to the studies by Baker et al. [2] and Kinney [18], the mechanism of this reflection can be accurately described. When the wave reaches the plate, the incident angle is zero. Kinney has shown that if this angle is lower than a certain limit, the reflection is regular. Beyond this limit the reflected wave cannot maintain the flow parallel to the wall. Then, it follows that the incident and the reflected waves coalesce in a triple point, and form a third shock wave which is detached from the wall — the Mach reflection. This shock is stronger and faster than the incident shock. The distance between the triple point and the wall increases as the reflection phenomenon goes on. For spherical shock waves, the locus of the triple point forms a curve away from the wall. The reflection of a shock wave on a structure is a complex phenomenon. Reflection coefficients are influenced by the shock characteristics and the properties of the atmosphere in which the reflection takes place [33].

From the point of view of structural dynamics, the considered blast pressure is a moving load, from its onset to its end. When the blast sweeps a wall, the rise time of the pressure is very short (a few µs for small scale detonations associated with over-pressure about 10^5 Pa) and occurs over a very narrow distance. This is why the moving pressure front is usually approximated by a discontinuity in analytical studies. The front starts to move with supersonic velocities (relatively to the acoustic wave in the fluid or in the structure) which rapidly decrease to subsonic velocities.

The first particularity of the present work is that the transient response of the plate is calculated only during the time the blast wave impacts the plate. Structural waves are analyzed before any reflection occurs at the boundaries. The second particularity is that the response is strongly influenced by the coupling with the underlying fluid. Indeed, in such very short times the fluid reacts on the structure due to its compressibility, and also with an added mass effect. In the two media, the small perturbations theory may be applied, namely, elastic waves and acoustic waves form the present response observed without boundary influences. Researching early time responses may rely on some hypotheses. For example, Sprague and Geers [32] applied partial series closure for solving the response of a spherical shell under a spherical shock. Here, the early response is separated into a closed-form portion (representing a planar wave approximation for the fluid–shell interaction), and a complementary mode-sum portion. Unlike such an approach, we have made a direct simulation, which benefited from some specific features of the fast dynamic response, as it will appear in Section 6. While cavitation is an unavoidable issue in UNDEX, it is a remaining question to determine whether cavitation occurs behind the plate considered in this study. In fact the pure acoustic fluid model may lead to negative pressure which may be less than the hydrostatic pressure; this suggests going further in the modeling. However, in the present work, we have focused the analysis on the very early stages of the system response observed in laboratory experiments with reduced scale explosions. The understanding of the coupled plate response and the modeling both rely on previous works we have done on analytical stationary responses of the plate system [30,29], with an acoustic model for the fluid. This is why cavitation was not considered in the paper. When comparing experiments with simulations, care was taken to verify that the numerical fluid pressure never fell below the hydrostatic pressure with moderate explosions. In the experiments, the explosive energy was limited to that used in the modeling. In the time considered the response takes the form of waves undisturbed by the boundaries. This is why real complex fluid–structure systems may be simplified since only elements of them are set into movement. This is an additional argument for designing in-house numerical codes rather than engaging full direct modeling with heavy commercial codes.

In the present work, the numerical simulation deals with both the explosion and the response of a plate–liquid system. Experimental