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RAPID SIMULATION OF BLAST WAVE PROPAGATION IN BUILT ENVIRONMENTS USING COARSE-GRAIN BASED INTELLIGENT MODELING METHODS

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14. ABSTRACT

The paper is concerned with the development and evaluation of a fast, accurate, and versatile method of simulating blast wave propagation within complex built environments. Existing methods of modelling the propagation of a blast wave each fail in at least one of the speed, accuracy or versatility requirements. Conventional simulation, for example, typically takes several days to complete a single run. An alternative, novel method proposed here is to use a simulation approach implemented within a coarse spatial and time framework, where the mesh elements and time steps are orders of magnitude larger than those used in conventional simulations. The approach requires the use of intelligent modelling techniques to capture the behavior of elements at the coarse level. The paper describes the new approach in detail, and provides preliminary results that demonstrate the feasibility of the approach and its potential to complete a simulation run within a few seconds.

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Rapid Simulation of Blast Wave Propagation in Built Environments Using Coarse-Grain-Based Intelligent Modeling Methods

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Abstract. The paper is concerned with the development and evaluation of a fast, accurate, and versatile method of simulating blast wave propagation within complex built environments. Existing methods of modelling the propagation of a blast wave each fail in at least one of the speed, accuracy or versatility requirements. Conventional simulation, for example, typically takes several days to complete a single run. An alternative, novel method proposed here is to use a simulation approach implemented within a coarse spatial and time framework, where the mesh elements and time steps are orders of magnitude larger than those used in conventional simulations. The approach requires the use of intelligent modelling techniques to capture the behaviour of elements at the coarse level. The paper describes the new approach in detail, and provides preliminary results that demonstrate the feasibility of the approach and its potential to complete a simulation run within a few seconds.

1 Introduction

The paper proposes and evaluates a new approach to simulating the propagation of blast waves that has the goals of being accurate, rapid (completing a run in a matter of seconds), and sufficiently versatile to model complex building configurations. Such a tool is necessary to facilitate the design of new structures (including new buildings, retrofits of existing buildings, and protective structures such as blast walls) that perform effectively in terms of both blast-mitigation and cost. The need for rapid simulation is made more important by the many uncertainties that exist about the blast environment, such as the size and location of a bomb and the status of temporary obstacles to the blast wave (such as whether blast doors are open or closed). Significant uncertainties require a simulation to be executed many times using, for example, Monte Carlo sampling to derive an accurate statistical assessment of the impact of the blast. Rapid simulation would also allow engineers to use immersive visualization techniques, such as virtual reality, to gain better insight into the behaviour of a blast wave and the way it interacts with the built environment.

Existing blast modelling tools trade off between the complexity of the environment they can model and the time they take to generate results. Modelling tools that can produce results rapidly are the empirically derived direct-mapping devices (see, for example, Remennikov (2003)), the best performing of which are the neural network models such as those described by Remennikov and Rose (2007) and Flood et al. (2009). Artificial neural networks are very versatile, and are capable of considering nonlinear problems with several independent variables. The Remennikov and Rose (2007) models were trained using data from miniature bomb-barrier-building experiments (Chapman et al., 1995), while the Flood et al. (2009) models were trained using data synthesized from CFD (Computational Fluid Dynamic) simulations and other established modelling techniques. These neural network models can produce results in a fraction of a second, and can be very accurate.

Unfortunately, empirically derived models (such as neural networks) cannot usually extrapolate to problems beyond those represented by the data set used to develop the model.

Moreover, the size of the data set required to develop direct mapping empirical models increases geometrically with the number of independent variables describing the problem. In practical terms, for blast wave modelling this limits the complexity of a problem to about five independent variables—this has constrained application to setups comprising, for example, a two-dimensional blast wave propagating over a blast barrier onto the face of a building, where the barrier and building are perpendicular to the plane of the blast wave (see, for example, Flood et al., 2009).

Blast waves propagating through more-complex environments, and acting in three spatial dimensions, can usually be considered only using CFD techniques (such as ANSYS (2008)). Unfortunately, three-dimensional CFD models of blast wave propagation, even when limited to a single barrier and building configuration and run on a supercomputer, can take several days or more to complete a single simulation run (Flood et al, 2009).

