

Background oriented Schlieren measurements for pressure relief systems in the free field

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1 Introduction

Shock waves or shocks are a supersonic phenomenon in which the flow variables change abruptly in a thin layer. These occur with super sonic flow, such as the supersonic flight of airplanes or rockets or with explosions.

As the pressure, temperature and density change in a shock, this can be recorded. The most commonly used approach is the use of pressure sensors. Pressure information is only available at the certain locations where the sensors are installed. Any body, such as free-standing sensors, that is introduced into the flow, distorts it. Therefore, not inverse measurement methods for measuring flow variables, such as the background orientated schlieren (BOS) method or the partial image velocimetry (PIV), are used.

For this reason, a BOS setup was carried out in an open field at the Test Site Technical Safety (TTS) of BAM using a shock wave generator to visualize the shocks that result from a gas explosion. These investigations are presented in this paper. The aim is also to draw conclusions about the pressure change caused by the shock and the advantages that such a simple structure provides to the tests.

2 Experiments

Experimental setup

The experiments were carried out at the BAM Test Site Technical Safety in Brandenburg. The test setup consists of a shock wave generator (SWG) in the open field. This SWG is a cylindrical autoclave with a volume of 65 liters. It is pressure-resistant up to 400 bar. The autoclave has a circular outlet with a diameter of 132 mm, which is sealed with a 0.2 mm aluminum diaphragm. This diaphragm is only there to separate the two different media (gas mixture, air) from each other and is located in the center of the autoclave at the outlet at a height of 1.35m.

A detonative gas mixture consisting of acetylene and oxygen (36,5 vol% & 63.5 vol%) is filled into the SWG. This mixture is metered into a previously evacuated system via a mass flow controller (MFC) system. The procedure is as follows: First, the entire system, consisting of a buffer tank, pipes and the SWG, is evacuated. Then the mixed gas is filled into the buffer tank. The gas is then transferred to the SWG under ambient pressure. There the gas has approx. 2 minutes to settle. During this time, the rest of the system, with the exception of the SWG, is purged with nitrogen for safety reasons.

The gas is ignited with an exploding wire. The advantages of this system have already been presented by Gerbeit and Seeber. The test setup was validated with an explosive, in this case PETN [1].

The pressure increase within the system causes the diaphragm to burst and the shock wave resulting from the reaction moves out of the SWG into the free field. 4 Kistler pencil probes (Kistler 6233A0025) are used to measure the overpressure caused by the shock with a sampling frequency of 2 MHz in the free field measuring section. The exact setup can be found in Figure 1.

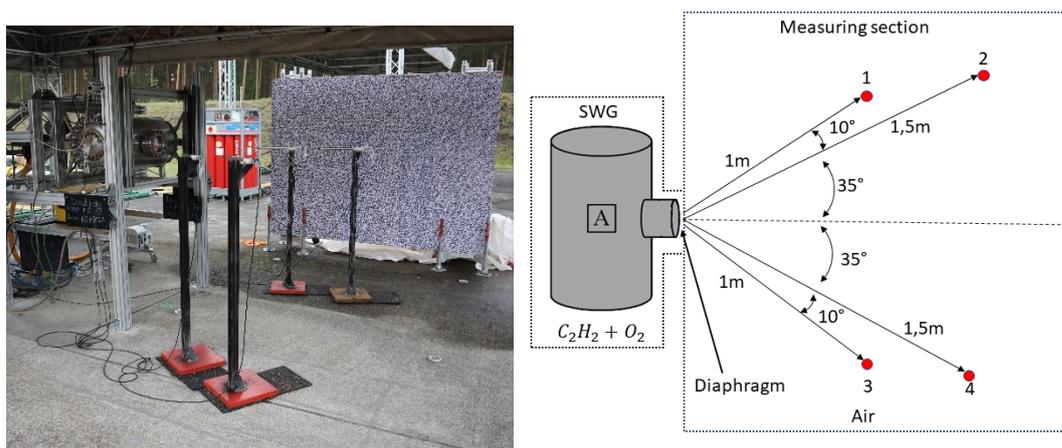


Figure 1: Test setup (left) and the corresponding schematic top view (right)

BOS

Background Oriented Schlieren (BOS) is an optical method for the detection of the distortion of a background. Such distortions can be caused by changes in the density of the flow medium. The refractive index is dependent on the density via the Gladstone Dale equation.

$$n = 1 + K\rho \quad \text{Eq. 1}$$

If two images of the background - one with and one without density perturbation - are compared with each other, the density gradients within the image with flow can be determined based on the apparent shift of the background pattern [2]. The resulting distortion of the

background depends on both the intensity of the event (in this case the shock) and the experimental setup.

