THE EFFECTS OF BLAST ON A COMBAT SYSTEM

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April 2021

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
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1. REPORT DATE April 2021	**2. REPORT TYPE** Technical Publication		**3. DATES COVERED**
4. TITLE AND SUBTITLE The Effects of Blast on a Combat System			**5a. CONTRACT NUMBER** FA8075-14-D-0001
			5b. GRANT NUMBER
			5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) James O. Pilcher II			**5d. PROJECT NUMBER**
			5e. TASK NUMBER
			5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADRESS(ES) Defense Systems Information Analysis Center (DSIAC) SURVICE Engineering Company 4695 Millennium Drive Belcamp, MD 21017-1505			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Defense Technical Information Center (DTIC) 8725 John J. Kingman Rd. Fort Belvoir, VA 22060-6218			**10. SPONSOR/MONITOR'S ACRONYM(S)** DTIC
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/ AVAILABILITY STATEMENT Distribution A: Approved for public release; distribution is unlimited.			
13. SUPPLEMENTARY NOTES			
14. ABSTRACT Modeling the response of ground vehicles and its occupants against underbody, buried blasts has been a continued challenge that is often tackled through utilizing complex computation simulations. However, approaching the scenario from first principles of physics and mathematics yields valuable insight and simple fast-running models. This report covers the basics of blast wave propagation and its interactions, specifically to ground vehicles. Additionally, it goes on to describe how to calculate global loads on the vehicle, local and structural responses in the vehicle, responses to internal occupants, and a brief discussion into experimental verifications of the calculations.			
15. SUBJECT TERMS blast, IED, shock wave, mine resistant, acceleration, buried blast, occupant injury, vehicle motion, shock seat, pressure wave			

16. SECURITY CLASSIFICATION OF: UNCLASSIFIED			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Vincent "Ted" Welsh
a. REPORT UNCLASSIFIED	**b. ABSTRACT** UNCLASSIFIED	**c. THIS PAGE** UNCLASSIFIED	UNCLASSIFIED	92	**19b. TELEPHONE NUMBER** *(include area code)* 443-360-4600

Standard Form 298 (Rev. 8/98) Prescribed by ANSI Std. Z39.18	**ON THE COVER:** *(Source: U.S. DoD)*

FOREWORD

James Pilcher, the author of this monograph, was a personal friend and coworker of mine for many years. He was a gifted, talented, and creative engineer, and his engineering mathematics skills were outstanding. This monograph is a lasting and fitting testament to his talents, his dedication to his craft, and his determination to preserve for future generations not only the benefits of his work but also a demonstration of what critical scientific engineering thinking is all about.

On numerous occasions, the author and I discussed how many modern computer engineering tools, although helpful, tended to sometimes obscure the mathematics and engineering processes required to fully understand the meaning of their output. This monograph is a "start-from-scratch" effort to develop the mathematics and engineering behind analyzing the complex effects of blast on a combat system. Moreover, that the process can be automated in as simple a framework as an Excel spreadsheet demonstrates the fundamental nature and elegant simplicity of the engineering mathematics presented herein.

This monograph is suitable for use as both a reference work and a teaching text, especially since the author's untimely passing left a portion of the narrative uncompleted. The diligent student/reader should undertake to "fill in the missing blanks," so to speak, which will further aid in the student's learning and understanding of the concepts.

I learned so much during the years I worked with the author that I am forever indebted to him. His devotion not only to his work but also to his family and faith are examples of all that is good and right. It is thus a great honor to introduce this important text. May the reader reap all the benefits of this effort!

James N. Walbert

THE AUTHOR

JAMES (JIM) O. PILCHER II was a seasoned ballistician and mechanical engineer, with more than 50 years of experience analyzing, testing, and developing a wide range of combat weapon systems and methodologies. His career began in 1959, when he joined the U.S. Army Ballistics Research Laboratory (BRL) at Aberdeen Proving Ground, MD. During his nearly 30 years at BRL, he held multiple bench-level and leadership positions, including serving as a research engineer in the field of projectile/gun dynamics modeling and analysis, as well as Team Leader of the Electro-Mechanics Team, the Tank Gun Dynamics Team, and the Experimental Mechanics Team.

From 1989 until 1999, Jim served as President of Pilcher & Associates, where he developed a simulation of the operational response of the IRS computer system to projected workloads; consulted on ballistic range upgrades at Warren Air Force Base, WY; and provided design engineering for development of a production model computer enclosure.

Jim joined SURVICE Engineering in the spring of 1999 to serve as a senior analyst in the Aberdeen Area Operation's Evaluation and Analysis Group. His many accomplishments during his 16 years with the company included developing an underbody mine blast analysis computer tool for the Mine-Resistant, Ambush-Protected program; analyzing energy safety limits for a blast test facility; analyzing the performance of the Joint Biological Standoff Detection System; and providing live-fire test and evaluation, ballistic survivability, nonballistic survivability, and/or technical management planning and evaluation support for countless combat systems and programs. In addition, he was the author of numerous technical reports and publications, as well as the recipient of numerous patents and awards.

EDITOR'S NOTE

While writing this monograph, Jim sadly passed away after an extended illness. We honor his legacy by completing this work so that it can be referenced by future ballisticians and engineers.

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FIGURES

Unless otherwise noted, all figure sources are from the author.

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CHAPTER 1. BASIC ELEMENTS OF THE BLAST WAVE AND THEIR NOMENCLATURE

1.1 INTRODUCTION

Chapters 1–4 are nonmathematical discussions of blast waves emanating from explosive charges and impinging on targets. The purpose of these discussions is to assist the reader in visualizing the dynamic processes involved in blast and target scenarios. Blast waves are, in reality, "shock waves." In the absence of fragments, shrapnel, and other penetration devices, shock waves are the primary lethal mechanism of blast.

This chapter will discuss the basic elements of the shock wave, their nomenclature, and the parameters that govern the severity of the wave and its propagation properties. Three models of initial conditions—"free-air," "surface-mounted," and "buried-charge"—will be briefly discussed at the end. A glossary of terms and some recommended readings is also provided.

1.2 IDEAL SHOCK WAVE

The "ideal shock wave" is an amalgam of physical theory, laboratory experiment, and field test results; its primary purpose is to provide an accurate characterization of shock wave behavior. First, we will discuss the defining characteristics of the classical ideal shock wave. A shock wave is energy passing through a homogeneous medium (in our case, air) with a velocity that is greater than the speed of sound of the medium through which it is travelling. Figure 1-1 shows the various parts of the ideal shock wave as it would look in a time-based recording. The diagram in this figure shows that the direction of travel is to the left (a matter of convention). The "shock front" is the first feature of the shock wave to arrive at the point of observation; the point of observation is the position of the sensor or observer relative to the center of the charge.

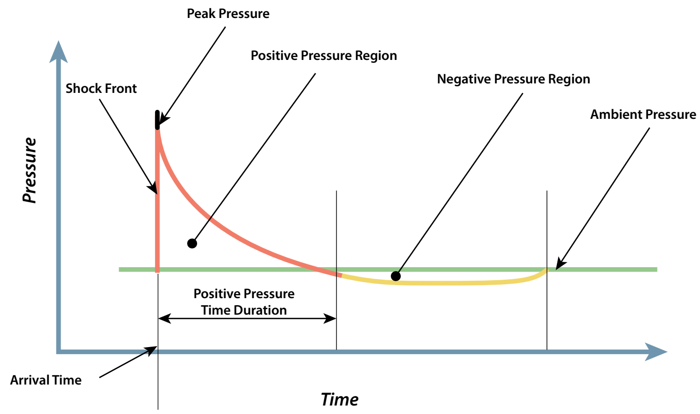

Figure 1-1. Classical, Ideal Shock Wave.

Because the air (gas) cannot dissipate the energy fast enough, the pulse forms the shock front shown in the diagram. The rise time of the shock front in a perfect gas would be zero; measured rise times, in reality, are extremely short (on the order of microseconds). A characteristic of the shock front is that there is no transfer of mass or energy across the shock front in either direction and that it behaves like a wall or barrier travelling faster than the speed of sound, creating a "jump" in the local pressure. The "time of arrival" is the time from the initiation of the charge to the arrival of the shock wave at the point of observation.

The peak pressure of the pulse occurs at the shock front as a sudden jump above ambient pressure and decays to ambient pressure behind the shock front, marking the end of the positive pressure region of the pulse. The pressure continues to decrease below ambient pressure, forming the negative pressure region, and then finally stabilizes asymptotically to ambient pressure. The portion of the shock wave trailing behind the shock front is diffusing energy at less than the speed of sound. The peak pressure and wave velocity decrease, and the time duration of the positive pressure region increases as the shock wave travels through the medium. When the pulse velocity drops below sonic velocity, the shock wave becomes a low-energy wave with more symmetry and roundness. The peak pressure, arrival time, and pulse duration of the "shock pulse" at a given point in space away from the source are determined by the energy released by the source and the distance traveled from the source. The peak pressure of the shock pulse decreases as the pulse travels farther away from the source; the time duration of the shock pulse increases as the pulse travels farther away from the source. The diagram in Figure 1-2 illustrates the distance effect.

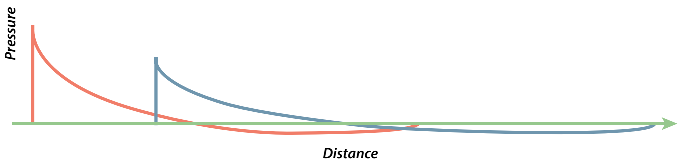

Figure 1-2. Two Shock Waves at Different Distances From the Same Source.

In Figure 1-2, the red-colored shock wave is closer in range to the source than the blue-colored shock wave. The peak pressure of the red wave is higher than the blue wave, and the positive pressure duration of the red wave is shorter than the blue wave. It should be pointed out that when there are no intervening obstacles and variations in the atmosphere between the source and the two waves, they are not affected by any difference in direction from the source but only by the differences in distance.

The ideal shock wave is an accurate approximation of the real behavior and, as such, can be used as an estimate of the values or pressure and time durations. The constraints to precision are the inadequate conservation of entropy theory and nonuniqueness of the D'Alembert's wave solution. This means that mathematical formulations of the pulse shape are arbitrary and not products of direct mathematical derivation and thermal dynamic behavior at extreme pressures is not adequately understood. These constraints cause a heavy reliance on empirical data with all the limitations of identifying, controlling, and measuring pertinent variables. Consequently, it is necessary that estimates of blast effects be verified by testing. Real charges are not usually geometrically spherical, and the blast field generated by the charge in the near field will not be spherical but distorted, according to the original geometry of the charge. An explosive material can have an inefficient detonation characteristic that leaves combustible products that "deflagrate," introducing delayed energy into the positive pressure portion of the pulse and causing changes in shape of the positive pulse. These distortions are smoothed out as the wave travels, thus approaching theoretical expectations. In addition, reflections from surfaces between the source and the point of observation cause spikes in the shape of the pulse. These effects close to the charge are called "near-field" effects. The near-field and far-field effects will be discussed further in Chapter 2. Figures 1-3 and 1-4 show some examples of near-field effects.

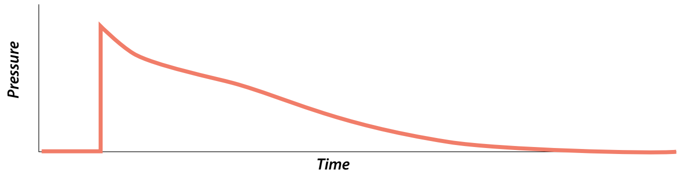

Figure 1-3. A Shock Wave With Deflagration Energy.

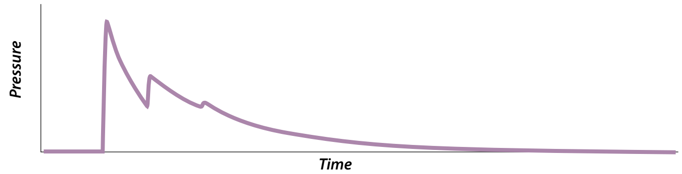

Figure 1-4. A Shock Wave With Reflections.

