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Estimation of Blast Overpressure From a Cylindrical Charge Using Time of Arrival Sensors

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Abstract

Time of arrival data for a blast wave generated by a cylindrical high explosive charge is presented and analysed to provide peak static overpressure as a function of distance from the charge. Comparison of the calculated pressure with measured peak pressure shows a close agreement. The advantage of using time of arrival data is that peak pressures can be determined at very close distances from the charge.

Introduction

The detonation of high explosives in air results in an initial localised high pressure and high temperature region. This initial pressure disturbance causes a shock wave in the surrounding air, commonly referred to as the blast wave. It is important to understand the characteristics of blast waves to determine the capability of conventional weapons and to assess potential terrorist attacks or industrial accidents.

Much work has been done to investigate blast and effects of blast against structures. Most of this earlier work focussed on blast waves generated by spherical charges. Lind et al. [2] investigated the protection of structures from the dynamic loading of blast waves. A numerical study was undertaken to determine the mitigating effects of grid like barriers. The initial boundary conditions of the shock wave were based on a blast wave generated by a spherical charge of Trinitrotoluene (TNT). Similarly, Ofengeim and Drikakis [3], conducted a numerical study of the interaction of a planar blast wave with cylinders, showing a strong influence of the initial shock conditions on the downstream flow after the cylinder. Varma et al. [5] also used spherical TNT charges in experiments to provide damage data for brick panel walls.

Typically, the blast waves produced from high explosive spheres have been categorised by recording free field static overpressure. This involves measuring the pressure at discrete points in the free field surrounding the explosion. The gauges are usually mounted side-on to the direction of the blast wave. The free field can be loosely divided into two flow regimes, “near field” and “far field”. Recording pressure in the near field is not a trivial exercise. The near field encompasses the fireball and detonation products, making it virtually impossible to measure the peak pressure and the pressure history in this range [1]. Gauges in the near field are exposed to a variety of stimuli and are subject to many forms of interference. The gauges are sensitive to light, heat and mechanical stresses as well as electromagnetic effects from electrical noise, the firing pulse and from the explosion [7]. Therefore, recording pressure histories at distances of fractions of the diameter of the explosive is extremely difficult.

Pressure measurements are generally recorded in the far field. The far field is a sufficient distance from the explosive to ensure that the pressure gauges are not effected by the fireball and detonation products. Spherical high explosives will generally create spherical blast waves and pressure measurements in the far field are usually sufficient. However, the blast waves generated by cylindrical charges differ significantly in the near field [6]. Cylindrical warheads are common in air-to-air missiles where the aim is to detonate the weapon as close as possible to the target. Therefore, understanding the characteristics of blast waves produced from cylindrical charges is important and techniques for determining pressure in the near field are required.

An alternative technique to recording pressure histories is adopted in the current investigation. Pressure is not measured directly, rather, the velocity of the blast wave is determined by recording the time taken for the blast to reach discrete points. This time is referred to as time of arrival (TOA). A distance versus time relationship is then used to calculate shock front velocity [4]. Static pressure is then determined using the Rankine-Hugoniot relation.

Sensors used in TOA measurements require a rapid response time ($< 1\mu s$), must be physically small so that they do not significantly distort the shock front and they must also be relatively inexpensive because they are usually disposable. Also, there is a need for large numbers of sensors to be used in order to get accurate spatial information of the shock wave. The advantage of this technique is that time of arrival sensors can be placed at very small distances from the explosive.

The current paper presents pressure data for a cylindrical charge and is part of an ongoing program to map the shape of blast waves produced from non-spherical high explosives. The focus of the current paper is determining peak pressures in the near field using TOA data. The technique has been validated by comparing calculated pressures with measured pressures in the far field.