One approach for simplifying the difficulty in blast load predictions is to use ray tracing. This uses an algorithm that identifies the most-significant paths (the shortest) that a blast wave can follow from the point of detonation to specific target points, taking into account reflection and diffraction. The time-based forms of the waves arriving along each path are determined using the semi-empirical TNT Standard Methodology and are then superimposed using the LAMB Shock Addition rules (Needham & Crepeau, 1981). Enhancements to the approach have been used by Frank et al. (2007a, 2007b) to predict behaviour in environments with complex geometries. The approach certainly provides a highly versatile method of modelling complex internal geometries, and it is claimed that the results are of reasonable accuracy and that the model runs fast. However, the algorithm required to determine all significant paths for the blast wave appears to be too complex to allow results to be generated in a matter of seconds for all target points across all relevant surfaces of the environment that would be required for the applications proposed in this paper.

An alternative approach that addresses these issues, considered by Löhner et al. (2004), was to test the sensitivity of processing time and accuracy on the coarseness of the modelling mesh for three-dimensional CFD simulations of blast wave propagation. In an example study of a concert hall, consideration was given to a range of resolutions ranging from main element sizes of 0.3 m to 1.2 m in length. It was found that moving to the coarser mesh reduced processing time from 18 hours to 7 minutes, although the predictions of the coarse mesh model were about 50% off compared to the fine mesh model. While the speed of processing of the coarse mesh approach makes it accessible to users of desk-top computers, the authors of this paper consider the prediction errors of the model to be unacceptable.

2 Coarse-Grain Simulation Modelling Approach

This paper proposes a coarse-grain approach to achieving a modelling system that is fast, accurate, and versatile. It differs fundamentally from the coarse-grain approach of Löhner et al. (2004) discussed above in that it uses empirical rather than theoretically derived functions to drive a simulation. In Löhner's study, the coarseness of a model was achieved by simply increasing the size of the spatial elements comprising a model, while using the same discretized driving equations used in the fine-grain models. Increasing the size of the elements reduces dramatically the number required for any given situation and thus similarly reduces the computational load of a simulation, hence the significant reduction in processing time. However, the driving equations used by Löhner are theoretically derived assuming an infinitesimally small element size, and do not extrapolate well (in terms of accuracy) to large discrete spaces and time steps. The coarse-grain approach proposed here proposes to overcome this problem in the following two ways:

1. The driving equations required to model the propagation of a blast wave within a coarse-grain environment will be developed using empirical modeling methods, specifically multivariate linear regression and artificial neural networks. These empirical models will be trained based on data gathered from a comprehensive set of CFD simulations of building element geometries.
2. These customized driving equations will receive input about the state of the system sampled from the temporal (recent past) as well as the spatial domain, to compensate for the loss of information resulting from the coarse spatial resolution of a model.

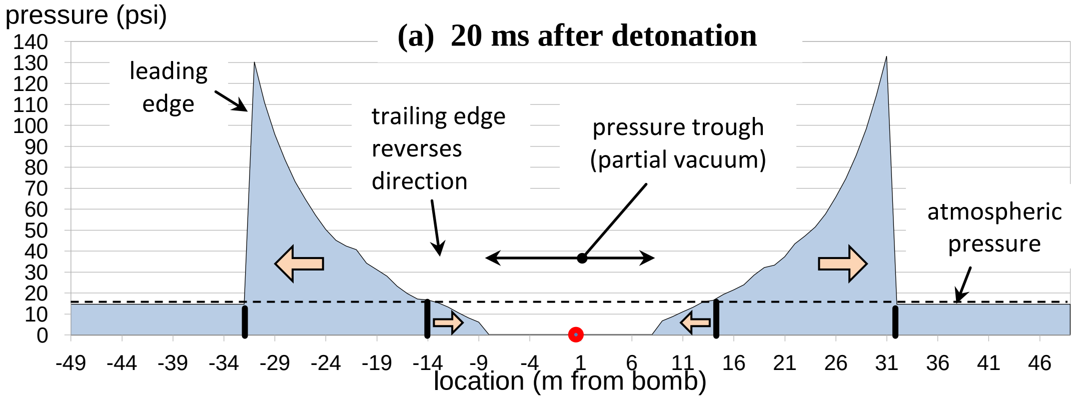
This approach, developing a set of discretized driving equations tailored to a coarse-grain modelling environment, has been demonstrated to be very effective in an earlier series of studies modelling dynamic heat transfer in complex building configurations (Flood et al. (2004)). However, there is a crucial difference between modelling heat transfer and blast wave propagation. That is, while the temperature distribution within a structure changes very gradually in the spatial domain (relative to the distance between the modelling elements) the pressure distribution of a blast wave can change very steeply particularly across the wave front. Consequently, an advancing blast wave may be lost within a coarse mesh, with its crest never intercepting more than one coarse-grain centre at a time. This means that there would never be enough information about the state of the blast wave to be able to make predictions about its state at a succeeding point in time. The coarse-grain approach described above for modelling transient heat transfer clearly needs to be modified to make it applicable to modelling the propagation of blast waves.