There are many other causes of near-field distortion of the ideal shock beyond the scope of this chapter. The ideal shock waves that have been discussed are only two dimensional; what follows are discussions of three different, three-dimensional (3-D) models of the shock wave used by analysts and engineers to estimate the effects of shock waves.

1.3 FREE-AIR MODEL

The first initial condition considered is where there are no reflecting surfaces between, beyond, and close to the charge and point of observation and that the charge behaves as a "point source." The 3-D aspects of the shock wave are that the ideal point source radiates a shock wave in all directions, forming a shock sphere. Figure 1-5 shows a cross section of the shock sphere. The shock sphere is not like the soap bubble that has a thin film defining the spherical surface of the bubble and an interior volume of a uniform pressure. The surface of the shock sphere is defined by the 3-D shock front with an interior volume consisting of three concentric spherical volumes. The purple circle defines the surface of the spherical shock front. The rose-colored zone directly inside the shock front is the positive pressure region, the following yellow zone is the negative pressure region, and the final zone is the ambient pressure region. The ideal pressure profiles in the left half of the diagram show the pressure distribution in the regions and their uniformity, regardless of direction.

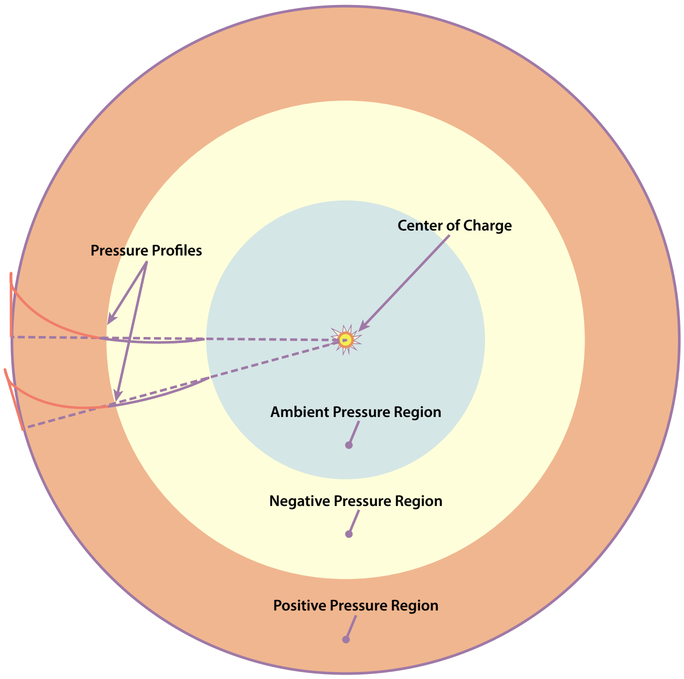

Figure 1-5. Free-Air Model.

Theoretically, as the point of observation is moved closer to the charge, the pressure distribution inside the shock sphere changes. However, the pressure profile measured at the point of observation has the same character but different magnitudes; the peak pressure would be much higher, and positive pressure time duration would be much shorter. Figure 1-5 shows the cross section of the blast sphere that has obtained a very large radius compared to the original radius of the explosive charge—an ideal "far-field" condition.

1.4 SURFACE-MOUNTED MODEL

The surface-mounted model is a simple modification of the free-air model. The charge is assumed to be mounted such that its center is in the plane of the surface, as shown in Figure 1-6. This model assumes that the energy confined in the spherical volume of the free-air model is now confined to the hemisphere of the surface-mounted model; this assumption is often used in the analyses of blast effects of surface mines on ground vehicles.

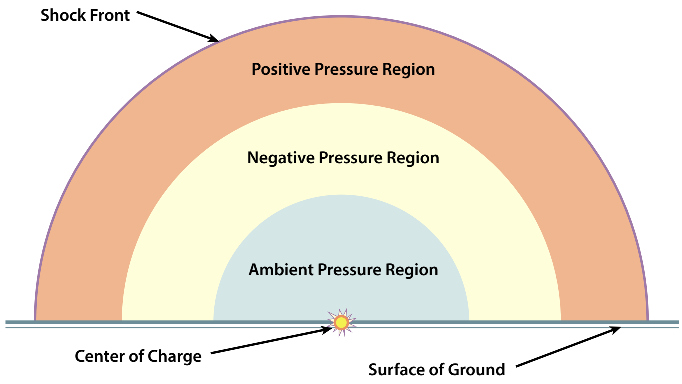

Figure 1-6. Surface-Mounted Model.

The energy release from the charge forms a hemispherical shock front, with an interior pressure distribution of similar character to that of the free-air model. Based on the perfect-gas law, the peak pressure is estimated to be ~26% higher in magnitude vs. free-air shock from the same energy and density of charge due to the initial constraint of the surface that reflects the energy back through the charge. It is assumed that the hemisphere contains the same energy as the free-air model.

1.5 BURIED-CHARGE MODEL

The buried-charge model is more complex than the previous models in that its effect is not only governed by the energy and density of the charge but also governed by the characteristics of the ground, the geometry of the charge, and the geometry of the burial. The energy from the charge is distributed simultaneously into two geometries—a cone of focus and hemisphere of residual energy. Depending on the density of the soil, the geometry and mass of the charge, and the geometry of the burial and overburden, the magnitude of pressure can be as much as 6× higher than a free-air blast from a charge of the same energy and density. A properly designed, buried charge can be very efficient against a close-in target. The basic assumption is that the energy normally reflected back through the charge center in a surface-mounted charge is restricted to a conical volume emanating from the center of the charge, as shown by the dashed lines in Figure 1-7. The cross section of the cone would be circular or elliptical, depending on the horizontal cross section of the charge.

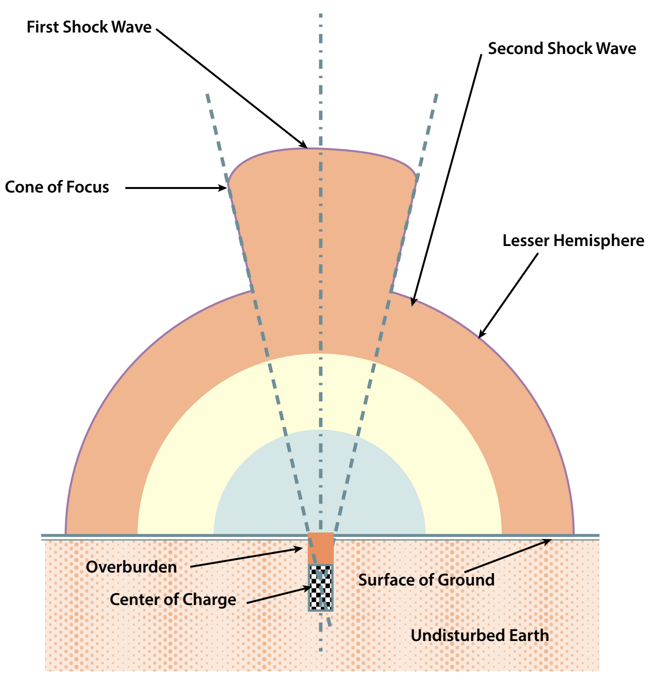

Figure 1-7. A Buried Charge Model.

The sharpness of the cone of focus is influenced by relative densities of the charge, surrounding earth, and overburden. The densities of the undistributed earth and overburden depend on the soil type, state of compaction, and water content. The peak pressure at the base of the cone (at the point of observation) would be proportional to the ratio of the volume of the hemisphere at that radius to volume of the cone of the same height above the center of the charge. This configuration generates two separate shock waves. The first wave has a very high supersonic velocity and much higher peak pressure within the boundary of the cone of focus because of the focused energy. The second shock wave outside the conical boundary has a lower supersonic velocity and peak pressure like that of a free-air wave of the same charge mass.

1.6 SUMMARY

We have discussed the nature of shock waves as they travel through air from the view of an observer at specific points in space without obstructing the progress of the wave or changing the medium in which the wave is traveling. The primary factors governing the energy of the shock wave are the mass and density of the charge and the distance from the charge center to the point of observation. A more detailed overview can be found in Army Technical Manual (TM) 5-855-1 [1] and Baker [2]. In Chapter 2, we will discuss how the shock wave impinges on an object in its path and the subsequent reactions of the object to the impingement.

REFERENCES

1. U.S. Army TM 5-855-1. "Design and Analysis of Hardened Structures to Conventional Weapons Effects." Chapter 5, August 1988.
2. Baker, W. E. *Explosions in Air*. Second Ed., San Antonio: Wilfred Baker Engineering, 1983.

GLOSSARY

Cone of Focus: The conical volume that contains most of the energy from a buried charge.

Far-Field Effect: The minimization of the near-field effect achieved by displacing the measuring device away from the charge a sufficient distance.

Free-Air Model: A model that assumes there are no obstruction or reflections between the charge and the target or point of observation.

Ideal Shock Wave: The conventional characterization of shock wave behavior based on theory and empirical observation.

Near-Field Effects: The anomalies in charge performance and variations in charge emplacement geometry that adversely affect the ability to measure the shock pressure in close proximity to the charge.

Overburden: The amount of earth placed over a buried charge.

Point of Observation: The position of the sensor of observer relative to the center of the charge.

Positive Pressure Time Duration: The time duration that the shock pressure remains above ambient pressure.

Rise Time: The time interval when a shock pressure jumps from ambient to peak pressure.

Shock Front: The first feature of the shock wave to arrive at the point of observation.

Shock Hemisphere: The shock front that emanates from a point source embedded in flat surface and forms a hemispherical surface.

Shock Sphere: The shock front that emanates from a point source and forms a spherical surface.

Shock Wave: Energy passing through air with a velocity that is greater than the speed of sound.

CHAPTER 2. BLAST WAVE AND TARGET INTERFACE

2.1 INTRODUCTION

In this chapter, the nonmathematical discussion of blast waves continues with the examination of the interface process at the point of contact between the shock wave and the surface of an object. The word "target" is used to indicate an object in the path of a shock wave, regardless of intent or chance. To illustrate the process, a flat plate (plane surface) is used. We will discuss the side-on pressure, the reflection process, the normal reflected pressure, and the effect of angle of incidence. The dynamic distribution of pressure over a flat plate and how it changes with time are also discussed, with the significance of global and local dynamic loading covered at the end of the chapter.

2.2 SIDE-ON PRESSURE

The peak pressure of an undisturbed shock wave is called the incident pressure, or the side-on pressure. The first name refers to the pressure of the ideal shock wave prior to impinging a surface; the second name refers to the method of measurement, as shown in Figure 2-1. The pressure gage is mounted flush with a surface that is aligned parallel to the line of travel of the passing shock wave. Special gages are designed for this purpose and produce reasonably accurate results. The following discusses what happens when the shock wave impinges onto the surface. Impinge is used instead of impact because impact in modern usage implies the collision of two rigid bodies of mass, which is not relevant for these discussions.

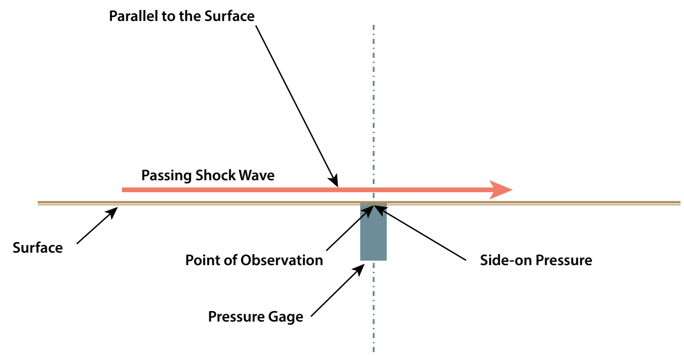

Figure 2-1. Side-on Pressure.

2.3 IDEAL SHOCK WAVE REFLECTION

When a shock wave impinges a surface, it reflects off the surface like a beam of light off a mirror and not like a fluid diverting across the surface.

