Application of background oriented schlieren (BOS) for quantitative measurements of shock waves from explosions

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1 Introduction

This paper describes application of a background oriented schlieren (BOS) technique in order to obtain quantitative measurements of shock waves from explosions by processing high speed digital video recordings. To illustrate the technique we present results from two explosions, a high explosive test and a gas explosion test. The experiments were performed at the NDEA test facility at Raufoss, Norway, June 2005, as part of an IEA-HIA task 19 project on hydrogen safety. The objective of this paper is to show that the shock wave overpressures in a field explosion test can be predicted quantitatively by means of this technique. In the case of the gas explosion test we can also show that the shock front is non-spherical. It should be possible to use this technique to investigate external blast waves and external explosions from vented gas explosions.

2 Image processing

Background Oriented Schlieren is an optical measurement technique, and it is used for visualizing density gradients [1]. The method depends on the variation of the refractive index of the transparent media (i.e. air) due to density gradients [2]. The principle of the method is numerical comparison of schlieren of a distorted and an undistorted image of a background. In our case the background was a forest (i.e. a row of spruce trees).

Figure 1. Principle of the image processing

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As illustrated in Figure 1 our image processing technique consists in principal of subtracting an undistorted image from a distorted image. The resulting image was then manipulated by a logarithmic intensity transformation. We read the positions of the shock front from the resulting image manually. By averaging the shock position versus time, the shock Mach number was estimated and the shock front pressure was calculated by $\Delta p/p_0 = (2\gamma/(\gamma+1))(M^2-1)$. We have developed numerical algorithms in MATLAB for the image processing and pressure calculations. The code also generated videos from the manipulated images.

3 Experiments

The tests reported here were part of a test series consisting of calibration tests with C-4 high explosives and 39 gas explosions tests with inhomogeneous hydrogen air clouds in an ISO container. The C-4 test we are referring to in this paper was a test with 100g C-4 mounted and detonated on a wood pole. The charge was placed on the outside of the container, 2.5 m from the container door, and 1 m above ground. A manipulated image of the C-4 test is shown in Figure 2. The hydrogen experiment, test #39, was performed in a standard 20’ ISO container with inner dimensions L = 5.94 m, W = 2.34 m and H = 2.39 m. The hydrogen filling system consisted of a 0.3 m^3 storage tank and a steel tube connecting the tank and the container. A downwards directed nozzle was mounted at the tube outlet. The nozzle had an inner diameter of 9 mm. The nozzle was placed inside the container 1.0 m from the back wall, at a height of 1.0 m above the container floor. The storage tank was filled with hydrogen at 24 bars overpressure. The fuel supply was controlled by a pneumatic valve. In test #39, eight ordinary euro pallets were placed inside the container to generate turbulence during the explosion. The container doors at one end were open. The hydrogen gas was ignited 15.0 seconds after the release of hydrogen inside the container started. The ignition source was mounted 1.0 m from the solid back wall, and 50 mm below the roof. Three Kistler 7001 pressure transducers were monitoring the explosion pressure inside the container. In addition, two LC-33 pressure transducers (P4 and P5 respectively), were mounted 6.5 and 8.7 meters from the container door. The pressure signals were recorded on a transient digital data logger. The hydrogen storage tank pressure was monitored with a pressure transducer mounted at the end wall of the tank. Theoretical calculations of the jet release imply that approximately 0.5 kg hydrogen was released before ignition. A Photron Ultima APX-RS high-speed monochrome camera with a Nikkor 50mm f/1.3 lens, was recording the explosion events at a rate of 3000 fps. The distance between the experimental set-up and the camera was approximately 30 m.

Figure 2. Manipulated image from the C-4 test

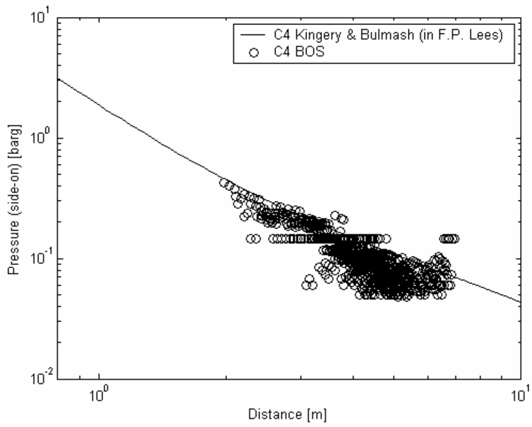

Figure 3. Predicted shock front pressures

4 Results and discussion

Figure 3 shows the predicted shock front pressures from the C-4 test compared with a pressure-distance curve based on the Kingery and Bulmash TNT curve [3]. A C-4 to TNT equivalence mass for pressure of 1.2 [4] was used converting TNT to a C-4 curve. Since the resolution (i.e. number of pixels and frame rate) is limited we got scattering in the predicted shock front pressures. Initially we tried standard averaging and polynomial curve fitting techniques in MATLAB, however we found that these techniques were not sufficiently robust for our limited data set. We therefore simply used the gradients between sampling points that was more then 10 time steps apart to calculate shock velocities and pressures. Even though the predicted shock front pressures shows scattering, the average value is following the Kingery and Bulmash curve quite well. The result shows that it is possible to estimate shock front pressures from a high explosive detonation by using a high speed digital video recording of the event.