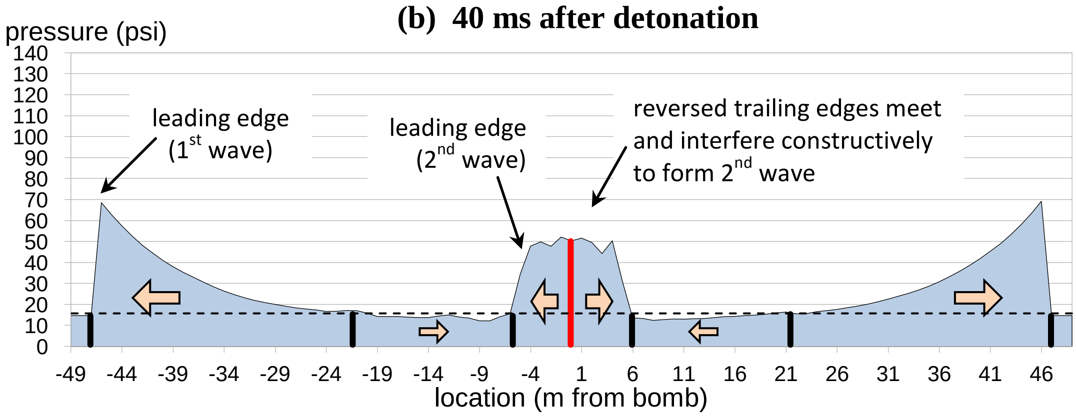
The basis of the proposed solution to this problem is to characterize the state of the blast wave by all coarse-grain elements adjacent to its crest, not just those intercepted by its crest, and to advance the simulation at each step by jumping to the time at which the blast wave intercepts the next coarse-grain element. A more detailed description of this procedure is provided in Flood et al (2010).

3 Characteristic Behaviour of Blast Waves at Intermediate Spatial Scales

Conventional CFD blast wave simulations are based on a set of equations that describe behaviour at infinitesimally small time and spatial scales and for a clearly defined set of modelling contexts (such as free field and boundary conditions). These are used to extrapolate behaviour (using a fine-grain discrete framework) to the macro-level of the built environment. In contrast, the proposed coarse-grain approach starts from a much higher spatial level, a 1-m grid for example. At this level, the behaviour of the blast wave is much more complex and so the range of types of discrete modelling element (each of which must have its functionality tailored to the physical context within which it will operate) is not immediately apparent. There was a need, therefore, to identify the characteristic high-level behaviour of a blast wave and thus determine an appropriate set of discrete modelling elements.