The resultant pressure at the point of incidence is governed by the angle of incidence, the energy of the charge, the distance from the charge at the point of incidence, and the energy loss during the reflection process. The diagram in Figure 2-2 illustrates the event. Due to the loss of energy, the angle of reflection is, in reality, less than the angle of incidence. Due to the inability to measure the governing parameters identified by physical theory at the point of incidence and time of incidence, an ideal reflection process is assumed where the reflected shock wave leaving the surface has the same pressure vs. time profile as the incident shock wave, and the angle of reflection is the same as the angle of incidence.

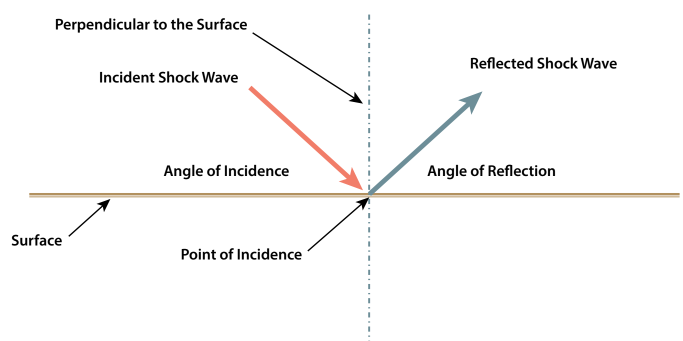

Figure 2-2. Shock Wave Reflection.

2.4 NORMAL REFLECTED PRESSURE

When the angle of incidence is 90° or perpendicular to the surface, the difference between the pressure at the surface and the side-on pressure at the time of arrival for that particular shock wave is at a maximum. This surface pressure is called the normal reflected pressure (normal refers to the

90° angle). Figure 2-3 shows the general arrangement for measuring the normal reflected pressure.

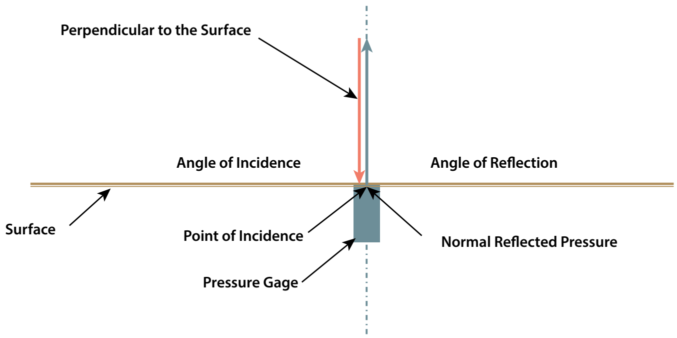

Figure 2-3. Normal Reflected Pressure.

When the shock wave reflects off a surface as shown in Figure 2-2, the reflected pressure at the surface is between the normal reflected pressure and the side-on pressure, depending on the angle of incidence. The curves in the chart in Figure 2-4 indicate the reflected pressure with respect to the angle of incidence for three different levels of energy in the shock wave.

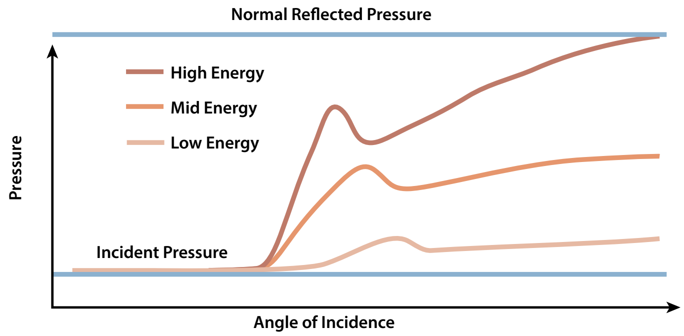

Figure 2-4. Reflected Pressures vs. Angle of Incidence for Three Energy Levels.

The humps in the curves indicate instability in the reflection process due to unknown factors in the process. These factors may be surface conditions such as smoothness or the heat transfer rate into the surface. Current physical theory does not yield a satisfactory answer. The curves in Figure 2-4 are from the analyses of empirical data.

2.5 REFLECTIONS ON FLAT SURFACES

When a shock wave impinges a surface, it reflects off the surface like a beam of light off a mirror. The resultant pressure and the subsequent transfer of momentum to the surface are governed by the reflection angle, distance from the charge, the energy or mass, and the density of the charge. The reflected pressure acts on a very small area about the point of incidence, forming a force against the surface in the direction normal to the surface. On flat surfaces, all of the forces formed by the pressures at the various points of incidence are parallel to one another and perpendicular to the surface, as shown in the diagram in Figure 2-5.

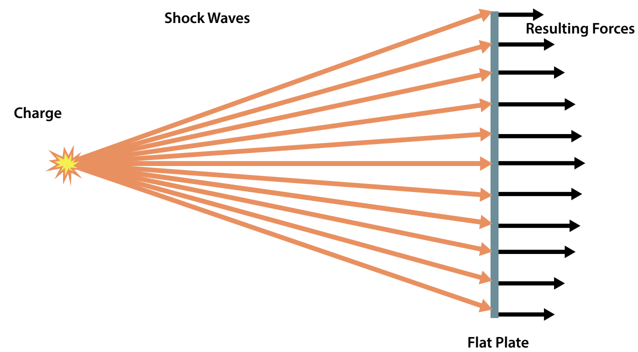

Figure 2-5. The Direction of Forces Generated by Shock Waves Impinging a Flat Plate.

The red arrows in Figure 2-5 depict shock waves impinging various points on a flat surface. Consider that all of the points on the surface will be illuminated during a specific time period from the first time of arrival based on the shortest distance and last time of arrival plus the positive pulse duration based on the longest distance from the charge. Note that the directions of the black arrows that depict the direction of the resulting impulses are parallel to one another and the normal of the surface and not necessarily parallel to the shock waves. Each resulting instantaneous force is the product of the reflected pressure and illuminated area. From an engineering point of view, the time duration of the positive pressure region is considered to be the significant portion of the pulse. This is the portion used in calculating the global and local dynamic loadings of structures. The remainder of the pulse is considered in developing more precise theories of the dynamic processes in shock waves. The remainder of the discussion of blast, which concentrates on the effects of the positive region of the shock wave, will be called the "pulse duration."

2.6 REFLECTIONS ON CURVED SURFACES

On curved surfaces, the resulting impulses are not parallel to one another. Concave surfaces divert the resulting impulses while convex surfaces focus on the resulting impulses. The effects for circular surfaces are shown in the diagrams in Figure 2-6. The resulting impulses are parallel to the normal surface as for flat surfaces but not parallel to one another.

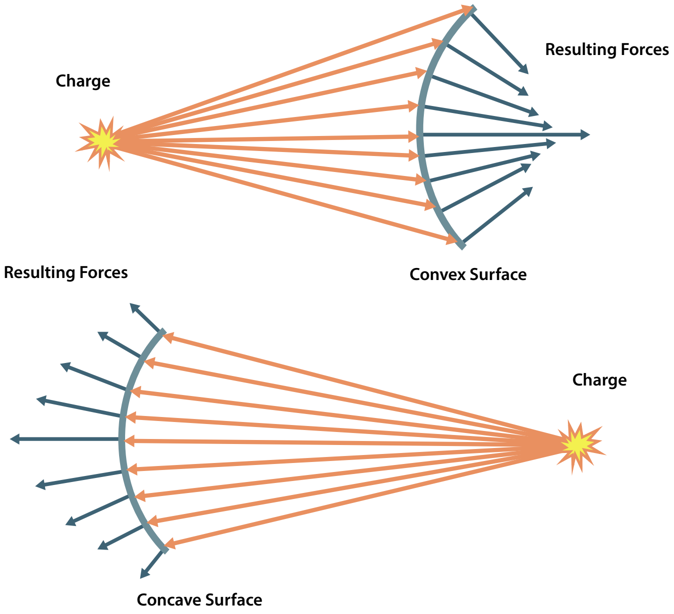

Figure 2-6. The Direction of Forces Generated by Shock Waves Impinging Circular Surfaces.

2.6.1 Pressure Distribution vs. Time

Because different points on the target surface are at different distances from the source, different areas of the target surface are illuminated at different times over the pulse duration. This dynamic behavior of the contact process is depicted in a series of plots of reflected pressure at different times during a blast pulse in Figures 2-7–2-9 and a plot of the total force vs. time history in Figure 2-10. The times cited in Figures 2-8 and 2-9 are the time from the initial contact of the shock wave.

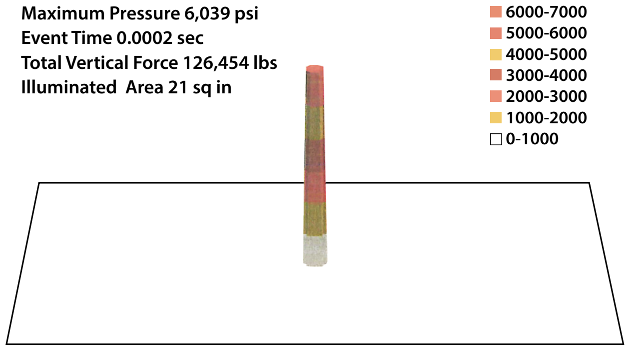

Figure 2-7. Initial Contact.

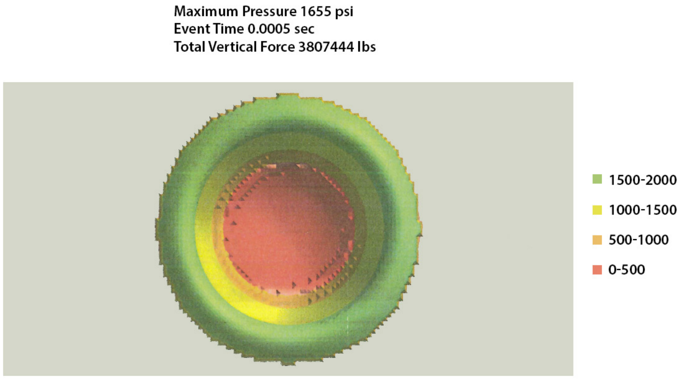

Figure 2-8. Three Hundred Microseconds Later.

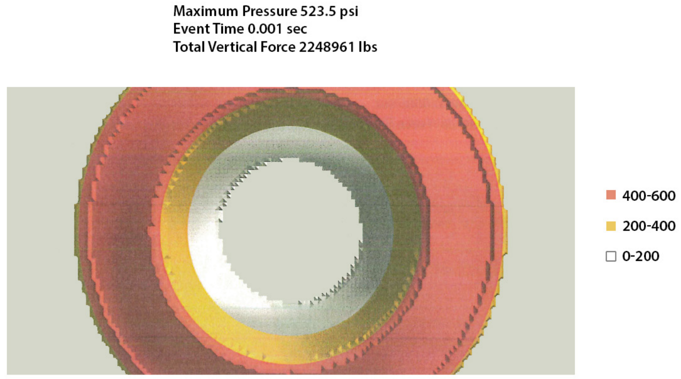

Figure 2-9. Eight Hundred Microseconds Later.

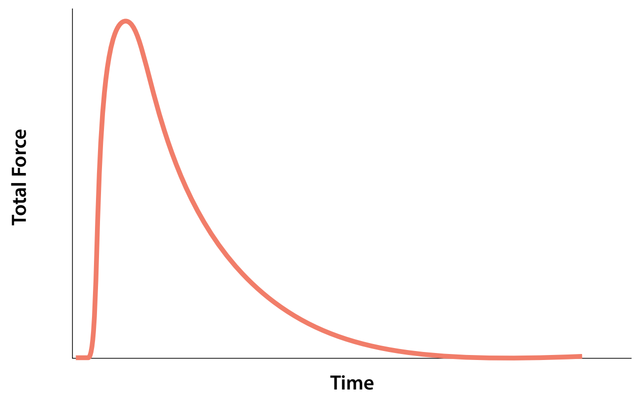

Figure 2-10. Total Blast Force on a Flat Plate.

Figure 2-7 depicts the initial contact of the shock wave on a flat surface. The illuminated area is ~21 in^2, while the total area of the surface is 10,368 in^2; only 0.2% of the exposed area is illuminated. The maximum pressure is 6,039 psi, and the total force is 126,454 lb.