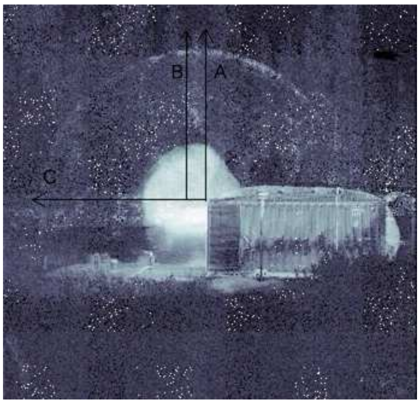

Figure 4. Manipulated image from the hydrogen gas explosion test

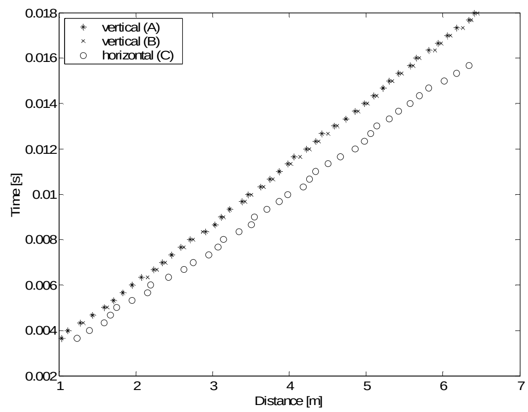

Figure 5. Shock propagation along axes A, B and C

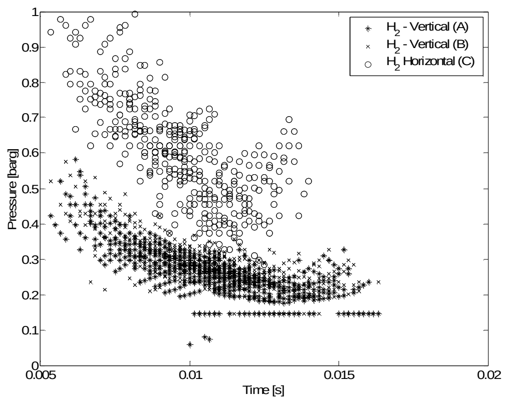

Figure 6. Estimated shock front pressure vs. time

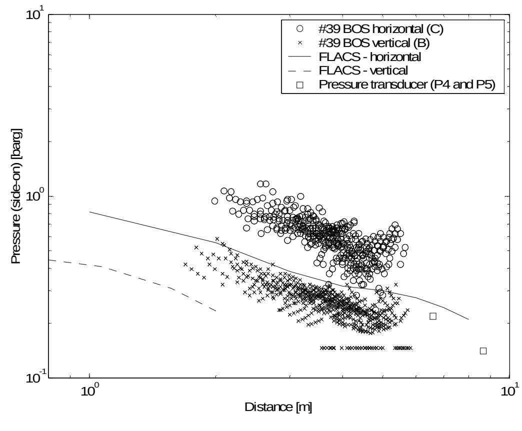

Figure 7. estimated shock front pressure vs. distance

Figure 4 shows one of the manipulated images from the hydrogen gas explosion test. From the manipulated images we have extracted three sets of shock trajectories along the axis A, B and C. We defined upper corner of the container as a reference point. Figure 5 shows the trajectories in a time-distance diagram for the shock front propagation along axis A, B and C. The estimated shock front pressure versus time can be found in Figure 6. It is clear that the shock in the horizontal direction propagates at higher velocity than in the vertical direction. We have made some preliminary CFD simulations with the FLACS code [5] and our own LES code. Both these codes indicated that the flow velocity ahead of the shock can not explain the differences in horizontal and vertical shock velocities. The asymmetrical shock is expected to be a result of the reflection off ground and the momentum in horizontal direction of jet from the explosion inside the container and possibly also the external explosion. Such phenomena have been investigated among others by Forcier and Zalosh [6], Chiu et al. [7] and Harrison and Eyre [8]. It is interesting to note that on the manipulated image video several shock waves follow the first shock wave.

Figure 7 shows the estimated shock front pressure versus distance. Preliminary FLACS simulations and measured pressures are also shown in the figure. In the FLACS simulations we assumed a homogeneous 20% hydrogen-air gas cloud in the upper half of the container volume. The estimated shock front pressures seem reasonable compared with the FLACS simulation and pressure measurements.

5 Conclusions

We have shown that this BOS technique can be used for estimating explosion overpressures from high explosives and gas explosions. For high explosives the method agreed quite well with a standard curve for side-on shock pressures.

For the gas explosion we found that the shock wave propagated faster in the horizontal direction than in the vertical direction. We observed also that the first shock wave was followed by several other shock waves.

It should be possible to use this technique to investigate external blast waves and external explosions from vented gas explosions.

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