The types of modelling element required can be understood from Figure 1 for free field and reflecting boundary conditions (note, diffraction behaviour will be considered at a later stage in this study and is outside the scope of this paper). The figure shows pressure profiles across a 100-m space with reflecting end boundaries, at 20 ms, 40 ms, and 75 ms following detonation of a centrally located 281-kg-TNT bomb. The direction of movement of the air is indicated by the block arrows. At 20 ms into the event (part (a) of the figure) it can be seen that while the leading edges of the blast wave are travelling away from the point of detonation (at supersonic speeds) the trailing edge has stopped and reversed, moving back into what is an almost full vacuum. There are several significant points to note about this. First, there is a turning point in space at which the trailing edge of the wave changes direction–before this point the time-wise pressure envelope will drop from its peak to almost zero, whereas not far after this point the pressure wave will drop down only to atmospheric pressure. This creates a need for two different types of modelling element, one for locations before the turning point and one for locations beyond it. Moreover, the distance from the point of detonation to the turning point (which can be measured in tens of meters) increases with the bomb charge, and so there is a need for a model pre-processor that can estimate this location and thus determine which type of modelling element to use at different locations.





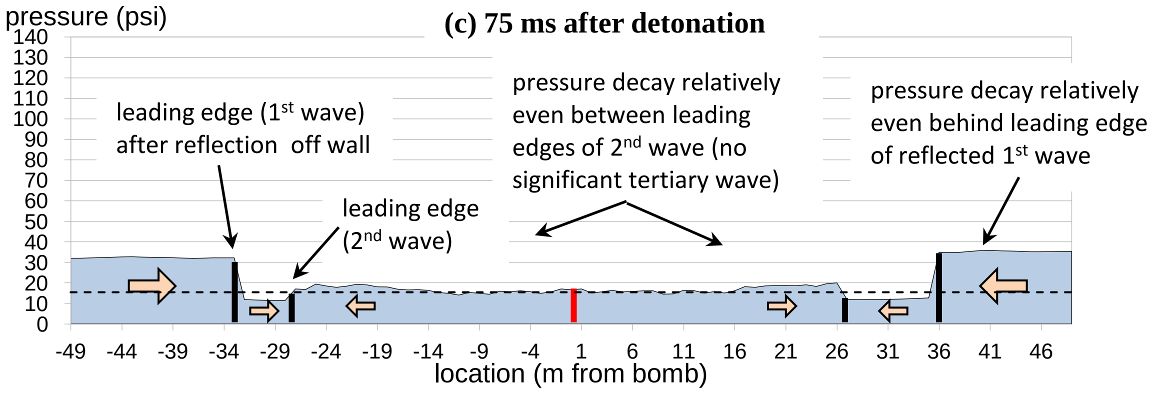


Figure 1: Blast Pressure Profiles and Air Movement (281 kg-TNT bomb)

At 40 ms into the event (see part (b) of Figure 1) the trailing edges have reversed direction, filled in the partial vacuum, and constructively interfered to form a second wave moving out from the point of detonation. Referring to the pressure profile at 75 ms into the event (part (c) of the figure) it is apparent that no significant tertiary wave has formed; in other words, the pressure profile between the leading edges of the second wave is fairly uniform across space at any given point in time. Thus, estimating the time-wise pressure profile at any given location (a necessity for determining impulse loading) need only consider modelling the propagation of the primary and secondary waves. These could be modelled independently and superimposed linearly in accordance with standard wave interference theory.

A third type of modelling element will be required to represent the behaviour of a blast wave as it is reflected off a boundary. Part (c) of Figure 1 shows that the behaviour of a reflected wave is relatively simple, maintaining a uniform pressure profile between the leading edge of the reflected wave and the reflecting boundary. However, the location of the boundary relative to the point of detonation of the bomb is also of importance in modelling the behaviour of the wave. For example, if the reflecting boundary is closer to the point of detonation than the turning point of the trailing edge of a wave then the span of the partial vacuum will be reduced. This may create a need for different reflective boundary modelling elements depending on their proximity to the point of detonation.

4 Model Development and Analysis

As a proof of concept, it was decided to develop a coarse-grain simulation system for one-dimensional blast wave propagation using 1-m spaced coarse-grain elements, the results of which would direct the development of subsequent two- and three-dimensional modelling systems. The study was limited to simulating the propagation of a blast wave in terms of the time of arrival of the peak pressure at successive coarse-grain elements, the peak pressures, and the corresponding velocities. Ultimately, information describing the time evolution of the pressure envelope at each coarse-grain element will be required to allow calculation of the impulse. Specifically, three dependent variables were considered in this preliminary study:

Δt = the time until arrival of the peak pressure at the next coarse-grain element;
p^+ = the peak pressure at the next coarse-grain element;
v^+ = the velocity of the wave on its arrival at the next coarse-grain element.