Experimental Set-up

Time of arrival and pressure histories have been recorded for four separate firings. A schematic diagram of the experimental set-up is shown in Figure 1. In each test, a bare cylindrical charge of Comp B (60/40) explosive was placed at a vertical height of 2m from a concrete pad. The diameter, length and mass of the cylinders was D=141mm, L=304mm and Mass=7.8kg, respectively. The charge is shown in Figure 2. For near-field blast measurements it is important to mount instrumentation as high as practically possible in order to minimise interference from ground reflections. Time of arrival sensors and pressure gauges were placed at the same vertical height of 2,000mm and varying distances, R, from the charge. Time of arrival gauges have been placed at $915mm \leq R \leq 3{,}185mm$. Pressure gauges have been placed as close to the charge as possible, $1{,}980mm \leq R \leq 9{,}995mm$. Moving the pressure gauges closer to the charge would have resulted in possible damage to the gauges or erratic results.

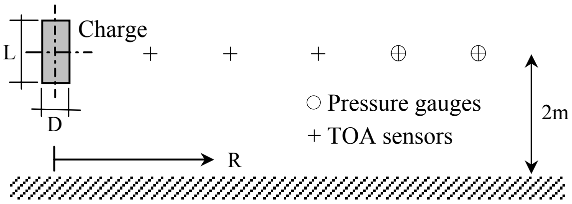

Figure 1. Schematic side view of the experimental set-up.

Figure 2. Cylindrical Comp B charge sitting on an ammunition box. The concrete pad and Unistrut channel are also shown.

Pressure was measured with Endevco (model # 8530B) pressure gauges. These are rated to a maximum pressure limit of 6,896kPa (1,000psi). The Endevco gauges employ a silicon diaphragm onto which a four-arm wheatstone bridge has been diffused. Compensation and balancing elements are also included. As stated earlier, these gauges were mounted side-on to the direction of the blast wave. For a static pressure measurement, the pressure gauge was mounted inside a machined nylon (Delrin) and O-ring mount, which in turn screwed into the centre of a baffle plate. The nylon mount is used in an attempt to damp high frequency vibration. A baffle plate is shown in Figure 3. The baffle plate is a machined aluminium knife edged disk, which is affixed to the top of a gauge stand. This ensures that the flow of the shock wave is normal to the gauge and that minimal aerodynamic interference is encountered in the vicinity of the gauge. The diameter of the knife edged disk was approximately 240mm. Gauges mounted in baffle plates were placed at 1,980mm≤R≤3,545mm.

Figure 3. Baffle plate used to mount pressure gauges.

Stands used for mounting pressure gauges must be extremely robust, yet still allow for fine position adjustment. The stands must also be designed to minimise gauge vibrations or "ringing". The stands used for this series of experiments were manufactured from 48mm O.D. galvanised water pipe which has a nominal wall thickness of 4mm. They consisted of a pair of forward legs and a longer diagonal piece that acted both as the third leg and the mounting arm for the gauge assembly. These two sections were held together by a commercially available coupling knuckle which allowed for some height adjustment. Pressure gauge stands are shown in Figure 4. The stands are designed to provide working heights from 1,000mm to 2,000mm. An additional section can also be added to increase the working height to 2,700mm, although only results from gauges at 2,000mm height will be presented in this paper. These stands were anchored to the concrete test pad (12m × 12m) with a clamp that fitted into Unistrut channels. This type of stand is usually used in an array of up to four or five gauges and these are aligned to minimise shrouding or interference from adjacent gauges.

Figure 4. Pressure gauge stands.

A PCB (model # 102A07) 345kPa (50psi) pressure gauge was also located 9,995mm away from the charge centreline. This type of pressure gauge is an ICP piezoelectric type and it was mounted in a Pitot tube configured to measure incident pressure, as shown in Figure 5. Although this gauge was located off the concrete test pad, its height was maintained at 2m. This gauge was only used to determine time of arrival information.

Figure 5. Pressure gauge mounted in a Pitot tube.

Pressure measurements were recorded on Digistar III stand-alone recorders. These feature a programmable digitising rate of up to 5 million samples per second at 12 bit resolution and have up to 4Mb sample memory. They can be powered by an external 12V supply and have been designed for operation in harsh environments. Measurements from each pressure gauge are recorded on individual Digistar units and are then downloaded onto a laptop computer where the information is subsequently processed.

