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Testing and computational analysis of pressure transducers in water filled tank impacted by hypervelocity projectile

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ABSTRACT

The experimental and computational results of a steel sphere impacting a water filled cylinder are presented here. The focus of the experiments was the measurement of shock loading in water with different gage designs. A single stage powder gun was used to launch a 1.59 cm diameter steel sphere at a nominal speed of 2.4 km/s into a water filled cylinder. There were five test shots with the same nominal impact conditions and different internal pressure gage arrangements. Three different pressure gages made by a pressure transducer manufacturer were used to measure the shock: a conventional tourmaline gage (Tygon), a chemically resistant tourmaline gage variant (PTFE), and a quartz gage that is typically used to measure shocks in gases. The tourmaline gage was first developed by the Navy in 1982 to measure underwater blast and has been used successfully in that environment. In more recent experiments, Tygon tourmaline gages have been used to accurately measure the pressure of water during high speed impacts. However, the Tygon tourmaline gage is unusable in tributyl phosphate (TBP). Using the Tygon tourmaline gage as a reference, the performance of the PTFE tourmaline gage, and the quartz crystal gage was assessed. Computational results from CTH simulations aided in test design and pressure gage placement. The computational results from a pretest calculation under predicted the pressures from the Tygon tourmaline gage. This discrepancy was attributed to shock asymmetry and a CTH calculation which purposefully introduced asymmetry matched the test data more closely. The PTFE tourmaline gage consistently showed a reasonable match to the Tygon tourmaline gage. The PTFE tourmaline gage also displayed direction insensitivity. The pressure data from the quartz gage was consistently higher than the pressure data from the Tygon tourmaline gage.

1. Introduction

Selection of the appropriate transducer to measure the pressure created by the passage of a shock can be challenging. There are issues regarding the gage rise time, maximum pressure, shock orientation sensitivity, survivability, etc. The impact of a high speed projectile into a liquid filled target generates a stress field dominated by pressure. Therefore, the accurate measurement of pressure is necessary to understand the dynamic response of the liquid and the target. The U.S. Navy developed a pressure transducer for measuring underwater blast in 1982 using a tourmaline crystal [1]. The tourmaline crystal is piezoelectric and produces a linear response over a wide dynamic range. Furthermore, it is hydrostatically sensitive and is thus insensitive to the direction of the shock. Tourmaline pressure gages have been used successfully in measuring the shock pressures in a water filled cylinder impacted by a spherical projectile [2].

Recently, the need has arisen to measure shock pressures in tributyl phosphate (TBP). In addition to being piezoelectric, the tourmaline crystal is also dielectric. Direct contact with water produces a current and corrupts the signal from the gage. Therefore, the crystal is surrounded by a Tygon boot filled with silicone oil. Unfortunately, TBP is a plasticizer and within hours the Tygon boot is volumetrically compromised, thus ruining the tourmaline gage. Therefore, two alternate gages were selected for use in TBP. First, a pressure transducer using a quartz crystal was chosen. The quartz crystal is piezoelectric and has a similar rise time and maximum pressure in comparison to the tourmaline pressure gage. Furthermore, the gage housing does not use polymers and is therefore unaffected by TBP. Quartz crystal gages have been used extensively in the air blast community and for measurements in solids, but the crystal piezoelectric response is sensitive to the direction of loading [3]. The other alternate gage was a TBP-resistant variant of the conventional tourmaline gage. The new gage

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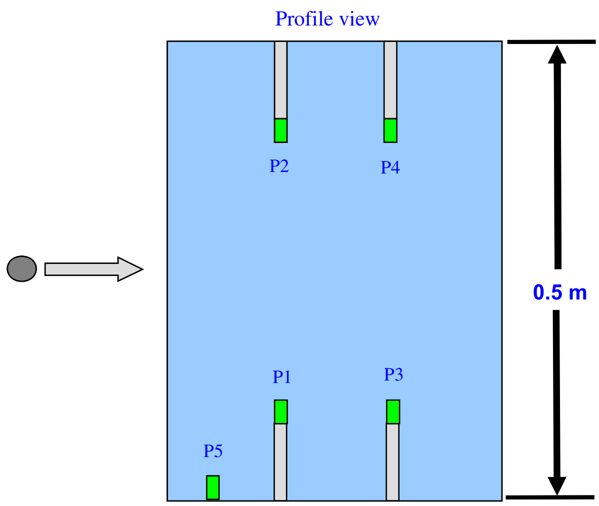

Fig. 1. Notional target diagram, profile view.

uses a polytetrafluoroethylene (PTFE) boot instead of the Tygon boot. PTFE is plasticizer resistant and allows the modified gage to be used in TBP.

