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IMPORTANT INFORMATIVE STATEMENTS

Waveform Reconstruction Method for Prescribed Experimental Blast Conditions in Numerical Simulations

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Abstract. Shock and blast tubes are often used to investigate shock-wave phenomenology, study the response of test articles, predict injury and evaluate the effectiveness of armour. Complementary numerical simulation work is often performed to gain a further understanding of the experimental observations, to visualize and predict the loading conditions and to predict structural response. For such studies, it is important that the numerical technique replicate the particular incident conditions produced in the test. A technique has been developed that involves a merger between pure experimental measurements and numerical simulations, allowing the numerical predictions to more accurately reflect those of the physical experiment. Measurement of the static pressure is relatively straightforward, and initialization of numerical simulations using experimental pressure measurements from upstream gauges has several advantages. However, measurements of static pressure alone do not fully define the characteristics of a blast wave, and therefore inaccuracies will result if pressure alone is used as input. In particular the dynamic pressure component of the blast, shown to play a significant role in the loading and mechanisms of blast injury, will not be accurately captured. An algorithm is described to reconstruct a fully-defined waveform (i.e. a combination of pressure, density, and particle/flow velocity) from an experimental pressure measurement. The resulting waveform can be applied as a time-varying boundary condition to numerical simulations, with the dynamic pressure being accurately preserved. By using this hybrid approach, the need to accurately mesh and model some of the intricacies and geometric aspects of advanced shock tubes is reduced while preserving the accuracy of the simulation. Simulations performed using this technique can produce loads on the test subject that are more representative of actual conditions and can reduce the size of the computational domain. Comparisons between shock tube experimental results, full tube simulations and partial tube simulations using this technique show excellent agreement at downstream gauge locations.

1. BACKGROUND

The shock response of small- to medium-sized objects is often assessed in the laboratory using blast and shock tubes. In a shock tube, driver sections need to be long, tube cross sections are generally constant, and the typical waveform is a normal shock, composed of a state discontinuity followed by constant properties (e.g. pressure, density, etc.). Blast tubes have varying cross-sectional areas, generally a small-diameter driver section with an expanding region followed by a constant-area test section. Waveforms generated in these tubes are more characteristic of a blast wave in the open – a sharp discontinuity followed by a decay.

Numerical simulations using computational fluid dynamics (CFD) or finite element analysis programs are often performed in conjunction with experimental blast/shock tube trials to gain further understanding of the observed measurements, including for personal injury research [1-5]. Modelling assumptions and uncertainties in initial conditions are potential sources of error in reproducing the experimental conditions. Therefore, several authors have taken the approach of applying experimental pressure histories as time-varying inflow boundary conditions to a reduced computational domain centred about their test item [3-5]. This approach has the added benefit of reducing the required size of the computational domain as all points upstream of the input gauge need not be modelled.

Pressure alone is not sufficient to fully define a blast wave. At least three state variables (such as density, velocity, temperature, energy, pressure) are needed to obtain a closed-form shocked state. For illustrative purposes, Figure 1 shows the expected inaccuracies in not fully defining boundary inflow conditions, both for a 69 kPa normal shock, and a 69 kPa incident pressure blast wave with a positive-phase duration of 5 ms. The wave propagation from a fully-defined inflow condition is shown along with 1) an input wave containing the experimental pressure and density, but with zero velocity, and 2) an input wave containing the experimental pressure, ambient density, and zero velocity. In the first case, the waveform has the correct mass and internal energy but the incorrect momentum (or dynamic pressure and kinetic energy). The mass, momentum, and total energy are unsuitable in the second case. While the exact propagation history is slightly dependent on the numerical methods and boundary condition used in the specific (CFD/FEA) simulation program, inaccuracies will persist as long as the waveform is not suitably defined.

