FLUID-STRUCTURE INTERACTION SIMULATION OF UNEVEN GEOMETRIES SUBJECTED TO BLAST LOADING

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ABSTRACT

Recently, improvised explosive devices have been widely used by terrorist or militant movements around the world. The blast wave propagation of an explosive detonation can cause destructive damage on the armored vehicles and also fatalities to the vehicle occupants. Field blast testing is very expensive and time consuming but by using computational based numerical simulations it is possible to virtually predict these blast wave propagation patterns. Computational Fluid Dynamics (CFD) is one of the effective tools to perform Fluid-Structure Interaction (FSI) analysis of free field air blast and against structure. This study presents two different blast analyses; free field air blast using CFD and blast loading subjected to the armored vehicle that focus on blast critical pressure point, front and hull sections using FSI method. Photogrammetry techniques were used to develop a three dimensional solid model of armored vehicle sections (Front and hull) for the blast wave analysis. A high explosive of 72 g of plastic explosive (PE4) blast peak overpressure data from ConWep program has been patched at the specific fluid domain. The computed results for CFD and FSI were found to be in agreement with the experimental data. It was also found that the developed CFD model can be used to predict the blast wave propagation impact to armored vehicles.

ABSTRAK

Sejak kebelakangan ini, alat peranti letupan telah digunakan secara meluas oleh pengganas atau gerakan militan di seluruh dunia. Perambatan gelombang letupan daripada bahan letupan boleh menyebabkan kerosakan yang teruk kepada kenderaan perisai dan juga kematian kepada pemandu dan penumpang kenderaan. Ujian letupan lapangan adalah sangat mahal dan memakan masa yang panjang tetapi dengan menggunakan pengiraan simulasi berangka hampir boleh meramalkan perambatan gelombang letupan ini. Computational Fluid Dynamics (CFD) adalah salah satu alat yang berkesan untuk melaksanakan Fluid-Structure Interaction (FSI) untuk membuat analisis letupan lapangan di udara dan juga terhadap struktur. Kajian ini membentangkan dua analisis letupan yang berbeza; letupan lapangan di udara menggunakan CFD dan letupan terhadap kenderaan perisai yang memberi tumpuan kepada titik letupan tekanan kritikal, bahagian depan dan bawah kenderaan perisai menggunakan kaedah FSI. Teknik fotogrametri telah digunakan untuk membangunkan model CAD 3D bahagian kenderaan perisai (depan dan bawah) untuk analisis gelombang letupan. Data untuk puncak tekanan letupan yang kuat seberat 72 g 'plastic explosive' (PE4) dari program ConWep telah ditampal di domain cecair tersebut. Keputusan yang disimulasi menggunakan CFD dan FSI didapati hampir menyamai dengan data eksperimen. Ia telah juga mendapati bahawa model CFD boleh digunakan untuk meramalkan kesan perambatan gelombang letupan terhadap kenderaan perisai.

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APPROVAL

I certify that an Examination Committee has met on **13th April 2017** to conduct the final examination of **Arif Shafiq Bin Mohamed Sohaimi** on his degree thesis entitled '**Fluid-Structure Interaction Simulation of Uneven Geometries Subjected to Blast Loading**'. The committee recommends that the student be awarded the degree of Master of Science (Mechanical Engineering).

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LIST OF ABREVIATIONS

°	Degree
2D	Two-dimensional
3D	Three-dimensional
AV	Anti-vehicular
AT	Anti-tank
ANFO	Ammonium nitrate/fuel oil
ASTM	American Society for Testing and Materials
C	Carbon
CAD	Computer Aided Design
cm	Centimeter
CFD	Computational Fluid Dynamics
CO	Cobalt
DAQ	Data Acquisition
DNT	2,4-Dinitrotoluene
FEA	Finite Element Analysis
FVM	Finite Volume Method
FSI	Fluid-Structure Interaction
FC	Field Calibration
FE	Finite Element
g	Gram
Gpa	Giga Pascal
H_2O	Water
HMX	Nitroamine High Explosive