An experiment was designed to test the performance of the quartz gage and PTFE tourmaline gage. A powder gun was used to launch a 1.59 cm diameter spherical steel projectile at 2.4 km/s into a water filled cylindrical target. Since the quartz crystal is direction sensitive, different gage orientations were investigated in the experiments. The Tygon tourmaline gage which has been used successfully before in water provided accurate reference measurements of the pressure in the target. Computational results from CTH hydrocode simulations aided in test design, and provided insight into interpretation of the pressure data. The performance of the three gage types was compared. No experiments in TBP were performed; however computational analysis can be used to assess gage performance in TBP. This is possible because previously an extensive experimental effort was undertaken to determine the equation of state (EOS) for TBP [4,5].

2. Test description

2.1. Test setup

The tests were conducted at the Denver Research Institute (DRI) using a 40 mm powder gun. The powder gun launched a 302 stainless steel sphere at a nominal speed of 2.4 km/s. The steel sphere has a diameter of 1.5875 cm (5/8 in) and a mass of 17.365 g. The target is a right circular cylinder and has five pressure gage stations. Fig. 1 shows a notional diagram of the target and the pressure gage stations, P1–P5. Note that there is a plane of symmetry around the shotline about which the pressures should be equal. Ideally, the pressure at P1 is equal to P2. The same holds true for P3 and P4. However, P5 has no mirror gage location and was intended to investigate gage response near a boundary.

Table 1
Test matrix with shot number and gage locations

Gage location	PTFE tourmaline gage	Tygon tourmaline gage	Quartz gage (°)				
			0	30	45	90	135
P1	5	1,2,3,4					
P2	2,3,4		1				
P3	1	3,5	2	4			
P4	4 (90°)	1			2	3	5
P5	5	3	4				

The quartz crystal is sensitive to shock direction. Therefore, the quartz gage was tested at several different orientations to quantify any sensitivity to shock angle. Because of the operation principles of the tourmaline gage, direction sensitivity was not expected. Table 1 shows the shots, locations and the angles at which the gages were mounted. The angle is with respect to the shotline. The reference data comes from the Tygon tourmaline gage. It was in the P3 location in shots 1–4 and in the P1 location in shots 1 and 3. The test matrix was structured to maximize data given just five shots.

The reference gage sensing element is a tourmaline crystal. These crystals are piezoelectric and produce a linear curve over a wide pressure range. The Tygon tourmaline gage, PCB model number 138M109, has a rise time of 2 μs and a maximum calibrated pressure of 100 ksi. This gage has been used extensively in the underwater blast community. The TBP-resistant tourmaline gage variant was designed by NSWCDD and PCB Piezotronics. Both of the tourmaline gages are shown on the left side of Fig. 2. The Tygon material was changed in favor of PTFE. PTFE is resistant to plasticizers and it showed no effects after several weeks of immersion in TBP. The density and sound speed of PTFE differ from that of Tygon. Therefore, a calibration curve was generated specifically for the PTFE tourmaline gage, PCB model number 100M44. The accuracy of this new configuration was investigated with this test series.

Quartz crystal gages are used extensively in the air blast community. This quartz gage has a rise time of 2 μs and a maximum calibrated pressure of 100 ksi. However, the quartz gage had not been proven in a liquid environment. Unlike the tourmaline gages, it requires no boot or silicon oil reservoir. The quartz crystal was inside the ceramic and metal housing which made it a physically more robust gage. A picture of the quartz gage can be seen on the right side of Fig. 2. The quartz gage used in these tests, 109M92, had several minor modifications to make the housing leak resistant and for use in liquid. The focus of the investigation of the quartz gage was the accuracy of this gage in liquid and the effect of orientation on the pressure data.

2.2. Target description

An exterior and interior view of the target is shown in Fig. 3. The target was a right circular cylinder mild steel shell held between two endcaps. The target inner radius was 25.4 cm and the shell thickness was 0.15875 cm. The target was 50 cm tall excluding the endcaps. The bottom endcap was steel and the top endcap was acrylic, both approximately 2.54 cm thick. The top endcap was transparent and allowed for video recording of the interior. Screws threaded through the endcaps held the assembly together. Aluminum gage mounts held the pressure gages in the correct orientation and locations. The gage mounts consisted of brackets and manifolds which supplied the appropriate mounting conditions for all three gage types. The mounting requirements for all three gage types were specified by the manufacturer.

3. Test 1 pretest calculation

The high velocity impact of the steel projectile, shock loading and subsequent response of both the liquid and the steel case was a complex high strain rate event. To capture the physics of the impact event, the Eulerian wave propagation code, CTH, was chosen to model the tests [6]. CTH solves the partial differential equations that describe the conservation of mass, momentum and energy. It uses a finite volume Eulerian numerical formulation that allows for the accurate solution of high strain rate large deformation problems. CTH has a large range of material models appropriate for use in high strain rate events and the capability for insertion of complex