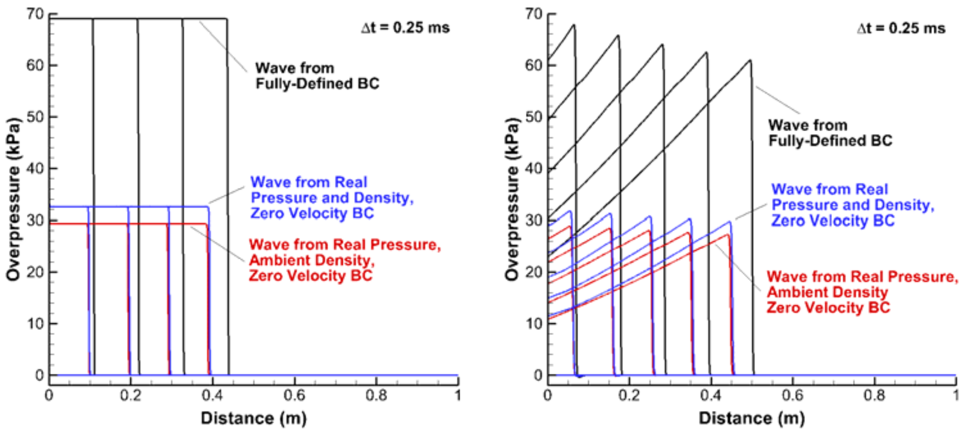

Figure 1. Effect of inflow boundary definition on shock propagation for (left) 69 kPa normal shock and (right) 69 kPa blast wave

The objective of the current research was to develop an algorithm for processing experimental pressure gauge results from the driven section of the tube to reconstruct the missing variable histories (specifically density and flow velocity), needed to fully define the inflow waveform on a reduced computational domain. Use of a reduced computational domain with experimental pressure gauge measurements as input is more computationally efficient and can produce loads on simulated test structures that are more representative of actual test conditions. The following sections describe the algorithm, the inherent limitations of the method, and results of testing using experimental and numerical simulation blast tube data. Alternative algorithms that were considered are also discussed.

2. BASELINE SIMULATIONS OF ADVANCED BLAST SIMULATOR

Evaluation of the wave reconstruction method was performed using data from the Defence Research & Development Canada - Suffield Research Centre Advanced Blast Simulator (ABS 30), a specialized blast tube currently being used in a Canadian program to study traumatic brain injury. A schematic of the ABS 30 is shown in Figure 2. The driver section and initial expansion region are hexagonal in cross section. By the $x = 1.26$ m point, a transition to a circular, 30.5 cm diameter cross-section is complete. The end of the tube can either be left open as was done for the experimental trial described in this work, or fitted with an end-wave eliminator which reproduces the effect of a very long tube. Five gauges along the walls of the tube (G1-G5) measure the static overpressure of the blast wave. Test articles are typically placed at the Gauge 4 (G4) location.

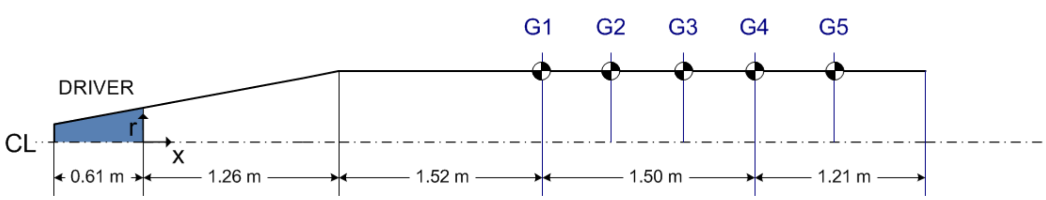

Figure 2. Schematic of DRDC Suffield Advanced Blast Simulator (ABS 30)

Prior to testing the shock reconstruction method, a first-principles CFD simulation of the entire blast tube was performed for comparison to an experiment involving a nominal 103 kPa incident shock overpressure at the test location (G4); this is henceforth referred to as the "Full Tube Simulation". The helium driver overpressure needed to achieve this shock pressure was approximately 965 kPa at 300 K. The blast tube was simulated assuming two-dimensional axial symmetry; the hexagonal cross-section regions were modelled as circular cross sections of equal area. The latter assumption is not anticipated to significantly affect the results. The diaphragm was not explicitly modelled.