The time of arrival sensors used for these experiments were Dynasen CA-1134 piezoelectric pins. These are 3.175mm (0.125") diameter and utilise 5.08mm (0.20") thick PZT-5A crystal. These small sensors produce an electrical signal proportional to pressure when impacted by a fast moving object or shock front. This type of piezoelectric pin is normally used for velocity of detonation measurements, where they are in direct contact with the explosive, or for measuring time of arrival of shock fronts through solid materials. Therefore, this type of sensor has been shown to be insensitive to many undesirable stimuli that can excite a pressure gauge. For a similar sized charge to the one used here, it has been determined that these sensors are sensitive enough to measure blast time of arrival at distances of up to 5,000mm. These sensors are considered to be disposable because they are approximately one hundredth of the cost of a pressure gauge.

The pin sensors were mounted in the tip of a solid aluminium cone that was attached to a 32mm diameter aluminium pipe that was approximately 400mm long, as shown in Figure 6. This assembly was affixed to a 2,000mm high stand that was manufactured from similar material to the pressure gauge stands. The TOA stand consisted of a slightly angled vertical pipe that was attached to a steel base plate. Since the height was fixed at 2,000mm, the stand was simply aimed at the charge centreline and bolted into position in the Unistrut channel. Some horizontal adjustment was possible by moving the aluminium pipe in and out. The array of TOA sensors is shown in Figure 7.

Figure 6. Close-up of time of arrival sensor.

Figure 7. Array of time of arrival sensors.

Although these sensors can easily be mutiplexed, it was decided not to in order to ensure reliability and simplicity. Each sensor was directly connected to a single channel with no added amplification or conditioning of the output signals. Four sensors were used for each firing and their outputs were sent to individual channels of a 4 channel Tektronix TDS 544A digital storage oscilloscope. Data from this was transferred onto a laptop computer via in house GPIB software.

Results

The time of arrival data is presented in Table 1. All the time of arrival sensors were placed at 2,000mm height, which corresponds to the center of the charge. The distances, R, in Table 1 are the horizontal distances from the charge centreline to the time of arrival probe. The data from Table 1 is plotted in Figure 8.

R (mm)	Time (ms)
915	0.3842
1330	0.5211
1360	0.5634
1751	0.7291
1775	0.7739
1885	0.7866
1850	0.8840
2235	1.0203
2240	1.084
2300	1.100
2305	1.194
2720	1.442
2735	1.485
2745	1.588
3165	1.929
3185	2.061

Table 1. Time of arrival data.

Time of arrival of 16.532ms was also recorded with the PCB pressure gauge located at 9,995mm. Only one result was obtained during the four firings. The peak pressure could not be given because the recorded pressure level was higher than the anticipated maximum that was preset on the Digistar recorder. Therefore, only time of arrival information was obtained. The time of arrival at 9,995mm has not been included in Figure 8, because the focus of this investigation is the near field.

In Figure 8, a curve of the form of Equation 1 has been fitted to the data, using the procedure of Mitalas and Harvey [4]. In Equation 1, R is the distance from the charge, and the values of the constants, a60, a62 and a63 are 8.988, 1.042 and 1.5E-06, respectively. The remaining parameters in Equation 1, are the speed of sound, c=340m/s, and time, t.

$$R = a_{60} + ct + a_{62}\ln(t) + \frac{a_{63}}{t} \qquad (1)$$

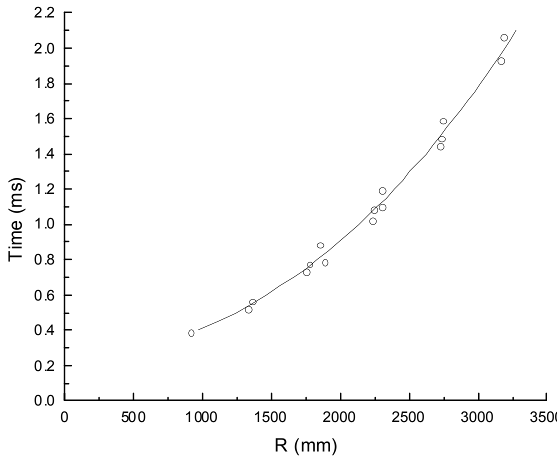

Figure 8. Shock front time of arrival versus distance from the charge.