The range of independent (input) variables considered were:

p = the peak pressure at the current coarse-grain element;
p^- = the peak pressure at the preceding coarse-grain element (this provides rate of change information when read in combination with p);
v = the velocity of the wave at the current coarse-grain element;
v^- = the velocity of the wave when its peak arrived at the preceding coarse-grain element.

A total of 440 training patterns were extracted from a series of CFD simulations executed using DYSMAS (McKeown, 2004). A 102-m wide space was simulated with the bomb located at the centre, reflecting boundaries positioned at each end, and pressures sampled at 1-m spacings. Five different bomb sizes were considered (50, 89, 158, 281, and 500 kg TNT). Before the coarse-grain modelling system was developed, a graphical analysis was made of the relationships between the dependent and independent variables to assess the degree to which they may be modelled using linear methods. The independent variables p^+ and v^+ both showed strong linearity with at least one of the independent variables, whereas Δt was observed to be inversely related to *v* (as might be expected) as shown in Figure 2. It was decided, therefore to use $1/\Delta t$ as the third dependent variable (rather than Δt) to facilitate the use of linear modelling. Figure 3 demonstrates that $1/\Delta t$ is a strongly linear function of *v*, with variance and a slight non-linearity resulting from the coarseness of the mesh (1 m).

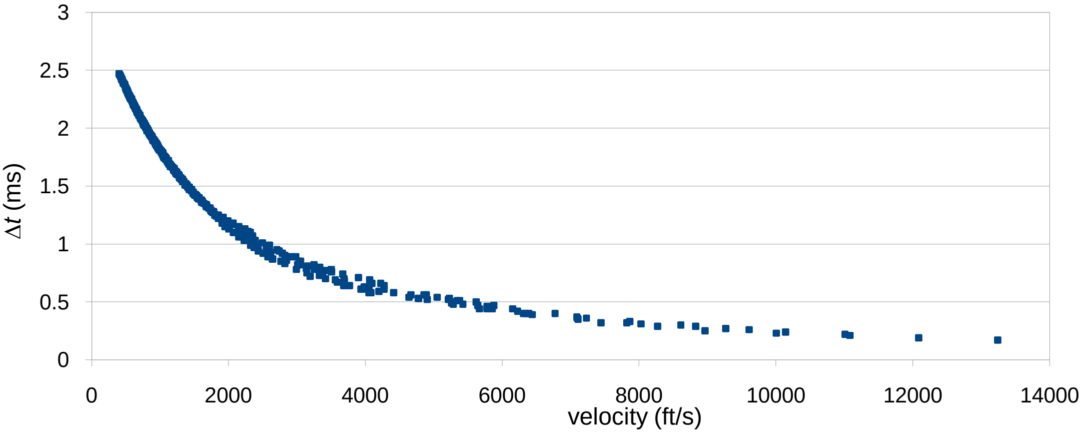


Figure 2: Initial function: Δt vs. velocity (440 observations)