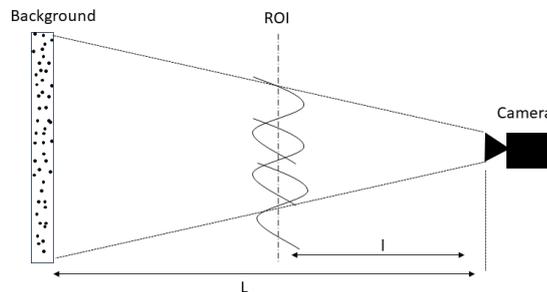


Figure 2: BOS setup

Background-orientated Schlieren (BOS) is of particular interest because it is easy to implement and is therefore suitable for a wide range of applications - from small test benches to large test setups. In addition, BOS is non-invasive, cost-effective and capable of visualizing complex flow phenomena with good spatial resolution [3].

A BOS setup was carried out on the test stand described above. For this purpose, a suitable background was placed behind the SWG, as can also be seen in Figure 1. A random dot pattern was applied to a wall for this purpose. Numerous studies have already investigated the setup and benefits of such a pattern [4, 5].

The wall is located at a distance of $L=6$ meters from the high-speed camera, a monochrome Photron SA-Z 2100K. The region of interest (ROI) is at $l=4$ m. The camera is at the same height as the outlet and is focused on the background. A 50 mm $f/2.8$ lens is used. The camera captures 1024×1024 pixel images at 20.000 fps. The global electronic shutter is independent of the images and is open respectively for $10 \mu s$. Four Lamps (Veritas Constellation 120E) were used to illuminate the background.

3 Results

The Figure shows the results of a test. In these BOS images, the histogram was equalized to make the images brighter. Subsequently, the false color display was used to make the shocks visible in the images.

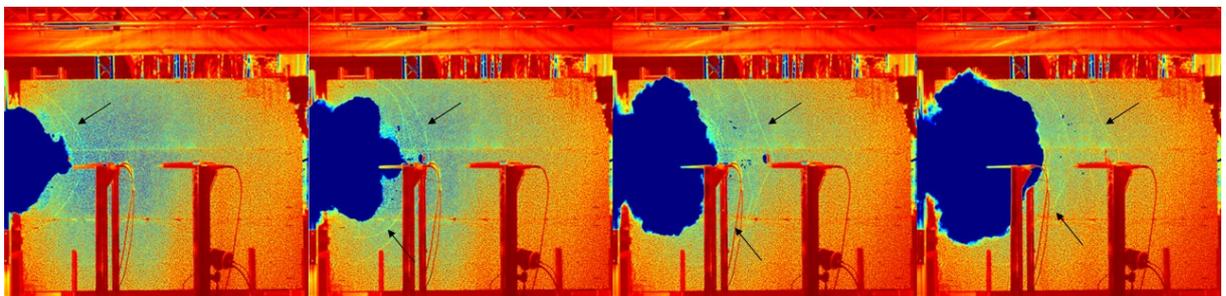


Figure 3: Manipulated image from the test after 1.5ms, 2ms, 2.5ms and 3ms ignition with marked shocks

The first shock is clearly visible in the images. The shock is hemispherical at the beginning. However, it becomes weaker over time and curves around the rupture disc. This phenomenon occurs because the impulse of the gas flame continues to accelerate the bursted diaphragm and it flies supersonically from a certain point in time. This results in a detached shock. This phenomenon is not a problem, as the pressure sensors are outside the area affected by it.

In addition, further subsequent shocks can be recognized in the images. These are also visible in the pressure values in Figure .

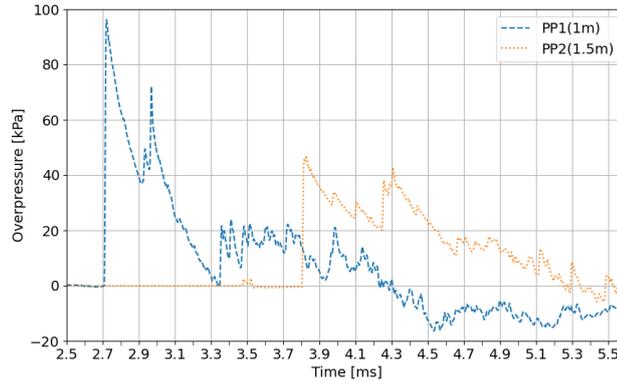


Figure 4: Pressure data from the pencil probes

Analogue to Sommersel procedure [6], the pressure were estimated using the BOS images. For this purpose, an image without flow was first subtracted from those with flow. The outermost positions of the shock were then read out using an edge detection algorithm [7]. Using a pixel to meter scale, a distance could be determined. A scale was initially placed in the picture and a picture was taken with this camera. The time between the images was 0.05ms. The propagation speed of the shock front (shock Mach number) was determined on the basis of the distance and the time interval between the images. The predicted shock front pressures could then be determined using the Rankine-Hugoniot equations:

$$\frac{\Delta p}{p_0} = \frac{2\gamma}{(\gamma + 1)} (M^2 - 1) \quad \text{Eq.2}$$