Figure 3 shows the comparison between the experimental and numerical side-wall pressure values at Gauges 1 and 4. Overall, the level of agreement is good. An expansion wave is generated from the primary shock exiting the tube, which travels upstream. This expansion is curbed by a shock which travels behind the expansion, created by the pressure difference at the end of the tube between outside and over-expanded inside conditions. This shock is evident at roughly 16 ms at Gauge 4, and at 22 ms at Gauge 1.

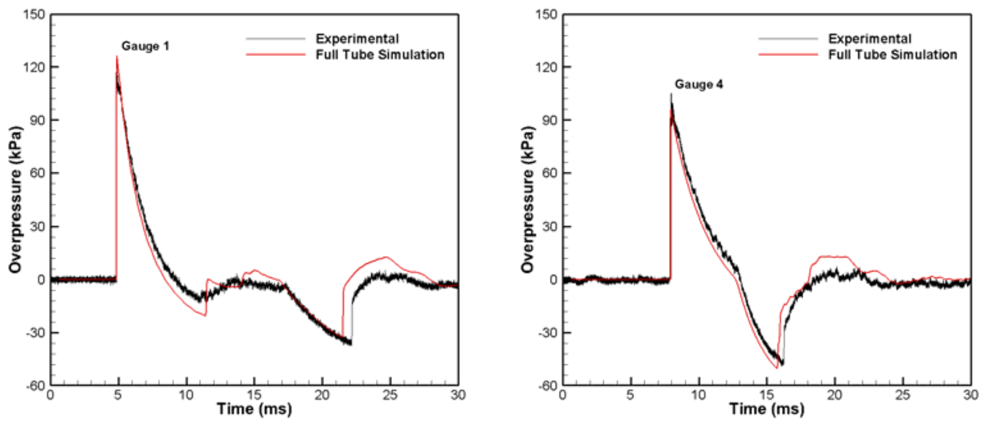

Figure 3. Comparison between experimental measurements and numerical predictions for simulation of full blast tube (left) Gauge 1 (right) Gauge 4

A wave diagram was created by extracting the density distribution on the blast tube centreline as a function of time. The results are plotted in Figure 4 to illustrate the key wave features. The positions of the diaphragm separating driver and test sections, Gauges 1 and 4, and the end of the tube are labelled. With the end of the tube open, the test item (at G4) only sees conditions representative of an undisturbed primary blast wave until the downstream expansion waves from the tube end reach the test position, which occurs at approximately the 13 ms mark.