IED	Improvised Explosive Device
IOCL	Indian Oil Corporation Ltd
ISO	International Organization for Standardization
kg	Kilogram
kPa	Kilo Pascal
K	Kelvin
MPa	Mega Pascal
GPa	Giga Pascal
m/s	Meter per Second
mm	Millimeter
m	Meter
mV	Millivolt
MRAP	Mine Resistant and Ambush Protected
MSC	Multi Sheet Calibration
N_2	Nitrogen
NO_2	Nitrogen Dioxide
NATO	North Atlantic Treaty Organization
NI	National Instruments
Pa	Pascal
PETN	Pentaerythritol Tetranitrate
psi	Pounds per Square Inch
RAD	Ringed Automatically Detection
RHA	Rolled Homogeneous Armour
Roe-FDS	Roe Flux Differencing Scheme
s	Seconds

t	Time
TNT	2,4,6-Trinitrotoluene
UDF	User Defined Function
VTF	Virtual Test Facility

CHAPTER 1

INTRODUCTION

1.1 Background

Explosions do not only occur in the battlefield, but also occur in the chemical industry or in the urban environment. Petrochemical related accidents, nuclear explosions and terrorist attacks are some of the blast situations that have been widely reported (Dyer *et al.*, 2012). The threat of terrorism is a high-priority national security and law enforcement concern in the United States. Terrorism itself has been an age-old threat to the public health and security of many populations throughout the world. Since the 1980s, terrorist attacks against the United States have led to legislative, regulatory, organizational and programmatic actions associated with comprehensive and ambitious expectations (Keim & Deitchman, 2016). Statistics showed that there has been an increase in the frequency of bombing incidents by terrorist organisations in recent years. For example, there was a more than 300 % rise in bombing incidents globally between 2004 and 2012, and a 50 % increase in suicide bombings, with an accompanying increase in mortality of 30 %. The current trend for increase in the frequency of terrorist attacks may can be attributed to bombings in the Middle East.

The attack on the World Trade Centre towers in 1993 is an example of a terrorist attack conducted in a mass populated area (Lange, 2013).

An explosion phenomena can be defined as the quick release of large amounts of energy within a limited space. It is comprised of the decomposition of energetic materials to produce gas, heat and rapid expansion of matter. An explosion can be described as any chemical compound, mixture or device, the primary or common purpose of which is to function by an explosion. Oxygen, ignition source and combustible substances are the factors of explosion (as shown in Figure 1.1).

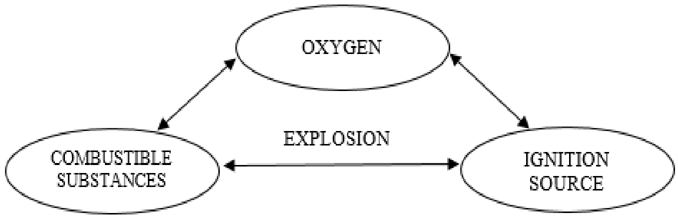

Figure 1.1: Factors of explosion.

A detonation process possesses specific physical characteristics. It is initiated by the heat accompanying shock compression; it liberates sufficient energy, before any expansion occurs, in order to sustain the blast or shock wave. The shock wave propagates into the unreacted material at supersonic speed, typically 1500 – 9000 m/s. The by-product which is the blast wave directly increases the pressure value above the ambient atmospheric pressure. Soon, the pressure behind the shock front may drop below the ambient pressure. The term blast wave is used to define an explosion or detonation-induced pressure-based wave propagating within the air surrounding the explosive charge, while the term shock wave represents the stress-based wave within the protective structure generated as a result of the interaction of the incident blast wave with the target structure (Grujicic *et al.*, 2013).

Blast waves have been studied for more than half a century and researchers have been increasingly interested in the study of blast waves. They have conducted experiments and simulations in attempting to analyse the physics of the blast phenomena. Blast wave study can be classified into three methods; (i) Empirical, (ii) Analytical and (iii) Numerical methods. The empirical method can be defined as a research based on experiment investigation, which is commonly using a pressure probe that is used to measure the blast wave (Figure 1.2). Then, analytical method can be calculated based from the shock parameters for an explosion to get the maximum blast peak-overpressure using Naumenko & Petrovskyi, (1956) & Sadovskiy, (2004) equations. These equations established similar formulae on the basis theory of models that were derived from several experimental results.