γ is the ratio of specific heats and amounts to 1.4 for air as an ideal gas. The pressure was determined at an angle of $0^\circ - 40^\circ$ relative to the centre axis of the outlet at the shock. This can be seen in Figure 5 on the left. For this purpose, every 5 images were analysed, as this had to be done manually in some cases, as automatic detection of the shock front failed. Although this reduces the effects of error ± 1 pixels in every axis, it can mean that the image selected in each case is not ideal. This results in an error of approx $\text{Ma} = 0.029$.

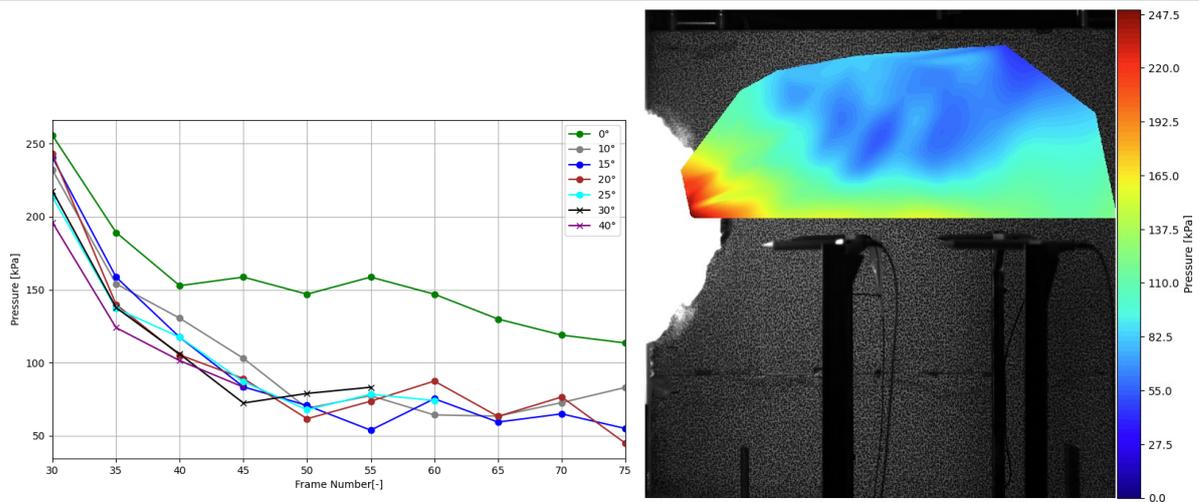


Figure 5: Estimated overpressure at a specific position (left); Interpolated shock pressure based on the estimate (right)

The pressure field is in line with expectations. As the shock propagates further away from the SWG, it's the pressure decreases exponentially. Only the shock close to the jet is an exception, as the bursting disc flies in the middle plane and a detached shock forms in front of the bursting diaphragm. This is driven further by the jet. This can be recognised by the non-decreasing pressures in this area. In addition, in some areas of the image, local discontinuity in the pressure field can be recognised that do not correspond to reality. These are errors that occurred during the identification of the shock front.

4 Conclusion

Pressure sensors are most frequently used in the shock wave generator tests. These pressure measurements offer precise information about the flow field at specific locations. However, since they are limited to discrete points, an additional measurement technique is necessary to gain insight into the propagation of the shock wave and the resulting state variables with a higher spatial resolution. Background-oriented schlieren (BOS) provides comprehensive data across the entire 2D field. This is particularly important as the individual shocks can be visualized there. This offers significant added value for the interpretation of the pressure values and the gasdynamics related to detonations. It can also be used for the validation of pressure sensors.

The results of the tests show that such a setup is a considerable information gain. Based on this setup, a phenomenon, the detached shock at the diaphragm cut out and propelled by the jet, and its effects, could be discovered that was not expected. The effect could also be seen in the estimated pressure field. The evaluation method to estimate such a pressure field needs further revision. By improving the shock front detection and visualising the results using a curve fit.

References

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