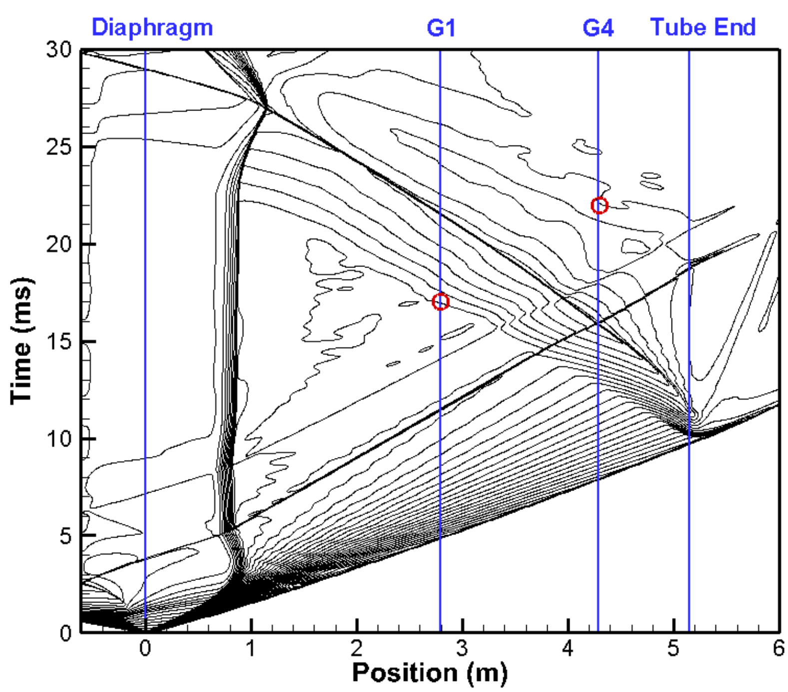

Figure 4. Wave diagram based on results of full tube simulation. Lines represent constant density. Circled points are referenced in Sections 4.1 and 4.3.

3. WAVEFORM RECONSTRUCTION ALGORITHM

The waveform reconstruction method is based on a moving-piston analogy applied to a fixed point in space. It uses a one-dimensional finite-volume computational fluid dynamics framework to compute the fully-defined waveform based on a specific pressure history. The inflow boundary is considered to be the piston face at each timestep; the domain is stationary with respect to the piston face. A wave is transmitted into the interior fluid by instantaneously applying a velocity to the piston. The shape of the transmitted wave can be manipulated by varying the piston velocity (Figure 5).

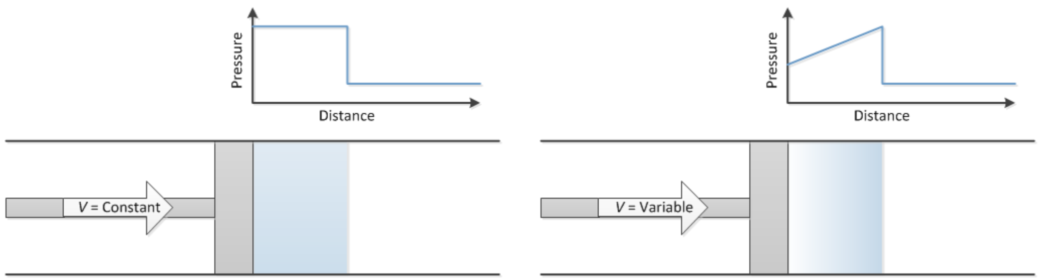

Figure 5. Effect of piston velocity on shock waveform produced: (left) constant piston velocity and (right) instant piston motion followed by a reduction in velocity

The pseudo-code for the reconstruction method is as follows. For each time step, *dt*:

1) Get "goal" pressure from target *P-t* curve (experimental pressure gauge measurement) given the current simulation time. Interpolate as needed.
2) Guess the "piston" velocity using the previous solution as a starting point.
3) Iterate until pressure convergence is obtained using Newton-Raphson method:
    a. Apply the piston velocity to the boundary cell, along with "goal" pressure and the density from the neighbouring interior cell.
    b. Calculate state variables and fluxes at cell faces, and update intermediate solution based on the estimated boundary conditions
    c. Check interior cell pressure for convergence
    d. Adjust velocity estimate if necessary
4) Perform full simulation time step calculation including update of governing equations
5) Record the full state in the first interior cell, and output pressure, density, velocity (and temperature) to a file.

2.1 Limitations of the Method

There are a few inherent limitations in the waveform reconstruction approach. First, it is assumed that the contact surface from the driver gas does not reach the experimental gauge being used as input. There is uniform pressure across the contact surface but there a density discontinuity. Since the contact surface is not evident in the pressure history, the density discontinuity cannot be reconstructed from the pressure history alone. The driver gases in the DRDC blast tube only reach a distance of 1.0 m, and therefore this limitation does not factor into this test as the first gauge is 2.79 m from the driver.