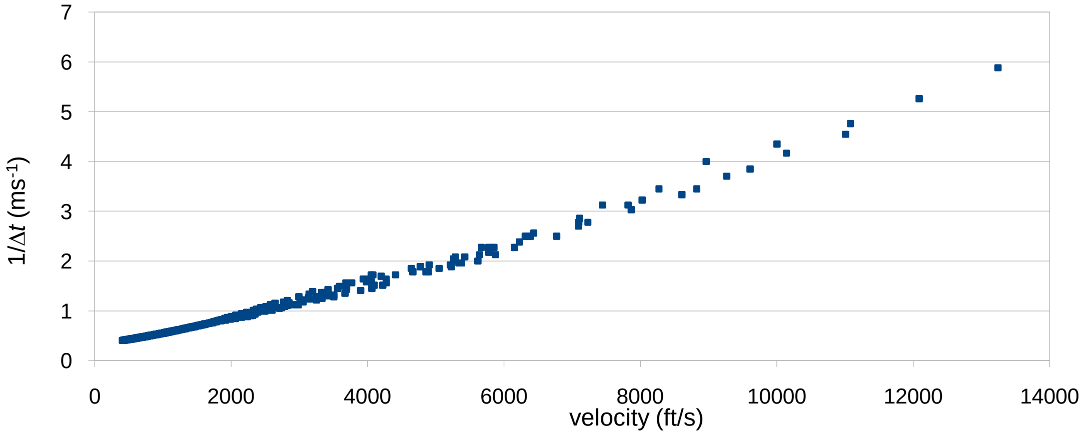


Figure 3: Inverse function: $1/\Delta t$ vs. velocity (440 observations)

The first series of experiments developed multivariate linear regression models for $\{p^+, v^+, 1/\Delta t\}$, in each case using the full set of independent variables $\{p, p^-, v, v^-\}$. All three models appeared to replicate the training data very well. The worst performing was the $1/\Delta t$ model, but this still had an *R*-Square value of 0.998786 for the training patterns, indicating very accurate modelling of the data. Figure 4 provides a scatter plot of actual $1/\Delta t$ values versus the linearly predicted $1/\Delta t$ values for the 440 training patterns. From this it can be seen that all points fall very close to the ideal 45° target line, and there are no outliers.

The true test of these models, however, is their accuracy when operating collectively within a simulation environment. In this case, the errors at the outputs from each of the models will feed back to the inputs and may compound over many simulation iterations. A validation was performed, therefore, using the linear models to simulate the propagation of a blast wave across a 176-m space (88 m in each direction). Figure 5 shows the results of one of these simulations (for a 158-kg-TNT bomb). Referring to this figure, each point on the solid blue line identifies the peak pressure (*p*) and timestep (Δt) predicted at one iteration in the simulation. This line provides a trace of the outputs from the simulation for 88 iterations in *p* versus Δt space. The dashed red line and points represent the target values. Comparing the two traces, it can be seen that the peak pressure predictions are accurate throughout the simulation, whereas the time-step predictions start off accurate but then tend to underestimate the target by about 7.8%. Similar results were found for the velocity predictions and for other bomb charge sizes between 50 and 500 kg-TNT.

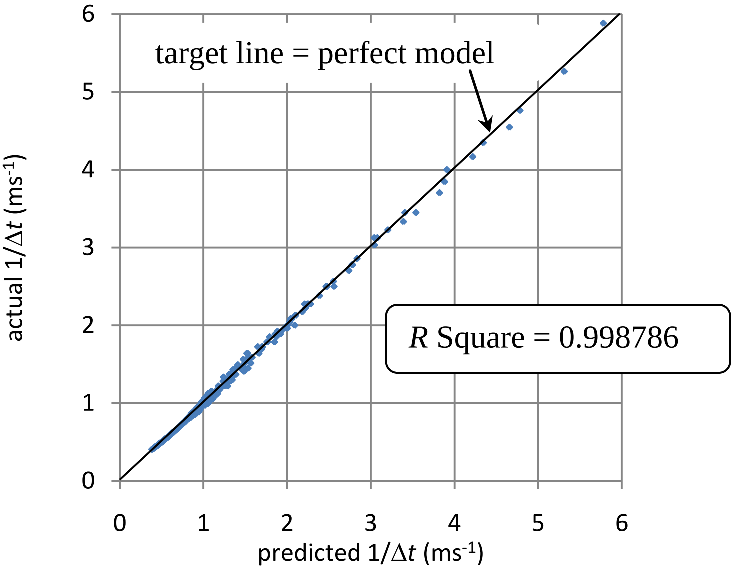


Figure 4: Scatter Plot of Actual (1/Δ*t*) vs. Predicted (1/Δ*t*)