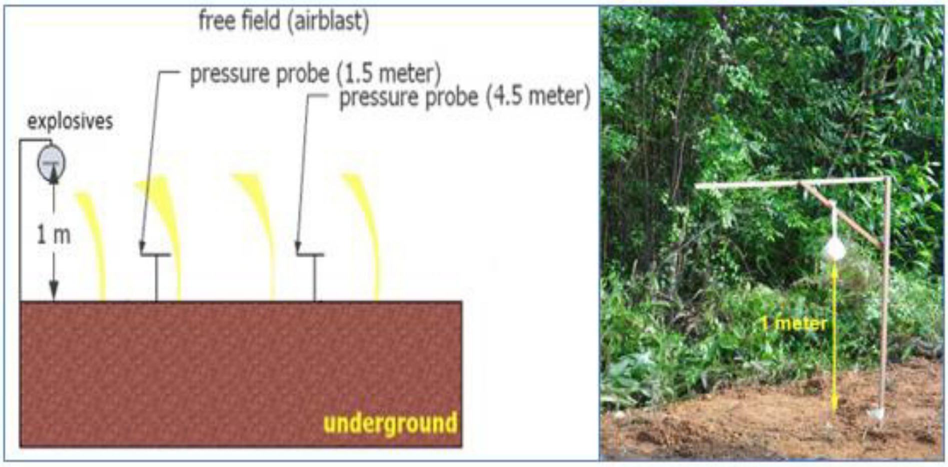

Figure 1.2: Schematic of free air blast test setup (Umar *et al*., 2015).

The numerical method is based on a simulation model using a computer code. Computational fluid dynamics (CFD) is one of the methods to predict the blast wave propagation apart from the finite element analysis (FEA) approach. CFD are implemented with the Euler scheme, which provides the qualitative and quantitative analysis of blast wave propagation. The fundamental theories of CFD problems are the Navier-Stokes equations, which include Navier-Stokes equation of motion supplemented by mass conservation equation and energy equation (Batchelor, 2000). CFD can be used to generalize and support experimental results in simulating blast waves (Alpman, 2012). The computational programs originally used to carry out these numerical studies were wave propagation codes capable of analysing the highly nonlinear and time-dependent nature of explosion, i.e., simulating the blast wave propagation (Doolittle, 1995).

When the Lagrange scheme is implemented with the CFD code, the solutions are commonly known as Fluid-structure Interaction (FSI). FSI can be defined as a multiphysics coupling between fluid dynamics and structural mechanics laws. This circumstance is characterized by interactions (oscillatory or stable) between a deformable structure and surrounding or internal fluid flow (Hou *et al.*, 2012). When a fluid flow is engaged in confrontation against a structure, strains and stresses are applied on the structure and the forces can lead to deformations. High pressure or high velocity of the fluid flow, will lead to large deformations, depending on the material properties of the structure.

1.2 Blast Protection in Armored Vehicles

Since their creation in the mid-19th century, antipersonnel mines have become a fundamental aspect of military strategy, revolutionizing infantry tactics. The blast mine is the most common. Hidden underground, the blast mine is activated when the victim or vehicle move and activates the trigger (Boutros-Ghali, 1994). Anti-vehicular (AV) landmine and improvised explosive device (IED) explosions may cause catastrophic structural failures of military vehicles and induce injuries or fatalities of the crew. When an AV explosive charge is detonated under a vehicle, a shock wave with intensive energy is generated. It is transmitted to the vehicular floor in microseconds and then results in large acceleration and deflection of the floor plate, which in turn applies high loads to the lower extremities of the occupants to induce injury (NATO, 2007). All in all, at the vehicle design stage particular attention should be paid to the vehicle hull construction (its shape and armour), its suspension, seat construction and seat fixing method in the crew compartment, as well as mobility both on- and off-road.

NATO standardization is the development and implementation of concepts, doctrines and procedures to achieve and maintain the required levels of compatibility, interchangeability or commonality needed to achieve interoperability (NATO, 2011). This study is focused on STANAG 4569 – Protection Levels for Occupants of Armored Vehicles (as shown in Table 1.1). The table shows the protection levels for occupants of armored vehicles for grenade and blast mine threats:

Table 1.1 Protection levels for occupants of armored vehicles for grenade and blast mine threats (STANAG 4569).

