A Coupled Eulerian/Lagrangian Simulation of Blast Dynamics

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ABSTRACT
Accurately modeling blast dynamics is critical in the assessment of structures subjected to blast loads as well as a wide range of fluid/structure interaction scenarios. The current industry standard for modeling blast effects in Lagrangian Finite Element simulations is CONWEP, an empirical curve-fit based on pressure data recorded from blast events. CONWEP is limited, however, and may not always be physically representative of the blast/structural interaction that occurs in the field. Eulerian hydrocodes provide advantages over CONWEP in that they can capture shock front interaction and model blast surface interfaces with fidelity due to the presence of the working fluid. Eulerian codes, however, break down over longer time scales which may be of interest in the evaluation of structures. Hence, a hybrid approach that couples the Eulerian blast modeling with Lagrangian system dynamics is necessary. The objective of this paper is to demonstrate improvements in blast modeling using a Coupled Lagrangian/Eulerian algorithm. Results using the Coupled Lagrangian/Eulerian algorithm are compared to simulations from an Eulerian hydrocode and simulations using the CONWEP algorithm.

KEYWORDS: Blast, mine, structure, CONWEP, Eulerian, hydrocode, coupled, Lagrangian

INTRODUCTION
A variety of modeling techniques have been used to study the effects of blast loading on structures. Remennikov gives a brief overview of the primary methodologies used to model the physics of blast loads, indicating that they fall into one of three categories: empirical (analytical) methods, semi-empirical methods, and first-principles numerical methods [1]. Empirical and semi-empirical methods are typically hindered by the accuracy and availability of empirical data for correlation. Computational physics approaches typically fall under the category of first-principles numerical methods because they directly model the physics of the problem using the fundamental nonlinear equations governing the behavior of the system. Since these solutions model physical behavior of materials and system dynamics, they are often an accurate way of predicting structural responses to impulse loads, which can be confirmed by comparison with reduced experimental data sets.

There are two basic types of computational physics approaches for hydrostructural dynamics, Eulerian and Lagrangian, and each has its advantages and limitations in modeling the effects of blast loading. An Eulerian model treats a problem domain with a fixed mesh and allows material to pass through it. In this way, an Eulerian solution can model structural interactions with the blast wave and blast byproducts with a high degree of fidelity due to the presence of the working fluid surrounding the structure. This methodology has been used extensively to study the behavior of blast loading of structures and has been well documented in literature as in [2 - 6]. Eulerian solutions, however, are often limited to relatively short simulation times—on the order of hundreds of microseconds to a few milliseconds—due to the accumulation of advection and interface tracking errors. Lagrangian finite element solutions provide the advantage of having a structural mesh that moves with the system, allowing for the calculation of material and structural behavior over large time scales. Lagrangian methods are often much faster to implement and execute, leading to shorter lead times. They are limited,
however, by the inaccuracies of modeling the impinging blast wave. In the absence of a non-structural fixed mesh to treat the blast wave, the primary method for modeling the effects of blast loading is empirical pressure curve-fits, such as in the CONWEP algorithm [7]. While these methods have been shown to be reasonable approximations to mine blast events under certain circumstances [8], they are limited by several factors. The first is that the accuracy of such empirical approaches is reduced as the blast becomes increasingly near field [2]. The second is that the interface surface must be manually "painted" with the pressure load, leading to inaccuracies in incident pressure. The third issue is their inability to treat the complex structural interactions and reflected pressure waves, especially when the explosive acts at close range to the structure or is confined by its surroundings (i.e. soil, mine casing, etc). The explosive and air could be treated using a Lagrangian mesh; however, the resulting mesh distortions from the rapid expansion of the explosive products tend toward inaccurate physical states, thereby increasing the calculation time to unreasonable levels or terminating the simulation due to numerical instabilities.

There is clearly a need for a methodology that can account for the system dynamic behavior while simultaneously treating the blast effects. Recently, there has been some effort in coupling the Eulerian and Lagrangian solvers to treat blast loading of structures [9, 10], but little effort has focused on practical implementation of the solver in a computational analysis tool. Recent developments in Velodyne™, Corvid Technologies’ in-house, massively parallel, nonlinear dynamic solver, have allowed for more comprehensive modeling of blast dynamics through the implementation of a Coupled Lagrangian/Eulerian (CLE) solver. This algorithm allows the analyst to combine the best aspects of both solution types. The Eulerian solution permits accurate modeling of hot gas expansion through fluid/structural interaction and adaptive mesh refinement while simultaneously calculating the material deformations and system-level dynamics in the Lagrangian domain. The objective of the present study is to demonstrate the improvements in blast modeling using a CLE algorithm in Velodyne. CLE results are compared to simulations in an Eulerian hydrocode and the CONWEP algorithm implemented in Velodyne.

SIMULATION SETUP

In order to demonstrate the necessity for a CLE solver, a simple test case was developed involving three metallic plates with a 10lb spherical TNT charge centered between them (Figure 1). In the Lagrangian and coupled simulations, constant stress solid elements are used to mesh the panels. It is assumed that the panels interact with the blast in the absence of gravity. The geometry of the problem was chosen so that secondary effects from the propagating blast wave would be influential on the dynamic behavior of the plates, specifically the third plate. Though it is a simple configuration, it demonstrates the physical behavior that is critical to capturing blast interaction with complex structures, especially with close-in charges.