Three hundred microseconds later, the maximum pressure (shown in Figure 2-8) is only 27% of the peak pressure, and the illuminated area is increased 470× the initial contact area. The colored areas in Figure 2-8 show that the pressure is maximum near the perimeter of the area and minimum in the center of the area. The maximum pressure is 1,655 psi, while the total force is 3,807,444 lb, with an area of 9,870 in^2.

Eight hundred microseconds later (shown in Figure 2-9), the pressure drops to 523.5 psi, and the total force decreases to 2,248,961 lb, even though the illuminated area has grown to 22,948 in^2.

As time progresses, the illuminated area continues to expand and develops into an annulus with zero pressure at the center, as shown in Figure 2-9. The annulus continues to grow until the shock wave no longer illuminates the surface.

2.6.1.1 Total Force

While it is highly desirable to measure the distribution of the normal pressure over the surface vs. time, it is very expensive and requires multiple channels of expensive equipment and many hours of data analyses. To empirically verify a specific series of pressure distribution tables is generally beyond the resources of a development program. The tables that were used to generate the charts depicting pressure distribution were generated by mathematical models of the known physics of the shock waves from the empirical results of centuries of testing from the invention of black powder. Chapter 3 will discuss modelling of blast/target scenarios. A more compact form of the blast force is the total force vs. time curve. For the case of the horizontal flat plate, which is the case used to illustrate the reflection phenomenon, all of the individual forces are in the same direction and combined into total force vs. time, as shown in Figure 2-10.

In reality, targets of interest are 3-D and combinations of flat and curved surfaces. The location of the charge usually generates asymmetric forces about the center of gravity (CG) of the target. Consequently, a six degrees of freedom (6DOF) description of the total forces or global forces is required to accurately determine environment imposed on the target. The determination of the three global components of force and the three global components of moment acting at the CG of the vehicle allows determination of the local forces at different positions throughout the body. For example, Figure 2-11 is a diagram showing the horizontal relative positions of six passengers, CG, and charge in a test of a flat-bottomed vehicle hull. The charge is shown near position 6; consequently, this asymmetric scenario creates moments about the CG that cause differences in the linear forces at different positions in the vehicle.

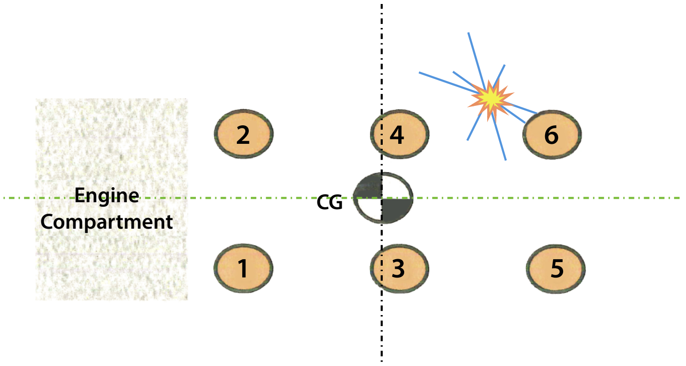

Figure 2-11. Layout of a Test Scenario for a Generic Vehicle.

Figure 2-12 shows the different vertical forces for the CG and positions 1 and 6. In the scenario discussed, the variations seem to be what is intuitively expected. As the geometry of the vehicle becomes more complicated, especially the underbody portion being other than flat, the distribution of forces becomes much less intuitive and more difficult to intuitively predict.

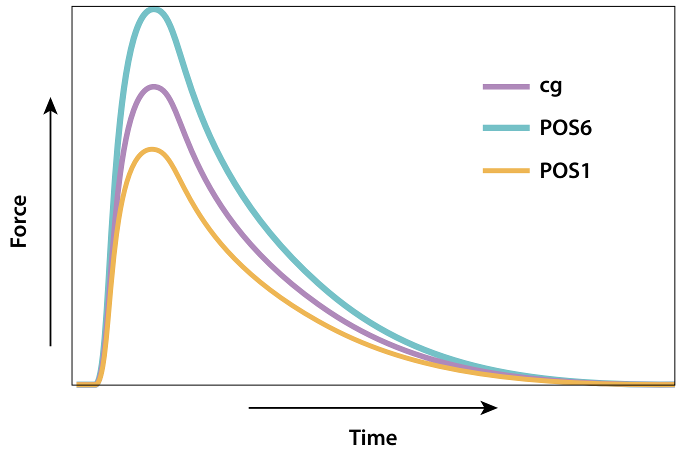

Figure 2-12. The Vertical Forces vs. Time for Different Positions in the Vehicle.

In addition to the blast loads, the global and structural response of the target is required to describe the complete dynamic environment at a particular position in the vehicle.

GLOSSARY

Angle of Incidence: The angle between the direction of travel of the incident shock wave and the surface at the point of incidence.

Angle of Reflection: The angle between the direction of travel of the reflected shock wave and the surface at the point of incidence.

Global Forces and Moments: The combines or total forces and moments acting on the structure at its CG.

Ideal Shock Wave Reflection: A process where the reflected shock wave leaving the surface has the same pressure/time profile as the incident shock wave and the angle of reflection is the same as the angle of incidence.

Local Forces and Moments: The forces and moments acting at a specific location on the structure.

Moment of Torque: The force acting at some distance from the CG of the body that causes the body to rotate about the CG.

Normal Reflected Pressure: The pressure on the surface at the point of incidence generated by a shock wave impinging perpendicular to the surface.

Point of Incidence: The point of the surface where the incident shock wave impinges the surface.

Pulse Duration: The time that the target is illuminated by the shock wave.

Reflected Pressure: The pressure on the surface at the point of incidence generated by a shock wave that is neither perpendicular nor parallel to the surface.

Side-On Pressure or Incident Pressure: The pressure on the surface at the point of observation generated by a shock wave passing parallel (normal) to the surface.

Six Degree of Freedom (6DOF): The three orthogonal forces and the three orthogonal moments that describe forces in 3-D space.

Target: An object in the path of a shock wave, regardless of intent.

CHAPTER 3. MODELLING OF BLAST EVENTS

3.1 INTRODUCTION

In this chapter, modelling and simulation (M&S); the validation, verification, and accreditation (VV&A) process; and live-fire testing (LFT) will be discussed. In addition to developing and proving the hardware, a parallel program called VV&A is conducted to prove the adequacy and credibility of M&S. The interplay among M&S, VV&A, and LFT will be discussed as it pertains to a conceptual simulation process to estimate survivability of crewmembers of a vehicle subjected to a blast environment.

3.2 M&S

M&S is used to provide estimates of force levels, the relative efficacy of alternative target geometries, crewmember environments, and the design of associated experiments and live-fire tests. The simulations contain groups of models that, when exercised in sequence, estimate the blast effects, the subsequent responses of protective equipment, and the survivability of personnel. Figures 3-1 and 3-2 illustrate a conceptual structure of an analysis process for estimating the incapacitation of crewmembers in a vehicle attacked by an explosive device. The blue tile is the operators' input to the model; the green tiles are intermediate calculations (submodels) required to generate the final output (red tile); the golden oval tiles indicate the tests or data used to validate and verify the associated intermediate calculations; and the yellow stars indicate intermediate calculations to be verified. All of the calculations must be validated.

The process shown in Figures 3-1 and 3-2 can also be considered to be two models; the diagram in Figure 3-1 outlines the model for calculating the blast environment for each crewmember that, in turn, is used as input into the incapacitation model depicted in Figure 3-2. Looking deeper into the blast

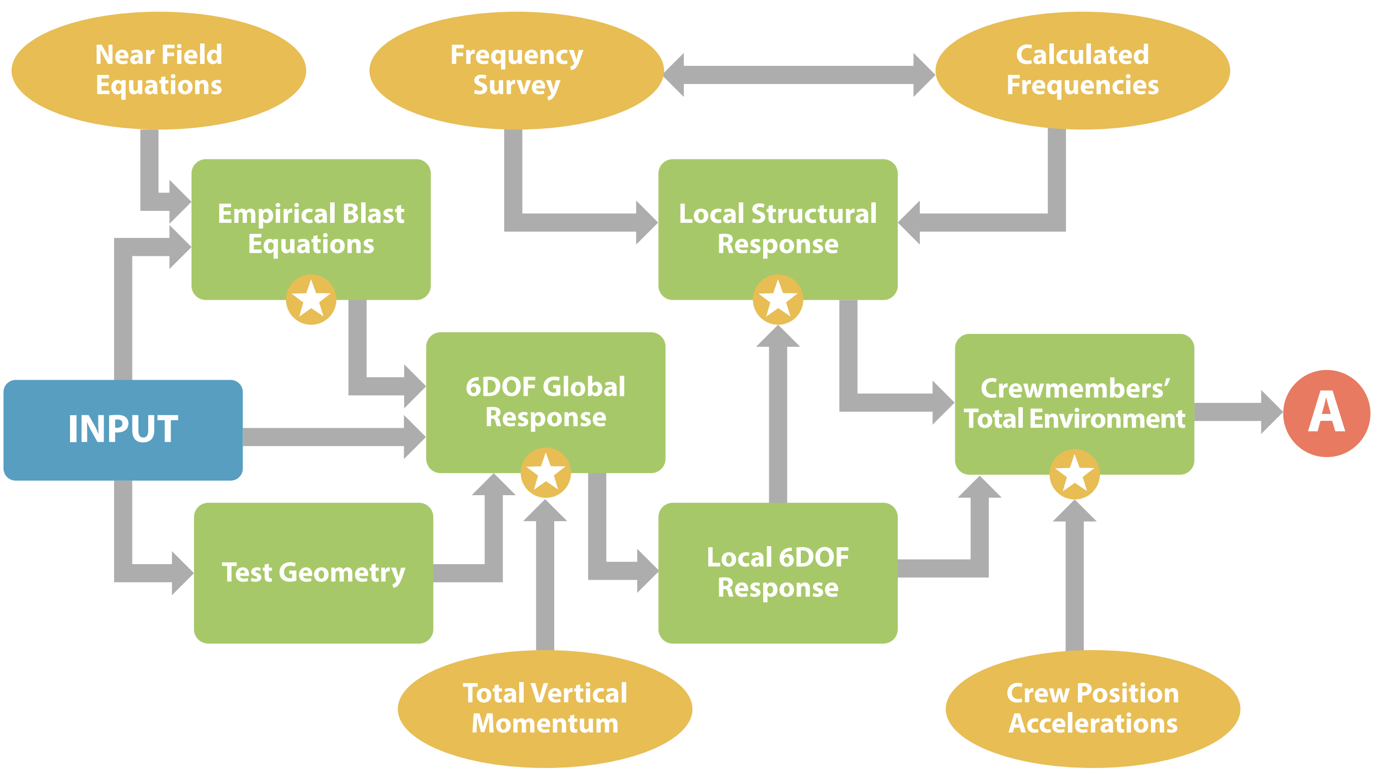

Figure 3-1. General Incapacitation Model, Part I Blast Effects.