Level		Grenade and Blast Mine threat	
4	4b	Mine Explosion under belly	10 kg (explosive mass) Blast AT Mine
	4a	Mine Explosion pressure activated under any wheel or track location	
3	3b	Mine Explosion under belly	8 kg (explosive mass) Blast AT Mine
	3a	Mine Explosion pressure activated under any wheel or track location	
2	2b	Mine Explosion under belly	6 kg (explosive mass) Blast AT Mine
	2a	Mine Explosion pressure activated under any wheel or track location	
1		Hand grenades, unexploded artillery fragmenting submunitions, and other small anti-personnel explosive devices detonated anywhere under the vehicle	

Currently, Malaysia has several types of armored vehicles that are used for military operations for example; SIBMAS AFSV, Condor APC and the latest model of armored vehicles, which are AV8 Gempita and Lipan Bara. AV8 Gempita is a new generation of 8 x 8 Armored Wheeled Vehicle and the hull consists of a composite aluminium and steel armor that provides protection for the crew and infantry against firing of small arms. AV8 Gempita was added with armour mounted at the front and to the sides of the hull.

The parts of the armored vehicle most exposed to the effects of a pressure wave from explosive elements are the front, undercarriage, wheels and the inner wheel arch (Slawinski & Dziewulski, 2016). Figure 1.3 shows the front and underbelly sections of SIBMAS AFSV. These sections are considered the most high pressure critical points when an explosion occurs. There is no technical data for blast mine threats being exposed due to the confidentiality of Malaysian government military assets especially, SIBMAS AFSV.

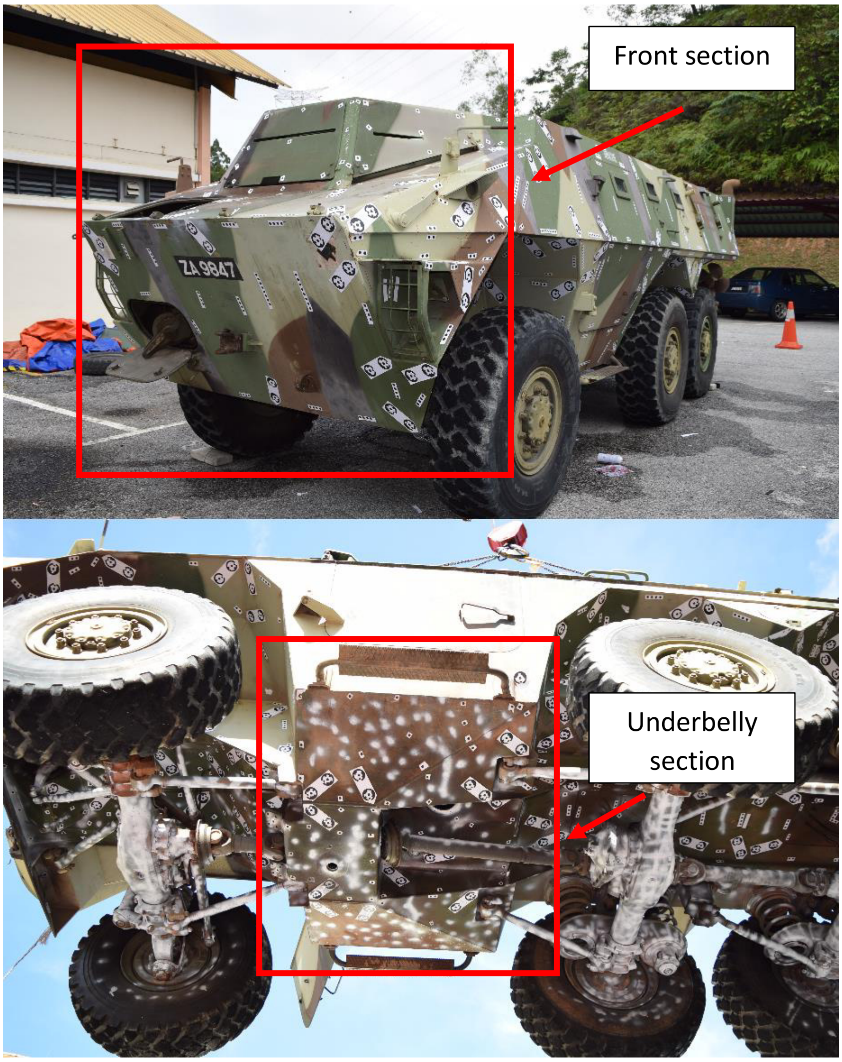

Figure 1.3: Front and underbelly sections of SIBMAS AFSV.