Air Bubble Dispersion and Coalescence Under Shock Loading Conditions: A Model for Cavitation

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***Abstract*— Head injuries associated with exposure to high energy explosive detonation are classified based on the predominant trauma factor. There are four distinct types of blast induced traumatic brain injury (bTBI) : 1) these caused by supersonic shock waves propagating in the atmosphere (primary), 2) high velocity impact of shrapnel and debris (secondary) 3) acceleration and deceleration of the body and collision with the solid objects in the field (tertiary) and 4) exposure to high temperature and toxic gases (quaternary). One of the mechanisms implicated in non-impact primary bTBI is cavitation. It is hypothesized that cavitation can occur in the cerebrospinal fluid (CSF) layer and possibly also in the cerebral blood and brain tissue contributing to injuries caused solely by shock wave overpressure. The *modus operandi* of the underlying mechanism of cavitation and its impact on brain trauma is still unclear. To investigate this potentially aggravating aspect of blast induced traumatic brain injury, a simplified experimental model was employed. The polycarbonate cylinder was machined in-house, instrumented with strain gages and pressure sensors and exposed to blast overpressure when the void space was replaced by two different media: distilled water and 50% glycerol solution. This assembly was exposed to a single shock wave with 70 kPa nominal intensity inside the shock tube. Bubbles of air are introduced into fluid filled cylinder in a controlled manner and the behavior of these bubbles during shock wave is studied. The data acquired from the pressure sensors mounted inside the cylinder indicate that presence of bubbles and their 'collapse' has minimal-to-negligible effect on the pressure changes in the media.**

I. Introduction

Improvised explosive devices (IED) have become more prevalent threat in theater of recent military conflicts in Iraq and Afghanistan, which in turn made blast injuries a more prevalent type of affliction among active military personnel [1-3]. A greater understanding of how shock waves interact with the human skull is thus required along with delineation of basic mechanisms responsible for development of TBI. Understanding the physical mechanism(s) of injury is critical for the development of preventative measures and therapeutic treatments for affected soldiers and civilians. This study investigates cavitation formation, a proposed injury mechanism, in response to a shock wave in a biomimetic head-brain system. When a shock wave is transmitted through the skull, cerebrospinal fluid (CSF), and tissue, causing negative pressure at the countercoup it may result in cavitation. Cavitation is a common process and is thought as responsible for surface erosion (the so-called 'pitting') in spinning brass boat propellers, demonstrating the potential for damage in softer materials such as brain [4]. Cavitation phenomenon has been previously studied in computational models but to date there are only limited reports on experimental investigation as a possible mechanism of bTBI.

II. Methodology

A. Shock Wave Testing

The 9-inch square cross section shock tube is a facility where generated shock waves mimic closely parameters of idealized real-life scenario where Friedlander type shock waves are generated (fig. 1) [5]. Helium was used as the driver gas. Depending on the number of membranes loaded between the driver and driven sections, the intensity of the shockwave can be changed. The specimen was placed in the observation deck in a freely moving configuration (fig.1, III).

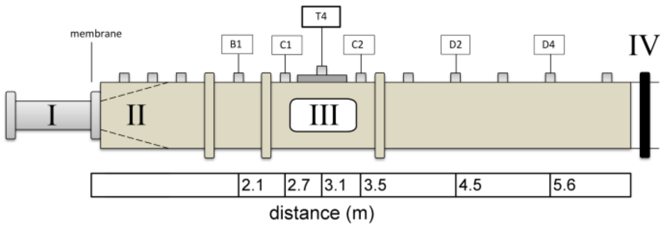

Figure 1. The 9 inch diameter square cross section shock tube schematics illustrating the location of pressure sensors (B1 to D4) employed to measure incident shock wave characteristics. The design of the shock tube consists of four components: the breech (I), the expansion section (II), the test section (III) and the end plate (IV) [5].

B. Cylinder Preparation and Instrumentation

A clear polycarbonate (PC) cylinder was selected as representative surrogate model of skull as its acoustic velocity nearly matches value of the skull [6]. The cylinder has a wall thickness of 1/16 of an inch, the diameter 2 inches and length of 7 inches. The PC cylinder was filled with two different fluids: 1) deionized (DI) water, and 2) 50% glycerol. This cylinder was instrumented with pressure sensors and strain gages. Two types of pressure transducers were used: Kulite XCL-100 and LE-125 series. Two of Kulite XCL-100 sensors were used to measure pressure inside the fluid-filled cylinder, and one Kulite LE-125 surface mount sensor was used to measure surface pressure on the front face of the cylinder. Moreover, incident pressure (C1 location) 0.4 m before the specimen was routinely measured (PCB 134A24 model pressure transducer). Single axis 120Ω or 350Ω strain gages were positioned on the front, back and side surface of the cylinder (fig. 2).

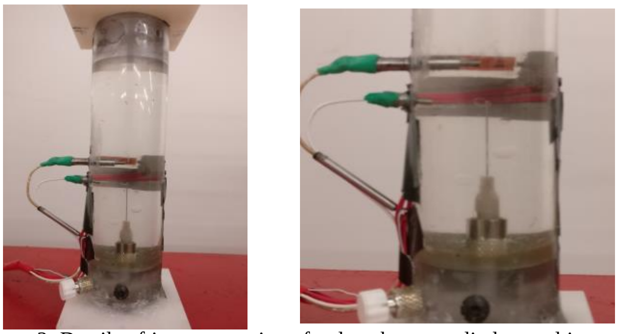

Figure 2. Details of instrumentation of polycarbonate cylinder used in testing of bubble collapse under shock wave loading: the location of two Kulite pressure sensors, strain gages and air delivery port with 27 gauge needle are illustrated.