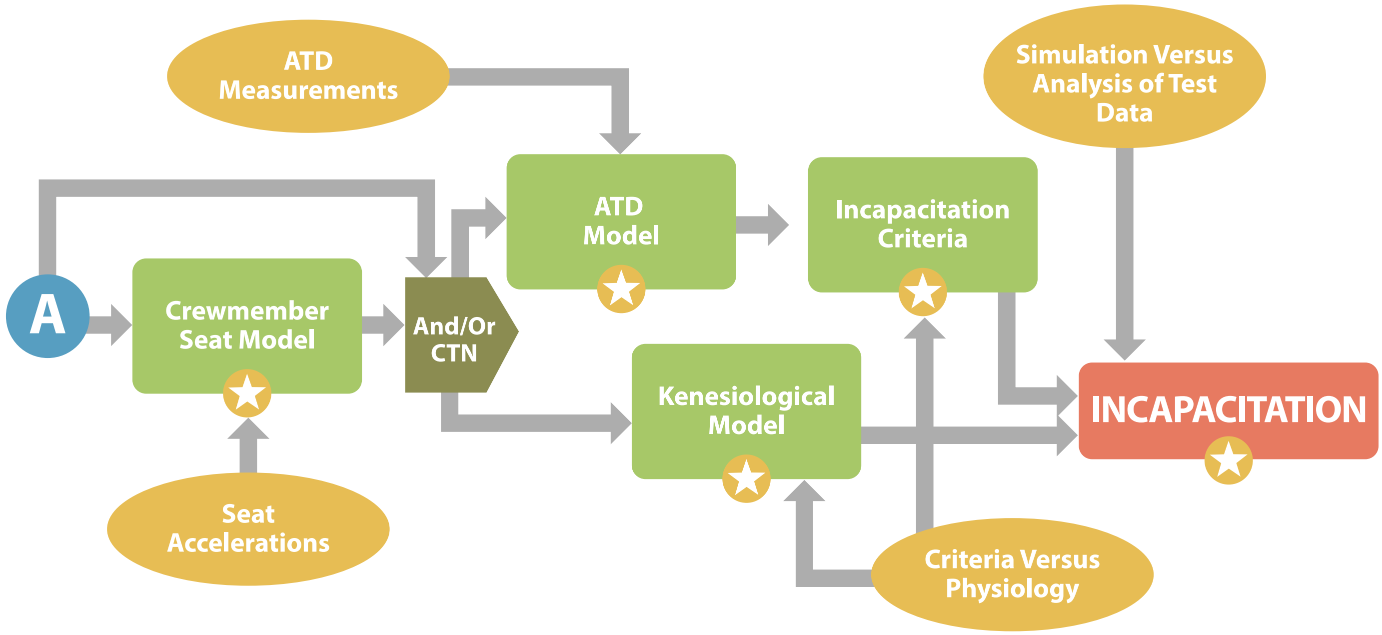

Figure 3-2. General Incapacitation Model, Part II Crewmember Incapacitation.

model (green tiles), the first three modules transform the input into the 6DOF global response of the vehicle to the blast. These three models form a global response model that can be used as an independent model to determine the relative severity for various external target geometries and charge positions. This ability can be used as a basis for evaluating design alternatives, test scenarios, and force distributions for finite-element stress analyses. For the purposes of the illustrated process, the output of these modules is tailored to the input requirements of the next step in the process. The last three modules transform the 6DOF global response into the multidegree of freedom acceleration environment for each crewmember position. The results of these calculations become inputs into the incapacitation model (Figure 3-2) through node A. Node A sends the input data to the crewmember seat model and the conditional transfer node (CTN). The CTN forwards the input data to the next modules in accordance with the mounting scheme—is the crewmember's body completely supported by the seat geometry, are there other points of contact between the crewmember and the vehicle, and is the anthropomorphic test dummy fully articulated? The remainder of the model has two tracks to provide a cross check between empirical and theoretical kinesiology to determine the estimated incapacitation. These three questions arise:

1. Is the model or every part of it creditable?
2. Is there a risk of accepting erroneous answers?
3. Is there a risk of rejecting correct answers?

3.3 GOODNESS AND ACCEPTABILITY

3.3.1 Goodness

In general, the "goodness" of a model is both the qualitative and quantitative agreement between the predicted and measured outcome of a specific event. Goodness can be divided into two categories—accuracy and precision. Each category can have different levels of agreement or disagreement.

3.3.1.1 Accuracy

Accuracy is the ability of the model to portray the character of the behavior of a system in response to a dynamic event. To illustrate the principle, Figure 3-3 shows a modeled response and measured response for a given event. The modeled and measured responses are significantly different in character. The model output is not accurately describing the character of measured response. When accuracy is not achieved, precision becomes meaningless.

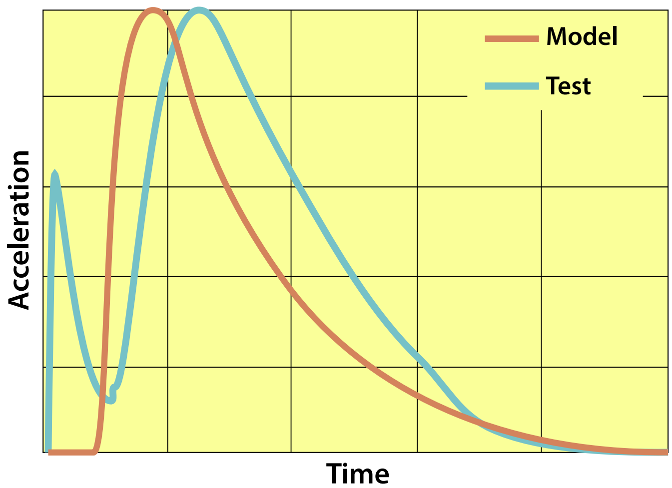

Figure 3-3. Comparison of Modeled and Tested Results.

In this case, the model input was describing a test scenario different from the actual test scenario. Although most input errors are not as severe and obvious as this case, they can significantly affect outcome of structural response calculations and the precision of the results. Once appropriate correction to the input is achieved and accuracy is established, precision can be addressed.

3.3.1.2 Precision

To determine the degree of precision of the model's ability to accurately estimate the response with the measured response, the following comparisons must be made:

1. Are the total momentums the same?
2. Are the frequency spectra the same?
3. Are the mode frequencies the same for each mode order?
4. Are the absolute amplitudes for each pairing of frequencies the same?
5. Does the model's output include the sensor's environment?
6. Does the model's input include the sensor's orientation and position?
7. Does the model's input include the sensor's triaxial sensitivity?

3.4 ACCEPTABILITY

Acceptability is achieved by meeting the following criteria:

1. Validity – The computation has a physical basis and mathematical consistency.
2. Facility – The software is executable on commonly available computer hardware and software.
3. Operability – The software is operable by technical personnel with modest computer skills and can be implemented and executed in minimal time (ideally, hours not days).
4. Utility – The output is useful in analyzing the efficacy of design options, severity of test options, crewmember environments, and/or crewmember incapacitation.
5. Verifiability – the output can be verified by tests, comparing other models, and live-fire tests.

Parallel with the effort to develop a model, there is a systematic process called VV&A.

3.5 VV&A

VV&A is a U.S. Department of Defense (DoD) process that assigns appropriate roles to M&S sponsors, developers, V&V agents, accreditation agents, and accreditation authorities; these roles have specific responsibilities. Before going further in our discussions, there are definitions to review. According to DoDI 5000.61 [1], the following are the accepted definitions of the terms used:

1. M&S Application Sponsor – The organization that utilizes the results or products from a specific application of a model or simulation.

2. Accreditation Agent – The organization designated by the application sponsor to conduct an accreditation assessment of an M&S application.
3. M&S Developer – The organization responsible for managing or overseeing models and simulations developed by a DoD component, contractor, or federally funded research and development center.
4. Validation and Verification (V&V) Agent – The organization designated by the M&S application sponsor to perform validation (or verification) of a model, simulation, or federation of models and/or simulations.

Typically, the application sponsor (who needs to use M&S) designates an accreditation agent. This agent is responsible for organizing, coordinating, and executing a comprehensive VV&A program, with the goal of guaranteeing the credibility of M&S results for the sponsor's application. The accreditation agent designates a V&V agent responsible for producing the V&V data or acts on his or her own as the V&V agent. The M&S developer is designated by the application sponsor to oversee M&S development activities and ensure coordination with the V&V agent; however, the application sponsor can retain the duties of the M&S developer. The exact relationship between these organizational entities can affect the credibility of the results of VV&A activities.

3.5.1 Collaboration and Independence

A common misconception is that V&V must be conducted completely independent of the M&S developer to avoid loss of credibility due to the presence of an advocate. Contrary to this misconception, the M&S developer is an essential and integral part of V&V; the developer contributes greatly to its efficiency because of the developer's intimate familiarity with the design and code details and involvement in the development from the start. Totally independent V&V efforts by the V&V agent can retrace much of the work already done by the M&S developer. The developer has the best understanding of the requirements, and the best V&V results have been achieved when the developer has maintained close contact with the application sponsor and the V&V agent. The matrix of Table 3-1 shows the interconnection of roles and responsibilities.

Table 3-1. Assigned Roles and Responsibilities

Activity	Party			
	V&V Agent	**M&S Developer**	**Application Sponsor**	**Accreditation Agent**
V&V Acceptability Criteria Report	*Assists*	—	**Responsible**	*Assists*
Accreditation Plan	—	—	**Responsible**	*Performs*
V&V Plan	**Responsible**, *Performs*	*Assists*	*Uses*	*Uses*
Verification	**Responsible**	*Assists*	—	—
Validation	**Responsible**	*Assists*	—	—
V&V Report	**Responsible**, *Performs*	*Assists*	*Uses*	*Uses*
Acceptability Assessment Report	*Assists*	—	—	**Responsible**
Accreditation	*Assists*	—	**Responsible**, *Performs*	*Assists*
Accreditation Report	*Assists*	—	**Responsible**	*Performs*

The terms in the table are defined as follows:

1. Responsible – The listed party ensures that the specified activity is accomplished.
2. Performs – The listed party carries out the technical work associated with the listed activity.
3. Assists – The listed party helps the responsible or performing party with the activity.
4. Uses – The listed party employs the product of the listed activity in performance of some function listed later in the table.

Table 3-1 is a suggested list of interactions and responsibilities. Ultimately, the application sponsor decides how much independence is necessary and affordable.

3.6 LFT

In general, LFT refers to tests of equipment and combat systems using existing threats or their equivalent; included in this definition are experiments or test of specific features or components of the system under development to confirm the meeting of specific design criteria. There are two categories of LFT—general and the Live-Fire Test (note the capitalization) mandated by Congress (Title 10, U.S. Code Section 2366, Chapter 139 [2]). The mandated Live-Fire Test is the final test of the developed system prior to acceptance for production. The results of LFT are reported through the Office of Secretary of Defense to Congress.

3.6.1 Preparation

About halfway through the development cycle, the LFT plan development is initiated using the available M&S, empirical, design data and criteria to formulate a test plan to demonstrate the ability of the system to meet the performance criteria by testing the system's vulnerabilities against the threat's lethality. The plan usually entails a series of tests, especially when there is a variety of lethal mechanisms involved. As an example, for armored vehicles, the critical issue is protecting personnel. This means that tests will be needed to confirm protection from penetrating threats as well as blast threats. Some of the tests will be performed on components of the system, such as penetration verification of the armor recipes. The test requiring the external surfaces of the system will be ordered in increasing severity, with the full-up blast test last. The planning, execution, and reporting of results of the Live-Fire Test series is under the purview of the Office of the Director of Live-Fire, Under Secretary of Defense for Research and Engineering. A team with representation from elements of the U.S. Army Systems Analysis Activity, Army Evaluation Center, Army Research Laboratory, Army Test and Evaluation Command, Program Manager, and associated contractors participate in planning, conducting, and analyzing the results of the Live-Fire Test. Other DoD organizations may be participants, especially if more than one service is involved.

REFERENCES

1. U.S. DoD. *Department of Defense Instruction.* DoDI 5000.61, 9 December 2009.
2. U.S. Code 2366. "Major Systems and Munitions Programs: Survivability Testing and Lethality Testing Required Before Full-Scale Production." Title 10, Chapter 139.

GLOSSARY

Accreditation Agent: The organization designated by the applications sponsor to conduct an accreditation assessment of an M&S application.

Accuracy: The ability of a model to portray the character of the behavior of a system in response to a dynamic event.

Assists: The listed party helps the responsible or performing party with the activity.

Facility: The software is executable on commonly available computer hardware and software.

LFT: The testing of equipment and combat systems using existing threats or their equivalent; included in this definition are experiments or tests of specific features or components of the system under development to confirm the meeting of specific design criteria.

Live-Fire Test (note the capitalization): A live-fire test in response to Congressional mandate of Title 10, U.S. Code Section 3266, Chapter 139 [2].

M&S Application Sponsor: The organization that utilizes the results or products from a specific application of a model or simulation.