A second limitation is that all waves present at the experimental gauge used as input must originate from the upstream direction. Using the piston analogy, piston accelerations in the normal flow direction result in pressure rises, while piston decelerations in the normal flow direction result in pressure decreases. If shock waves reflect off of downstream structures, or expansion waves are generated at open tube ends, and these waves propagate back up the tube to the input gauge location, the piston analogy is no longer valid as the acceleration/deceleration of the piston does not match the flow direction. While the wave reconstruction method will appear to function correctly with the pressure-history being matched at the boundary, the downstream wave solution will not be correct. Much like with the previous limitation, there is no method for the wave reconstruction algorithm to determine the source of all waves in the gauge result, and therefore it is up to the analyst to ensure that the gauge used as input is appropriate.

Finally, when using this method, the reconstructed waveform is used as a boundary condition input to a subsequent simulation. The underlying assumption is that the flow is in the boundary-normal direction only. Reconstructed gauge results from locations where there is a measurable transverse wave component to the flow will result in differences in the downstream results.

4. TESTING

Several tests of increasing complexity were performed to ensure the accuracy of the method. The primary comparisons made were:

1) Reconstruction of a numerical *P-t* (pressure-time) history from the full simulation. Results of a range of flow variables are compared at the reconstruction location.
2) Reconstruction of a numerical *P-t* history from the full simulation, with comparison of results at downstream gauge locations.
3) Reconstruction of an experimental *P-t* history with comparison of numerical results to experimental measurements at downstream gauge locations.

4.1 Reconstruction Verification

As only pressure measurements are available in the trials, it is difficult to confirm that all variables are reconstructed correctly through comparison to experimental data. Therefore, a numerical pressure-time measurement from the full tube simulation was reconstructed to first test the waveform reconstruction method. Doing so allowed the reconstructed variables, both the primary variables used as input (velocity and density) and secondary, computed variables (temperature), to be compared directly with the full tube simulation calculation results to check for accuracy in all reconstructed variables. The Gauge 1 (G1) numerical pressure measurement from the simulation of the full tube was used for the reconstruction, and the numerical domain was shortened to include only the tube sections downstream of the G1 gauge.

Figure 6 illustrates the pressure, density, velocity, and temperature histories for both the original source data ("Full Tube Simulation") and the reconstructed wave. The reconstructed pressure profile shows excellent agreement; this is expected since this is the main input. There are slight deviations in the density and temperature profiles; the temperature profile is shown for testing purposes only and not actually used.