<table>
<thead>
<tr>
<th>PLATE</th>
<th>DIMENSIONS (cm)</th>
<th>MATERIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Lower)</td>
<td>350 x 350 x 10</td>
<td>AISI 1018</td>
</tr>
<tr>
<td>2 (Upper)</td>
<td>150 x 150 x 2.5</td>
<td>AL 7075-T6</td>
</tr>
<tr>
<td>3 (Side)</td>
<td>190 x 43 x 2.5</td>
<td>AL 7075-T6</td>
</tr>
</tbody>
</table>

Figure 1: Problem geometry

Four simulations were conducted in order to evaluate the effectiveness of the coupled algorithm. These included a purely Lagrangian Velodyne simulation using CONWEP, two purely Eulerian simulations conducted in the
hydrocode CTH [11], and the coupled Eulerian/Lagrangian simulation conducted in Velodyne. Each represents a unique method for modeling blast load effects. CONWEP represents blast loading through curve fits of pressure data taken directly from a large database of experimental results for simple geometric shapes in an open field environment. As such, it is limited to the modeling of the primary blast effects from the initial expansion of the pressure wave and cannot account for reflected waves and elevated pressures that would occur due to confinement of the expanding explosive products by their surroundings. The CLE and CTH simulations provide an advantage in that they can account for the secondary blast effects through the presence of the working fluid in the Eulerian mesh. Two CTH simulations were conducted to provide comparisons to both the CONWEP representation and CLE representation of the blast. The first CTH simulation included the explosive material and represents the detonation reaction and corresponding pressure wave; this simulation provides a more direct comparison to CONWEP which accounts for the lag due to detonation. The second simulation accounts only for the expansion of the hot gases associated with detonation, which is similar to the current CLE representation of detonation in Velodyne.

Figure 2: Difference between explosive blast and hot gas expansion after first 15 μs

Figure 2 demonstrates the differences between modeling the explosive explicitly and modeling the explosive as expansion of a hot gas. In the explosive model (left), detonation occurs at the center of the explosive, causing a pressure spike that diminishes exponentially with time as expected. Alternately, it was chosen to start the hot air expansion model (right) as a uniform high pressure “bubble” corresponding to the maximum pressure seen in the detonation model at 15 μs, immediately after the explosive products had fully reacted. Currently, the Velodyne CLE algorithm only supports the uniform pressure bubble as an initial condition. The background properties are those of air at standard temperature and pressure in both domains.

RESULTS
Pressure distributions and nodal velocities were recorded in all four simulations for the purpose of comparison. It is expected in the Eulerian and CLE simulations that the confinement of the blast by plates 1 and 2 will cause a second set of reflected shock waves to impinge upon the third perpendicular plate, increasing the impinging blast pressure and thereby increasing the final velocity of the panel. This behavior cannot be captured in the CONWEP simulations due to the limitations of the algorithm.

Figure 3 and Figure 4 illustrate the change in velocity at the center of mass of the lower and upper plates, respectively. Note that in the simulations that include the explosive (CONWEP and CTH), the velocity magnitudes are lower than the simulations using hot gas expansion to model the explosive. This increased response is caused by the initial condition used to model the blast in the hot gas expansion. Essentially, the uniform pressure “bubble” assumed as the initial condition overestimates the energy in the expanding shock wave. However, the results from the CLE simulations correlate well with the purely Eulerian CTH results assuming similar initial conditions. Also note that the velocity profiles are contain less numerical noise in the CLE simulations, resulting from the treatment of the solid material as a Lagrangian mesh. By allowing a second mesh to deform with the solid material rather than advecting material through a fixed mesh, a more accurate
representation of the long-term system dynamics can be achieved. This accuracy is particularly important when considering the effects that blast loading has on the dynamic behavior of structures.

Figure 3: Velocity history in upper plate for 4 simulations

Figure 4: Velocity history in lower plate for 4 simulations

Figure 5: Velocity history of side plate in 4 simulations

Of particular interest in this study is the dynamic behavior of the side plate. Figure 5 illustrates the change in velocity of the center of mass of the side plate. The results indicate that the CONWEP simulation under-predicts the response of the side plate by a factor of 2. The confinement of the blast by the upper and lower panels causes a second set of reflected shock waves that impinge upon the side plate, resulting in an increase in final velocity (Figure 6). Since the CONWEP algorithm only considers the initial expansion of the shockwave, any secondary effects are lost and will not affect the system dynamics. This is the major advantage in the CLE treatment of the problem; it can consider secondary effects such as reflected shock fronts in the Eulerian domain while simultaneously treating the system dynamics in the Lagrangian domain. The phase shift and magnitude increase in the hot gas simulations is again caused by the underlying assumption that the pressure in the expanding gas is initially uniform. This behavior can be observed visually in Figure 6. Note that the time of arrival for the blast wave modeled using high explosive lags the hot gas expansion wave. Also note that the pressure in the expanding wave dissipates more rapidly for the HE simulation versus the hot gas expansion. Although the initial conditions for the CLE simulation over-predict the impinging pressure wave and resulting dynamic behavior of the panels, the purely Eulerian CTH simulation and the CLE simulation correlate well for similar initial conditions. Again the velocity profile in the CLE simulation contains less noise due to the treatment of the coupling and system dynamics using a Lagrangian mesh.
CONCLUDING REMARKS
The development of a Coupled Lagrangian/Eulerian solver in Velodyne permits a more accurate treatment of blast effects on complex structures. The Eulerian grid can treat the primary and secondary effects from expanding gases while interacting with the material deformations and system dynamics in the Lagrangian domain. Simple models have demonstrated the need for treating secondary blast effects and have shown the effectiveness of capturing these effects using the CLE algorithm. Near-term developments include the incorporation of an explosive burn model that will be more representative of the blast effects from detonation of an explosive, at which point a direct comparison of all of these methods will be conducted.

REFERENCES