M&S Developer: The organization responsible for managing or overseeing models and simulation developed by a DoD component, contractor, or federally funded research and development center.

Operability: The software is operable by technical personnel with modest computer skills and can be implemented and executed in minimal time (ideally, hours not days).

Performs: The listed party carries out the technical work associated with the listed activity.

Precision: The ability of a model to quantify the magnitude of a measured response without error.

Responsible: The listed party ensures that the specified activity is accomplished.

Uses: The listed party employs the product of the listed activity in performance of some function.

Utility: The output is useful in analyzing the efficacy of design options, severity of test options, crewmember environments, and/or crewmember incapacitation.

Validation and Verification (V&V) Agent: The organization designated by the M&S application sponsor to perform V&V of a model, simulation, or federation of models and/or simulations.

Validity: The computation has a physical basis and mathematical consistency.

Verifiability: The output can be verified by tests, comparison with other models, and Live-Fire Tests.

VV&A: The DoD-instituted process (DoDI 5000.61) to accredit the worthiness of a model.

CHAPTER 4. CALCULATION OF THE GEOMETRIC ELEMENTS OF THE TARGET-CHARGE SCENARIO

4.1 INTRODUCTION

Chapters 4–10 present the detailed mathematical description of the blast phenomena discussed in Chapters 1–3 and provide tools for the engineer, designer, tester, and analyst who are concerned with the estimation and testing of the survival of personnel and equipment to blast environments. The emphases are on the mathematics and implementation of the estimates of blast effects and their verification.

This chapter describes the mathematical processes used to define the coordinate system, the target surfaces, and the methodology used to survey parallelepiped and triangular flat panels. The calculation process defines the critical parameters required for calculating the blast dynamics. The results of this chapter are the inputs to the mathematical processes in Chapter 5.

4.2 SETUP AND GROUND RULES

Before discussing the mathematics of estimating blast effects and structural responses, the coordinate system, conventions, and ground rules must be established; these are necessary to maintain the basic continuity of the mathematics and directional order of the geometry. The chosen coordinates are the Cartesian coordinate system that consists of three orthogonal axes commonly labeled X, Y, and Z, as shown in Figure 4-1. The red arrows show the positive direction for angular forces and accelerations parallel to the axes; the circular arrows show the positive direction for angular forces and accelerations about the axes. This setup follows the right-hand rule where when you extend the thumb of the right hand and curl the fingers to the palm and point the thumb in the positive direction of a given axis, then the curled fingers indicate the positive direction of rotation about the axis.

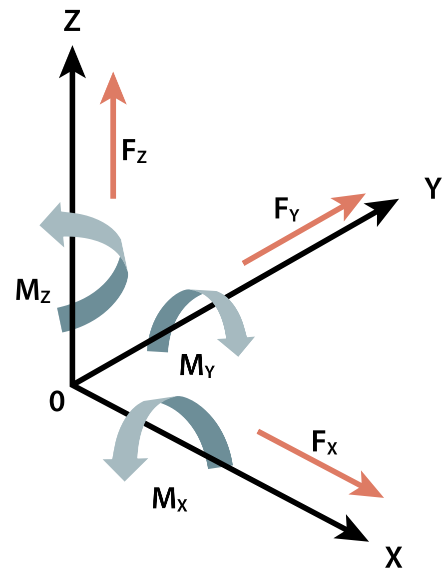

Figure 4-1. Cartesian Coordinates System.

All of the target and reflection surface geometries are contained in what is called the "first octant," where all of the coordinates have positive values; any negative coordinate contained in a reflection surface geometry exceeds the boundaries of that portion of the model and can cause singularities in the calculation, rendering the model suspect if not useless. Figure 4-2 shows the boundary planes XY, YZ, and ZX with a vehicle hull suspended above the XY plane; the vertical offset is set to the minimum clearance between the vehicle hull and the road. The offsets for the remaining planes, YZ and ZX, are a matter of mathematical convenience and depend on other reflecting surfaces in the scenario represented. In the scenario illustrated, the charge is surface mounted and positioned at $Z = 0$; for buried charges the charge will be below the XY plane at $Z < 0$. The procedure for calculating the blast dynamics often requires that the normal to the surface at the point of incidence of the shock wave be calculated based on the normal form of the equation of the plane. Consequently, the origin of the coordinate system $P(0, 0, 0)$ can never be within the boundaries of the surface of interest; this condition causes a divide by zero error.

The target must be offset from the boundary planes, as shown in Figure 4-2, to avoid ambiguities in the calculation.

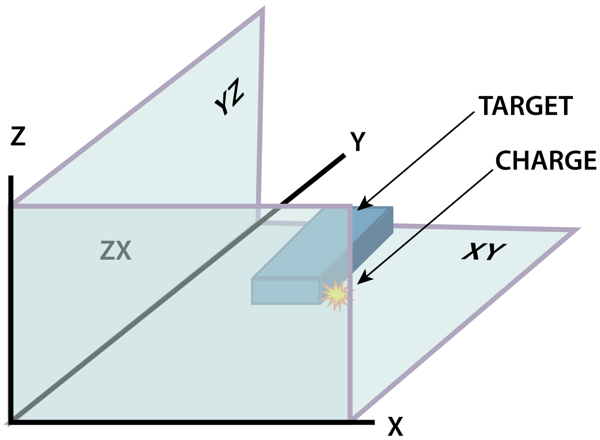

Figure 4-2. The Relationships Between Target, Charge, and Global Coordinates.

4.3 VEHICLE GEOMETRY

Armored ground vehicles are made from thick steel or aluminum plate, with the primary armor enclosing the crew compartment and critical equipment. Armor plate is not easily formed into a curved surface; armored vehicles are generally fashioned out of a collection of flat panels. Each panel can be described by a combination of parallelograms and triangles. Figure 4-3 shows the two panel types.

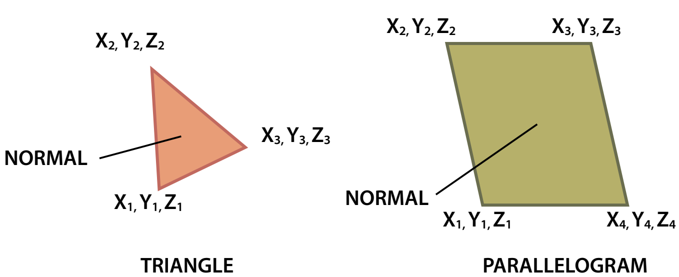

Figure 4-3. Panel Types.

The panels are described by the *general form* of the equation of a plane.

$$Ax + By + Cz + 1 = 0. \qquad (1)$$

A, B, and *C* are the direction the numbers of the plane; these numbers form the direction cosines for the normal to the plane when divided by the square root of the sum of their squares, resulting in the *normal form* of the equation of a plane.

$$x \cos\alpha + \cos\beta + z \cos\gamma = \rho. \qquad (2)$$

The point 0, 0, 0 cannot satisfy equation 1; therefore, to satisfy equation 1, the plane cannot pass through point 0, 0, 0. The purpose of the previously discussed offset scheme is to avoid this condition.

It takes three points—$P1(X_1, Y_1, Z_1)$, $P2(X_2, Y_2, Z_2)$, and $P3(X_3, Y_3, Z_3)$—to define a plane, regardless of the shape of its perimeter. The three conditions that follow provide simultaneous solutions for direction numbers *A, B, C.* The three points of a flat plane parallel to any of the boundary planes yield an ambiguous solution from the simultaneous equation process. The normal to the plane is determined by inspecting the geometry of the condition; when one of the coordinates in the three points has the same value from point to point, the normal to the plane is that coordinate axis.

For example:

1. If $x_1 = x_2 = x_3$, then the normal is always parallel to the x-axis and $\cos\alpha = 1$, $\cos\beta = 0$, and $\cos\gamma = 0$.
2. If $y_1 = y_2 = y_3$, then the normal is always parallel to the y-axis and $\cos\alpha = 0$, $\cos\beta = 1$, and $\cos\gamma = 0$.
3. If $z_1 = z_2 = z_3$, then the normal is always parallel to the z-axis and $\cos\alpha = 0$, $\cos\beta = 0$, and $\cos\gamma = 1$.

Apart from these conditions, the normal to the plane can be determined by equations 3 and 4 using the simultaneous equation process for three unknowns. By entering the general coordinates of the three points defining the plane into the general form of the equation of a plane (equation 1), equations 3–5 are generated as follows:

$$Ax_1 + By_1 + Cz_1 + 1 = 0\,. \tag{3}$$

$$Ax_2 + By_2 + Cz_2 + 1 = 0\,. \tag{4}$$

$$Ax_3 + By_3 + Cz_3 + 1 = 0\,. \tag{5}$$

It follows that by the method of simultaneous equations, equations 6–8 are the direction numbers A, B, and C for the normal to the plane.

$$\boldsymbol{A} = \frac{-(y_2 - y_1)(z_2 y_3 - z_3 y_2) + (y_3 - y_2)(z_1 y_2 - z_2 y^1)}{(x_1 y_2 - x_2 y_1)(z_2 y_3 - z_3 y_2) - (x_2 y_3 - x_3 y_2)(z_1 y_2 - z_2 y_1)}. \tag{6}$$

$$\boldsymbol{B} = \frac{-(z_2 - z_1)(x_2 z_3 - x_3 z_2) - (z_2 - z_3)(x_1 z_2 - x_2 z_1)}{(y_1 z_2 - y_2 z_1)(x_2 z_3 - x_3 z_2) - (y_2 z_3 - y_3 z_2)(x_1 z_2 - x_2 z_1)}. \tag{7}$$

$$\boldsymbol{C} = \frac{-(x_2 - x_1)(y_2 x_3 - y_3 x_2) + (x_3 - x_2)(y_1 x_2 - y_2 x_1)}{(z_1 x_2 - z_2 x_1)(y_2 x_3 - y_3 x_2) - (z_2 x_3 - z_3 x_2)(y_1 x_2 - y_2 x_1)}. \tag{8}$$

The direction cosines for the direction angles α, β, and γ are the derived equations 9–11.

$$\boldsymbol{cos\alpha} = \frac{A}{\sqrt{A^2 + B^2 + C^2}}. \tag{9}$$

$$\boldsymbol{cos\beta} = \frac{B}{\sqrt{A^2 + B^2 + C^2}}\,. \tag{10}$$

$$\boldsymbol{cos\gamma} = \frac{C}{\sqrt{A^2 + B^2 + C^2}}\,. \tag{11}$$

4.4 PARALLELEPIPED PANEL

Once the boundaries, aspect, and normal to the plane have been established, the plane is divided into discrete areas to examine effects of blast on the surface of the panel. Equations 12–14 show the relationships for the total and incremental areas of the parallelepiped panel. Equation 15 determines the angle θ required to calculate total and incremental areas of the panel. Figure 4-4 diagrams the geometry.

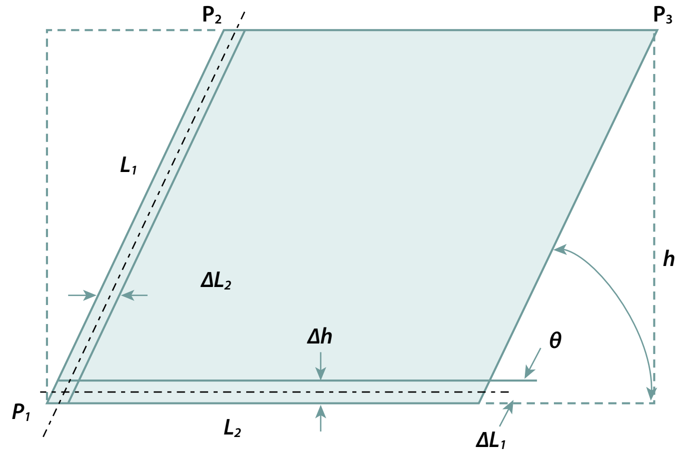

Figure 4-4. Parallelogram Panel.