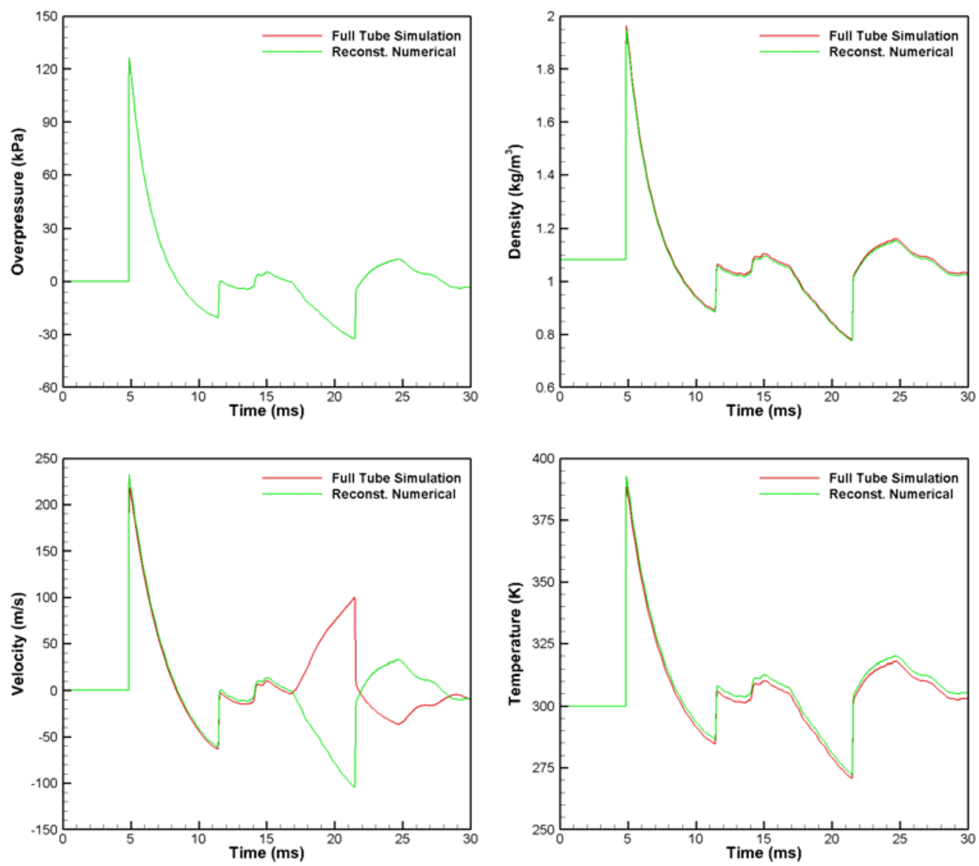

Figure 6. Comparison between the Gauge 1 reconstructed wave and original source (full tube simulation) at the Gauge 1 location.

While the initial blast wave velocity profile shows very good agreement with the results from the full simulation, the velocity profiles are fully out of phase after about the 17 ms mark. This time corresponds to the point at which the expansion wave from the tube end reaches the gauge position/inflow boundary (see circled G1 point in Figure 4). This demonstrates one of the aforementioned method limitations: all waves must originate from the upstream direction. For a period after this point the waveform reconstruction method predicts the correct velocity magnitude but the wrong sign, and still reconstructs accurate density and temperature profiles with this magnitude.

It should be noted that this feature in the velocity profile was not seen in any reconstructions of "infinite"-length blast tubes (i.e. experiments with the end-wave eliminator in place, not shown). When the end-wave eliminator is used, there are effectively no waves created from downstream blast tube features which can then travel upstream and interact with the reconstruction location.

4.2 Numerical Reconstruction

The reconstructed numerical waves were used as input to a simulation of the blast tube using the reduced computational domain highlighted in Figure 7. By performing this intermediate test involving reconstruction of a numerical solution, results for all flow variables (not just pressure) could be investigated, and any variations in the results due to differences between the experimental and numerical configurations could be discounted.

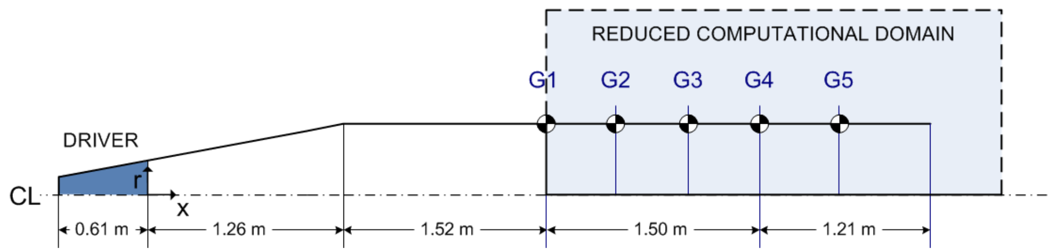

Figure 7. Schematic of reduced computational domain

A time-varying, pressure-density-velocity boundary condition was used to apply the waveform. Results at Gauges 1 and 4 are given in Figure 8. The expansion wave originating from the open tube end passes Gauge 4 at about 13 ms. As expected, the Gauge 1 results show excellent agreement until the 17 ms point, at which time this expansion wave begins interacting with the inflow boundary (G1 location). This interaction wave propagates downstream to the Gauge 4 location at roughly 21 ms, before which the agreement in the full and reconstructed simulations is very good.