The fitted curve in Figure 8 accurately represents the trend of the data. Although the time of arrival at 9995mm has not been included when fitting the curve in Figure 8 to the data, Equation 1 gives a time of arrival of 15.7ms. Comparing this with the measured value of 16.5ms gives a difference of around 5%. This is considered acceptable, given the large distance involved and also that data was recorded for only one shot. Therefore, a reasonable approach is to differentiate Equation 1 to determine velocity of the blast wave. This enables Mach number to be calculated as a function of distance. By assuming the shock to behave as an ideal gas, the Rankine-Hugonoit relation can be used to give Equation 2, where P is the shock wave pressure, P_o is ambient pressure, γ the ratio of specific heats and M is Mach number. Overpressure is $P-P_o$.

$$\frac{P}{P_o} = 1 + \frac{2\gamma}{1+\gamma}\left[M^2 - 1\right] \quad (2)$$

Table 2 shows the maximum measured static overpressures and the corresponding horizontal distances for the pressure gauges. As stated earlier, the vertical height of the pressure gauges was nominally 2,000mm to coincide with the charge centerline. This data is shown graphically in Figure 9. Overpressure as a function of distance can be determined from Equation 2. This is the curve shown in Figure 9. In Figure 9, there is very good correlation between the measured overpressure data and the calculated pressure from time of arrival data. The calculated pressure in Figure 9 is given for distances of 1,000mm to 4,000mm. This range is determined by the distances for which time of arrival data was recorded.

Distance (mm)	Maximum Measured Overpressure [kPa]
1980	1983
2010	2280
2520	1159
2525	1058
2950	573
2950	674
3512	355
3545	337

Table 2. Maximum overpressure measured with pressure gauges.

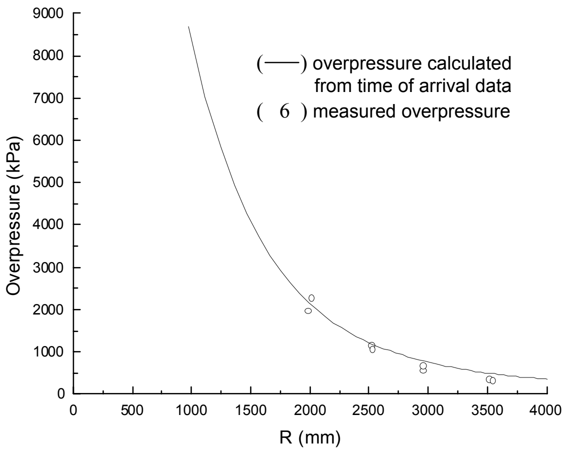

Figure 9. Overpressure versus distance from the charge.

Future Work

The current work is part of a research program undertaken by the Defence Science and Technology Organisation to investigate blast waves in the near field. Of particular interest is the blast generated by non-spherical high explosive charges. The current work was limited to the use of time of arrival sensors in one-dimension. Future work will extend the use of time of arrival sensors in the near field to two-dimensions. Future work will also feature blast / target interaction with pressure measurements on the surface of cylinders and acceleration histories for hanging cylinders.

Conclusions

Time of arrival sensors have been used successfully to determine blast overpressure (gauge pressure) in the near field. Comparisons with pressure data recorded in the far field show good agreement. Therefore, it is expected that a good agreement will also be achieved in the near field. However, verifying this assumption is extremely difficult, since pressure in the near field could not be recorded.

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