The area of a parallelogram is

$$A = L_2 h. \tag{12}$$

Similarly, the incremental area is

$$\Delta A = \Delta L_2 \Delta h, \tag{13}$$

$$\Delta h = \Delta L_1 sin(\theta), \tag{14}$$

and

$$cos\theta = cos\alpha_1\, cos\alpha_2 + cos\beta_1\, cos\beta_2 + cos\gamma_1\, cos\alpha\gamma_2, \tag{15}$$

where the symmetric equations for lines L_1 and L_2 are

$$Cos\alpha_1 = (x_2 - x_1)/d_1;\ cos\beta_1 = (y_2 - y_1)/d_1;\ cos\gamma_1 = (z_2 - z_1)/d_1, \tag{16}$$

$$Cos\alpha_2 = (x_3 - x_2)/d_2;\ cos\beta_2 = (y_3 - y_2)/d_2;\ cos\gamma_2 = (z_3 - z_2)/d_2, \tag{17}$$

$$\boldsymbol{d_1} = \sqrt{((x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2)}, \tag{18}$$

and

$$\boldsymbol{d_2} = \sqrt{((x_3 - x_2)^2 + (y_3 - y_2)^2 + (z_3 - z_2)^2)}. \tag{19}$$

Generally, the major panel dimensions range from 1 to 7 m, with areas on the order of 14,000,000 mm²; it is not unusual to have incremental areas numbering in the 35,000s for a major panel with ΔL_1 and ΔL_2 ~20 mm. The centroid of each incremental area is surveyed to determine the shock load at the centroid at the time of observation.

4.4.1 Surveying the Panel

At each time step, T_h, every increment of each illuminated panel is surveyed to determine the incident pressure acting at each centroid. For a parallelogram, the centroids are on a line parallel to line 2, with an offset distance of $\frac{\Delta h}{2}$ and spaced in intervals of ΔL_2 along the line. The coordinates for each centroid (equations 20–22) are as follows:

$$x_{ij} = x_i + \left(i\Delta h - \frac{\Delta h}{2}\right)cos\alpha_1 + \left(j\Delta L_2 - \frac{\Delta L_2}{2}\right)cos\alpha_2. \qquad (20)$$

$$y_{ij} = y_i + \left(i\Delta h - \frac{\Delta h}{2}\right)cos\beta_1 + \left(j\Delta L_2 - \frac{\Delta L_2}{2}\right)cos\beta_2. \qquad (21)$$

$$z_{ij} = z_i + \left(i\Delta h - \frac{\Delta h}{2}\right)cos\gamma_1 + \left(j\Delta L_2 - \frac{\Delta L_2}{2}\right)cos\gamma_2. \qquad (22)$$

The upper limits of i and j are n_i and n_j, respectively. The constant C is specified by the analyst.

$$n_i = INT\left(\frac{L_1}{C}\right). \qquad (23)$$

$$\Delta h = \frac{L_2}{n_j}\, sin\theta. \qquad (24)$$

$$n_j = INT\left(\frac{L_2}{C}\right). \qquad (25)$$

$$\Delta L_2 = \frac{L_2}{n_j}. \qquad (26)$$

4.5 TRIANGULAR PANEL

The geometry of a triangular panel is shown in Figure 4-5. Generally, the triangular panel dimensions range from 1/2 to 2 m on a side, with areas on the order of 1,000,000 mm². It is not unusual to have incremental areas numbering in the 2,500 for a major panel with Δh and ΔL_i ~20 mm. The centroid of each incremental area is surveyed to determine the shock load at the centroid at the time of observation.

The area of a triangle is

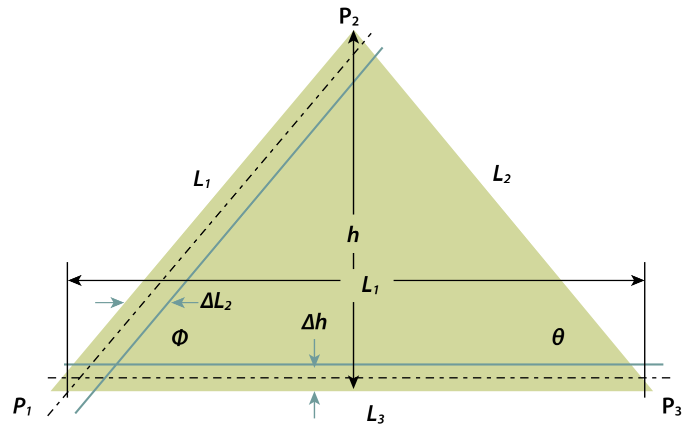

Figure 4-5. Triangular Panel.

$$A = \frac{L_3 h}{2}, \qquad (27)$$

where

$$h = L_1\, sin\varphi. \qquad (28)$$

Similarly, the incremental area is

$$\Delta A = \frac{\Delta L_1 \Delta h}{2}. \qquad (29)$$

The cosines of the angles are

$$Cos\varphi = cos\alpha_1\, cos\alpha_3 + cos\beta_1\, cos\beta_3 + cos\gamma_1\, cos\alpha\gamma_3, \qquad (30)$$

and

$$Cos\theta = cos\alpha_2\, cos\alpha_2 + cos\beta_2\, cos\beta_2 + cos\gamma_2\, cos\alpha\gamma_2, \qquad (31)$$

where the symmetric equations for lines L_1, L_2, and L_3 are

$$Cos\alpha_1 = (x_2 - x_1)/d_1;\ cos\beta_1 = (y_2 - y_1)/d_1;\ and\ cos\gamma_1 = (z_2 - z_1)/d_1, \qquad (32)$$

$$Cos\alpha_2 = (x_3 - x_2)/d_2;\ cos\beta_2 = (y_3 - y_2)/d_2;\ and\ cos\gamma_2 = (z_3 - z_2)/d_2, \qquad (33)$$

and

$$Cos\alpha_3 = (x_1 - x_3)/d_3;\ cos\beta_3 = (y_1 - y_3)/d_3;\ and\ cos\gamma_3 = (z_1 - z_3)/d_3, \qquad (34)$$

and

$$d_1 = \sqrt{((x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2)}, \tag{35}$$

$$d_2 = \sqrt{((x_3 - x_2)^2 + (y_3 - y_2)^2 + (z_3 - z_2)^2)}, \tag{36}$$

and

$$d_3 = \sqrt{((x_1 - x_3)^2 + (y_1 - y_3)^2 + (z_1 - z_3)^2)}. \tag{37}$$

4.5.1 Surveying the Panel

At each time step, T_h, every increment of each illuminated panel is surveyed to determine the incident pressure acting at each centroid of an element. The centroids of elements on a triangular panel are on a line parallel to line 3, with an offset distance of $\left(n\Delta h - \frac{\Delta h}{2}\right)$ and spaced in intervals of ΔL_i along the line; the Δh and ΔL_i change as the index i increases; the coordinates for each centroid (equations 38–40) are as follows:

$$x_{ij} = x_1 + \left(i\Delta h - \frac{\Delta h}{2}\right)cos\alpha_1 + \left(j\Delta L_i - \frac{\Delta L_i}{2}\right)cos\alpha_3, \tag{38}$$

$$y_{ij} = y_1 + \left(i\Delta h - \frac{\Delta h}{2}\right)cos\beta_1 + \left(j\Delta L_i - \frac{\Delta L_i}{2}\right)cos\beta_3, \tag{39}$$

and

$$z_{ij} = z_1 + \left(i\Delta h - \frac{\Delta h}{2}\right)cos\gamma_1 + \left(j\Delta L_i - \frac{\Delta L_i}{2}\right)cos\gamma_3, \tag{40}$$

where

$$L_i = L_3 - \left(i - \frac{1}{2}\right)\Delta h\left(cot\varphi + cot\theta\right). \tag{41}$$

4.6 CRITICAL GEOMETRIC PARAMETERS

The critical parameters required to determine blast load at a specific point on an illuminated surface are the time of observation, the angle of incidence, and the distance from the center of the charge to the point of contact. The time of observation is the time elapsed from the initiation of the charge as determined by the analyst. The time of observation is a series of time steps generally 20–30 µs long, covering a total time period of 150 ms from initiation of the charge.

Figure 4-6 shows the basic geometry of a particular blast-panel scenario.

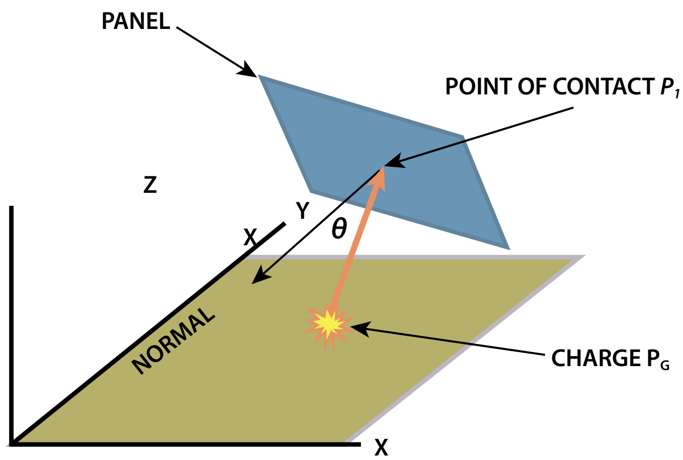

Figure 4-6. Blast-Panel Scenario.

The distance from the point of contact to the center of the charge and the angle of obliquity, θ, along with the time of observation, are the independent variables for the calculation of the pressure impinging the panel at the point of incidence on the panel.

4.6.1 Distance From the Charge

P_{ij} is the point of incidence, and P_c is the center of the charge; it follows that the distance d_{ij} is

$$d_{ij} = \sqrt{((x_{ij} - x_c)^2 + (y_{ij} - y_c)^2 + (z_{ij} - z_c)^2)}. \tag{42}$$

4.6.2 Angle of Obliquity

From equations 9–11 for the angle θ from symmetric equations for the normal to the surface N, and the $line_{ij}$ are as follows:

$$Cos\theta = cos\alpha_{ij}\, cos\alpha_n + cos\beta_{ij}\, cos\beta_n + cos\gamma_{ij}\, cos\gamma_n. \tag{43}$$

4.6.3 Angle of Incidence

The angle of incidence φ is defined as follows:

$$\varphi = \frac{\pi}{2} - \theta. \tag{44}$$

4.7 SUMMARY

This chapter has shown the analytical processes for describing the reflective surfaces of a structure comprised of multiple planar facets. The equations set forth are basic analytical geometry and are well known; they can be found in any textbook expounding analytical geometry or introductory calculus. The equations date back to the ancient Greek philosopher Pythagoras and the 17th century French philosopher and mathematician René Descartes; the author recommends reading the first section of McCrea [1].

This completes the geometric aspects of the blast-target scenario; the analysis of the blast load at the point of contact is examined in Chapter 5.

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1. McCrea, W. H. *Analytical Geometry of Three Dimensions.* Second Ed., Dover, NY, 2006.

CHAPTER 5. CALCULATION OF THE SIX DEGREES OF FREEDOM GLOBAL LOADS ON A VEHICLE

5.1 INTRODUCTION

This chapter deals with the impinging shock wave at the target's surface. Unlike the analyses in Chapter 4, where the equations are derived directly from analytical geometry, the analyses in Chapter 5 rely totally on empirical equations that are time sensitive. This is especially true for the equations dealing with the near-field shock wave environment. Consequently, the analyst must reexamine the state of the art every few years before he or she starts a new analysis. Because of the great expense of experimentation and associated measurement difficulties, the pace of research in blast is dependent on federal funding and congressional mandates that are, in turn, dependent on social and political priorities and perceived foreign threats. Consequently, what follows is based on engineering judgment concerning the most appropriate, current practice. For ground vehicles, the most common scenarios encountered are the surface-mounted charges and the buried charges within the footprint of the hull or crew compartment of the vehicle. The surface-mounted charge is discussed here because there is a significant amount of experimental data from which general equations have been developed to estimate the blast parameters.

5.2 ASSUMPTIONS AND UNITS

To establish more common bases for interpreting the calculations in this chapter, the assumptions and units that follow are presented and based on the analyses in McCrea [1] and von Mises [2].