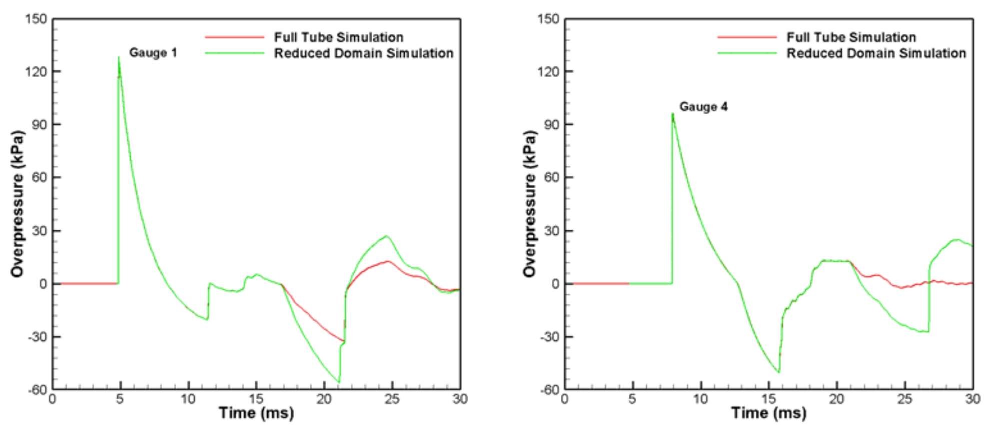

Figure 8. Comparison of reconstructed numerical waveform (reduced domain) relative to the original source (full tube simulation) (left) Gauge 1 (right) Gauge 4

4.3 Experimental Reconstruction

Finally, the Gauge 1 experimental pressure gauge result was reconstructed, and applied as a time-varying inflow boundary to the reduced computational domain, as was done in the previous test. The resulting pressure histories at Gauges 1 and 4 are shown in Figure 9. As in the equivalent numerical-only test, the reconstructed wave shows excellent agreement up to the arrival of the expansion wave from the end of the tube, at approximately 17 ms. Excellent agreement is also shown at the Gauge 4 location up to roughly 22 ms, the point at which the wave interaction initiated at the Gauge 1 location propagates downstream. This point is shown in the Figure 4 wave diagram as the circle at the G4 location.

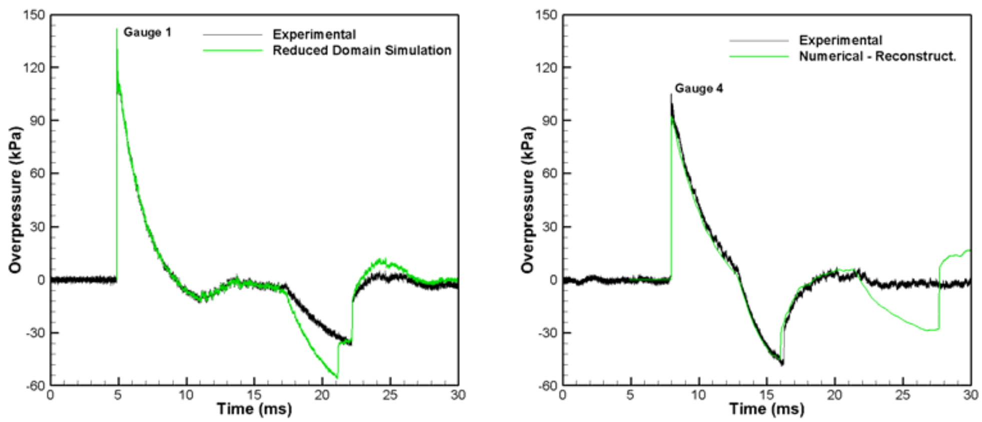

Figure 9. Comparison of reconstructed experimental waveform (reduced domain) relative to the original experimental measurements (left) Gauge 1 (right) Gauge 4

Although the reconstructed wave has some limitations which restrict the duration over which the method can be accurately applied, the time duration for which it does produce good results is at least as great as in the experiment itself. It is very important to note that when performing a test using an open-ended tube, the conditions in the test section are only representative of actual blast conditions from the initial shock arrival to the time the expansion wave from the end of the tube reaches the test location. After this point, the loads on the test article are no longer the intended test conditions. In the test cases shown in this work, this point is reached at 13 ms at the test location (Gauge 4).