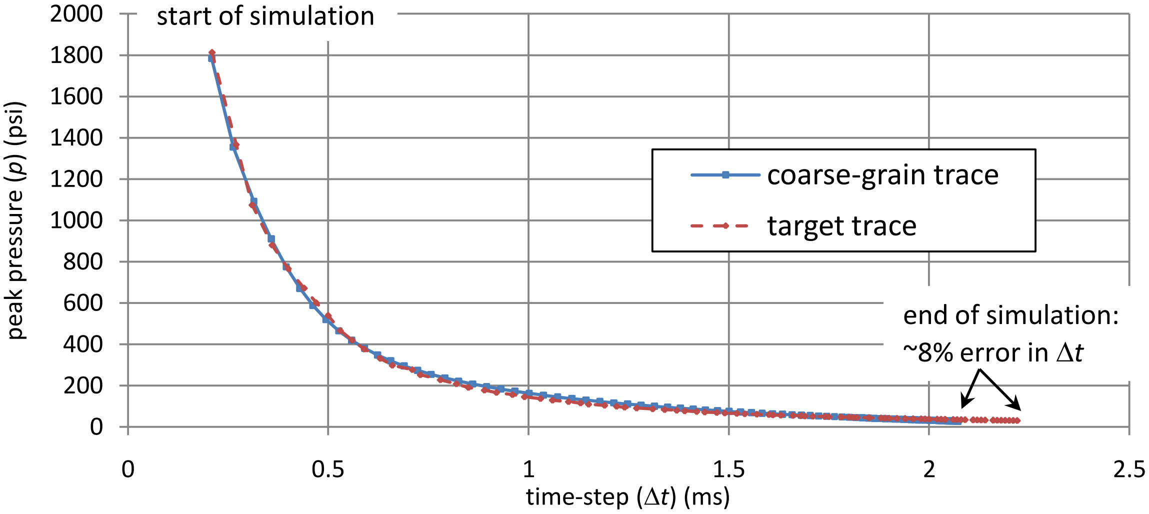


Figure 5: Blast Wave Propagation as a Trace of Points of Peak Pressure vs. Time-Step: (158 kg-TNT, 88 coarse-grain simulation iterations, propagation over 176-m space)

Clearly, the component requiring most improvement in the above coarse-grain simulation implementation is the Δ*t* predictor. Its errors result from the non-linear component of this function's behaviour not captured by the linear model, and/or from behaviour that cannot be explained solely by the chosen set of independent variables. As a result, a second set of experiments was performed using an artificial neural network to try to capture the nonlinearities. The radial Gaussian artificial neural network system (rGIN) proposed by Flood (1999) was used for this purpose. The rGIN model was trained on the errors output from the linear 1/Δ*t* predictor and then combined with it to form a linear-rGIN hybrid model. The hybrid was then tested on the same 158-kg-TNT scenario considered in Figure 5 above.

The errors in the Δt predictions that were previously around 7.8% (towards the end of the simulation) were reduced to about 1.1%. Similar results were found for other bomb sizes.

5 Conclusions and Future Work

This study has demonstrated the ability of the coarse-grain approach to simulate blast wave propagation within a one-dimensional framework, and has provided the insights necessary to extend the approach to modelling in two and three dimensions. Results have indicated that a stable and accurate simulation can be maintained across a wide space using largely linear modelling with some non-linear refinements provided by artificial neural networks. The significance of this is that linear models are much less demanding computationally than neural networks, helping to reduce further the time required to execute a simulation. The processing time for the trial coarse-grain simulations was consistent with the projection (provided by Flood et al., 2010) that these models will run as much as six orders of magnitude (1,000,000 times) faster than a conventional CFD simulation.

The proposed coarse-grain approach is, however, still in its early stages of development. Continuing work is focussed on developing and evaluating the approach to include reflected boundaries; two- and three-dimensional frameworks with diffraction boundaries; coarse-grain elements that operate within the partial vacuum zone around the point of detonation; the advance of the secondary wave; and modelling the time evolution of pressure at each coarse-grain element (for prediction of impulse). In addition, the study will evaluate different permutations of independent variables and the use of alternative neural network systems, in an attempt to improve the speed of execution and accuracy of a simulation.

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