C. *Data Acquisition and Data Analysis*

The data from the pressure transducers were recorded at 1 MHz sampling rate for the 200 ms duration. All data were acquired via NI-PXIe-6366 DAQ module. Signal processing and quantification of the raw data was performed in Origin 9.4 software.

III. Results

The preliminary results show that exposure to shock wave with 70 kPa intensity there is no striking difference in pressure trends between runs where bubbles were present or absent in both media (pure water and 50% glycerol in water solution). The pressure rise of these signals could reach approximately only 5 psi level (fig. 3). This is in spite the relatively high reflected pressure values (>30 psi) reported by sensor located on the front surface of the cylinder. The signals inside the cylinder demonstrated in fig. 3 mostly reflect the dissipation of energy via vibration, which corresponds to compression/tension cycling during (5 ms) the shock wave residence time. The vibrations persisted for the total time of 30-40 ms. There were no visible pressure waveforms with sharp rise times (in the microsecond range) characteristic for shock wave transmission.

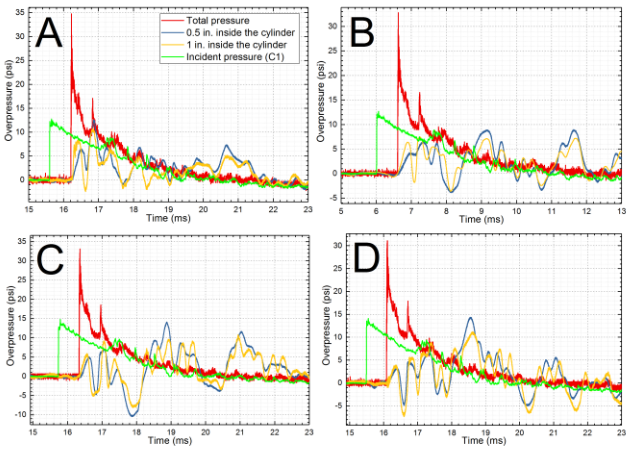

Figure 3. Pressure-time profiles recorded by incident (C1), total (on the front surface of the cylinder) and fluid (inside the cylinder) sensors: A) deionized water without bubbles, B) 50% glycerol in water solution without bubbles, C) deionized water with bubbles, D) 50% glycerol in water solution with bubbles.

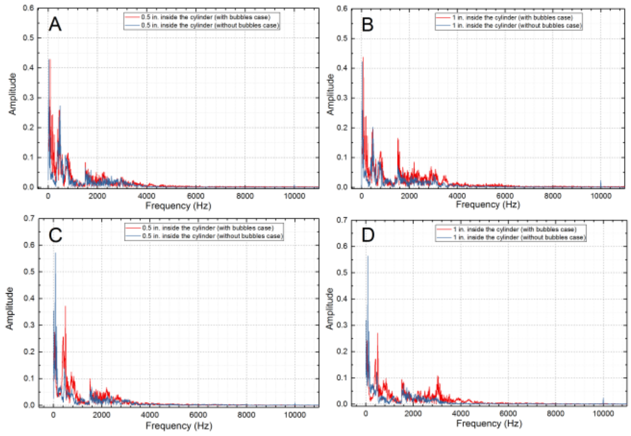

Figure 4. The effect of air bubbles on frequency of pressure histories reported by sensors immersed in: A) glycerol (bottom sensor: 0.5 in. inside), B) glycerol (top sensor: 1 in. inside), C) water (bottom sensor: 0.5 in. inside) and D) water (top sensor 1 in. inside).

The Fast Fourier Transform (FFT) was performed in Origin 9.4 software (fig. 4). For qualitative analysis we used the 'Amplitude' plot where the output of the y-axis scale of the FFT plot is the relative strength of each individual frequency present in the original signal. We noted four discrete frequency bands (0-200 Hz, 200-650 Hz, 650 Hz-1.1 kHz, and 1.4-2.8 kHz) are observed in the signal (fig. 4), with some discrepancies in the frequency bands and the intensities in experimental conditions where bubbles were present or absent during shock wave exposure. Furthermore, the amplitude of FFT for the signal acquired in pure water media is higher than the one in glycerol solution.

Acknowledgment

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References

1. Elder, G.A., Mitsis, E.M., Ahlers, S.T., Cristian, A.: Blast-induced mild traumatic brain injury. Psychiatr Clin North Am **33**(4), 757-781 (2010). doi:10.1016/j.psc.2010.08.001
2. Hoge, C.W., McGurk, D., Thomas, J.L., Cox, A.L., Engel, C.C., Castro, C.A.: Mild traumatic brain injury in U.S. Soldiers returning from Iraq. The New England journal of medicine **358**(5), 453-463 (2008). doi:10.1056/NEJMoa072972
3. Moore, D.F., Jaffee, M.S.: Military traumatic brain injury and blast. NeuroRehabilitation **26**(3), 179-181 (2010). doi:10.3233/NRE-2010-0553
4. Salzar, R.S., Treichler, D., Wardlaw, A., Weiss, G., Goeller, J.: Experimental investigation of cavitation as a possible damage mechanism in blast-induced traumatic brain injury in post-mortem human subject heads. Journal of Neurotrauma(ja) (2016).
5. Kuriakose, M., Skotak, M., Misistia, A., Kahali, S., Sundaramurthy, A., Chandra, N.: Tailoring the Blast Exposure Conditions in the Shock Tube for Generating Pure, Primary Shock Waves: The End Plate Facilitates Elimination of Secondary Loading of the Specimen. PLoS One **11**(9), e0161597 (2016). doi:10.1371/journal.pone.0161597
6. Selvan, V., Ganpule, S., Kleinschmit, N., Chandra, N.: Blast wave loading pathways in heterogeneous material systems–experimental and numerical approaches. Journal of biomechanical engineering **135**(6), 061002 (2013).