5. ALTERNATIVE METHODS

It may appear as though there should be a more straightforward method to compute the density and velocity from a pressure measurement. Shock dynamics, particularly in air, are well quantified. It is very simple to fully compute the shock jump conditions corresponding to the incident wave – density and particle velocity can be determined for a specific pressure ratio using standard shock tables. Reconstructing the resulting decay is less straightforward.

A reconstruction method for the decay region was attempted by which density was first computed using a basic isentropic relation:

$$\frac{p}{p_{ref}} = \left(\frac{\rho}{\rho_{ref}}\right)^{\gamma} \tag{1}$$

where p is pressure, ρ is density, γ is specific heat ratio, and the subscript *ref* refers to a reference state. Although the approach seemed very promising with density being reconstructed exactly, a closed-form solution for velocity could not be found using equations which included:

$$\frac{p_o}{p} = \left[1 + 0.5(\gamma - 1)\mathrm{Ma}^2\right]^{\gamma/\gamma-1} \tag{2}$$

$$\frac{\rho_o}{\rho} = \left[1 + 0.5(\gamma - 1)\text{Ma}^2\right]^{1/\gamma - 1} \quad (3)$$

where Ma is Mach number and the subscript *o* refers to a stagnation quantity, as enough unique equations could not be found. It is possible that this method is not feasible since some equations above are applicable to the state evolution of a fixed mass of material, not the inflow of a new mass of material as observed at a static gauge location.

6. CONCLUSIONS

The waveform reconstruction method was developed using a piston analogy and a one-dimensional CFD framework in which the "piston velocity" is varied to recreate a specific blast wave profile. The reconstruction technique was tested using both numerical and experimental data, and showed excellent results compared with actual downstream pressure gauge measurements and, in the case of the numerical reconstruction, with other flow variables.

Although there are limitations to the method, it functions well for planar waves in air, and the duration for which the results are valid is at least as great as in the experiment itself. The conditions in the test section of an open blast/shock tube are only representative of actual blast conditions from the initial shock arrival to the time the expansion wave from the end of the tube reaches the test location. After this point, the loads on the test article no longer sufficiently represent the desired test conditions.

Further studies are necessary to determine the applicability of the method to shocks in other materials (such as water), and to assess whether the method can be adapted to reconstruct cylindrically- or spherically-expanding blast waves such as found in larger experimental trials.

Acknowledgement

The authors wish to acknowledge David Ritzel (DynFX Consulting) for originally proposing the "piston analogy" for waveform reconstruction.

References

[1] Josey, T., Sawyer, T.W., Ritzel, D.V., Donahue, L., High Fidelity Simulation of Free-field Blast Loading: The Importance of Dynamic Pressure, Personal Armour Systems Symposium, Amsterdam, NL, Sept 18-23, 2016.

[2] Varas, J.M., Philippens, M., Meijer, S.R., van den Berg, A.C., Sibma, P.C., van Bree, J.L.M.J., and de Vries, D.V.W.M., Physics of IED blast shock tube simulations for mTBI research, Frontiers in Neurology 2:58, (2011), pp 1-14.

[3] Sundaramurthy, A., Alai, A., Ganpule, S., Holmbery, A., Plougonven, E., Chandra, N., Blast-induced biomechanical loading of the rat: an experimental and anatomically accurate computational blast injury model, Journal of Neurotrauma, 29, (2012), pp 2352-2364.

[4] Ganpule, S., Mechanics of blast loading on post-mortem human and surrogate heads in the study of Traumatic Brain Injury (TBI) using experimental and computational approaches, PhD Thesis, University of Nebraska – Lincoln (2013).

[5] Greer, A., Numerical Modeling for the Prediction of Primary Blast Injury to the Lung, Masters Thesis, University of Waterloo (2006).

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