5.2.1 Assumptions

The following assumptions are made concerning blast waves:

1. Blast waves are strong shock waves that travel at velocities much greater than the speed of sound.
2. There are no transfers of mass across the shock front.
3. Shock waves are energy that is reflective rather than diverting flow; shock wave behavior is analogous to the behavior of light rather than the behavior of fluid flow.
4. The reflection is assumed to be perfect, where the angle of reflection is the same as the angle of incidence. The transfer of energy in the reflection process and the dynamic behavior of the shock wave are not sufficiently understood to develop an adequate theory nor is the means available to measure the rates of energy that occur.
5. The reflective pressure of a perfect reflection follows the sum of the products of the cosine squared times normal reflective pressure and the sine squared times the side-on pressure at the angle of obliquity, θ, for a point of incidence on an infinite plane. Since the majority of incident points are away from panel edges, the assumption is made for all points of incidence on the vehicle.
6. The Hopkinson scaling law is assumed to be appropriate for these engineering calculations.
7. The negative pressure region is ignored.
8. The surface charge forms hemispherical shock waves with double the energy of a free-air blast from a charge of the same mass.
9. The surface is assumed to be directly illuminated.
10. The formulations that follow are based on the assumption that the mass of the charge is 1 kg.
11. The panels that are not directly illuminated do not introduce significant effects.

Table 5-1 defines the units of measure that will be used in the equations that follow.

Table 5-1. Table of Units

Measure	Description	Units
R	Range (length) in meters	m
m	Mass in kilograms	kg
T	Time in milliseconds	ms
ΔT	Incremental time in microseconds	µs
V	Shock front velocity in meters per millisecond	m/ms
A	Area of panel in square meters	m^2
ΔA	Incremental area in square millimeters	mm^2
P	Pressure in kilopascals	kPa
I_O	Moment of inertia about the CG	kgf
J	Impulse in kilo Newtons – milliseconds	kgf-ms
M_O	Moment about the CG – kilo Newtons – m-ms	Kgf-m-ms
J_O	Torsional impulse about the CG	Kgf-m-ms
θ	Angle in radians	rad
ω	Angular velocity in radians per milliseconds	rad/ms
$\dot{\omega}$	Angular acceleration in radians per square meters	rad/ms^2
Z	Range divided by the cube root of charge mass	$m/kg^{1/3}$

5.3 THE TIME WINDOW OF CONTACT

The first order of business is to determine the time window when the shock wave will be at a point of contact on the vehicle surface. Figure 5-1 shows the timeline for shock wave contact at a point of contact. The time window at a specific point on the surface of the target is the time from the time of arrival, T_a, to the end of the positive pulse duration, T_d. Then the time of observation, T_v, is within the time window the shock wave is reflecting off the surface at the point of contact; prior to the time of arrival and after the pulse duration, there is no contact (neglecting the negative pulse duration) with the shock wave at that point.

5.3.1 Time of Arrival

The time of arrival, T_a, is calculated by the empirical equations presented in Army TM 5-855-1 [3]. The time of arrival in milliseconds is evaluated by equations 45–47.

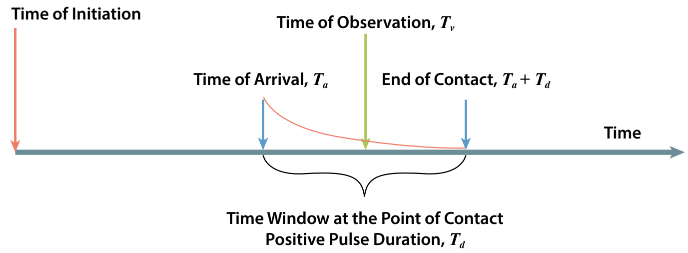

Figure 5-1. Contact Timeline.

T = log R and R = the range from the center of the charge

Range of applicability: 0.0674 to 40.0 m

$$U = 0.202425716178 + 1.37784223635\mathbf{T}. \tag{45}$$

$$\begin{aligned}\log T_a = &-0.0591634288046 + 1.35706496258U + 0.052492798645U^2 \\ &- 0.196563954086U^3 - 0.0601770052288U^4 + 0.0696360270891U^5 \\ &+ 0.0215297490092U^6 - 0.0161658930785U^7 - 0.00232531970294U^8 \\ &+ 0.00147752067524U^9.\end{aligned} \tag{46}$$

$$T_a = 10^{\log T_a}. \tag{47}$$

5.3.2 Positive Pulse Duration

The positive pulse duration, T_d, is calculated by the equations presented in Army TM 5-855-1 [3]. The positive pulse duration in milliseconds is evaluated for three different range groups by equations 48–54. The definitions of ***T*** and ***R*** remain the same.

Range Interval 1 Range of applicability: 0.178 to 1.01 m

$$U = 1.92946154068 + 5.25099193925\mathbf{T}. \tag{48}$$

$$\begin{aligned}\log T_d = &-0.614227603559 + 0.130143717675U + 0.134872511954U^2 \\ &+ 0.0391574276906U^3 - 0.00475933664702U^4 - 0.00428144598008U^5.\end{aligned} \tag{49}$$

Range Interval 2   Range of applicability: 1.01 to 2.78 m

$$U = -2.12492525216 + 9.2996288611T. \tag{50}$$

$$\log T_d = 0.315409245784 - 0.0297944268976U + 0.030632954288U^2$$
$$+ 0.0183405574086U^3 - 0.0173964666211U^4 - 0.00106321963633U^5$$
$$+ 0.0056206003977U^6 - 0.0001618217499U^7 - 0.0006860188944U^8. \tag{51}$$

Range Interval 3   Range of applicability: 12.78 to 40.0 m

$$U = 3.53626218091 + 3.46349745571T. \tag{52}$$

$$\log T_d = 0.686906642409 + 0.0933035304009U - 0.0005489420883U^2$$
$$- 0.00226884995013U^3 - 0.00295908591505U^4 - 0.00148029868929U^5. \tag{53}$$

$$T_d = 10^{\log T_d}. \tag{54}$$

5.3.3 Time Window of Illumination

Because of the reflective nature of the shock wave, the shock wave can be in contact with the target at a specific point of contact only during a specific interval of time. If the time of observation, T_v, is outside that time interval, there is no contact at that particular point; the effective pressure, P_e, is zero. The logic is expressed as follows:

$$\text{If } T_a < T_v \text{ and } T_v < (T_a + T_d), \tag{55}$$

then

$$P_e = P_r\left(e^{-c\left(\frac{T_v - T_a}{T_d}\right)}\right) \tag{56}$$

else

$$P_e = 0. \tag{57}$$

The peak pressure of the pulse is the reflected pressure, P_r.

5.4 REFLECTED PRESSURE

The reflected pressure is a function of the side-on pressure, the normal reflected pressure, and the angle of obliquity. The reflected pressure is that pressure sensed by the target at the point of contact. The reflected pressure is a combination of the side-on pressure, P_{so}, and the normal reflective pressure, P_{nr}, modified by the effects of the angle of obliquity, θ, between the ray to the charge and the normal to the surface. There are two commonly used functional forms used to parametrically estimate the pressures at specific ranges. Both forms are determined by fitting the respective functions to existing experimental data. The form put forth is an exponential function where the side-on pressure is the product of the reference pressure times the ratio of the range to the point of contact to a reference range raised to a negative power.

Equation 58 is the exponential form of the side-on blast pressure based on the near-field portion of the data presented by Goodman [4] and Baker [5].

$$P_{so} = \left(\frac{R}{R_0}\right)^{-1.45}. \tag{58}$$

5.4.1 Normal Reflective Pressure

$$P_{nr} = 22P_{so}\left(\frac{R}{R_0}\right)^{-.5}. \tag{59}$$

Figure 5-2 shows a normalized plot of P_{so} and P_{nr} at the R to R_0 ratio.

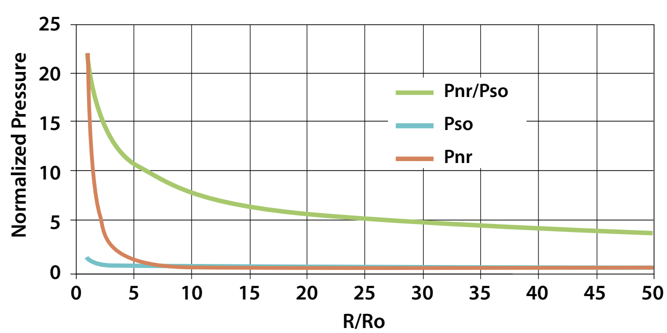

Figure 5-2. Comparison of P_{so} to P_{nr} and P_{nr}/P_{so}.

5.4.2 Effect of Angle of Obliquity

Other than providing the normal reflective pressure, most current theories for reflective pressure do not provide the direct calculation of effects due to the angle of incidence or obliquity [5]. The effective pressure, P_E, at a point on the surface of a target is also dependent on the angle of obliquity, θ, between the ray emanating from the center of the charge to the point on the surface and the normal to the surface at the same point. Figure 4-6 in Chapter 4 shows the geometry of an oblique attack. The calculation of the sensed pressure can be between the magnitudes of P_{nr} and P_{so} and is dependent on θ. Since there has not been any theory verified from experimental data, the model of obliquity effects is an engineering judgment call but must be based on sound physical reasoning. This means that while accuracy is obtainable, precision is modest at best. With the difficulties of measurement, replicating tests, and validating models, 10% agreement between estimate and measurement is obtainable. There are three basic assumptions to be made; they are as follows:

1. There are a sufficient number of incremental areas displaced away from surface discontinuities such that turbulence effects can be ignored and planar surfaces are infinite.
2. The energy delivered by the shock is proportional to the square of the velocity normal to the surface.
3. The independent pressures, P_{so} and P_{nr}, are orthogonal and coalescent.

The chart in Figure 5-3 illustrates the problem. The green curve shows the cosine square model, and the blue curve shows some of the Brode data [2, 3, 5]. The pink curve shows the difference between the blue and green curves. There are plausible reasons for the behavior indicated by the pink curve, but none of them have been verified. The cosine square model described by equation 60 fits the assumptions.

$$P_r \cong P_{nr}\,(\cos\theta\,)^2 + P_{so}\,(\sin\theta\,)^2. \tag{60}$$

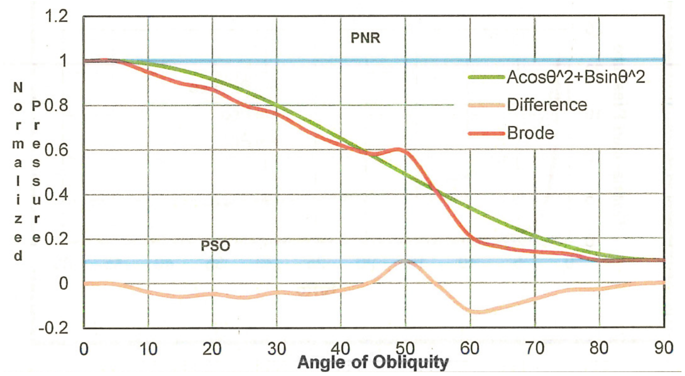

Figure 5-3. Comparison of Cosine Squared Model With Data.

5.5 GLOBAL 6DOF REFERENCE - CENTER OF GRAVITY

The effective pressure impinging the surface at the point of contact generates force that is directed in the general direction toward the CG of the vehicle. The magnitude of the force is the product of the effective pressure times the area of the impinged element. The direction of the force is perpendicular to the element and thereby parallel to the normal to the element, as shown by equation 40.

5.5.1 Global Force Components

$\overline{F_n}$ is the force vector parallel to the normal vector, $\overline{N_n}$. The instantaneous force components are f_{xn}, f_{yn}, and f_{zn}. The letters m and n are the general indexes for time of observation, T_{vm}, and the area element, ΔA_n. $Sig(\,)$ is the function that defines the sign of the direction.

$$\left.\begin{aligned} \overline{F_n} &= P_{en}\,\Delta A_n\,\overline{N_n} \\ f_{xn} &= sig(\,x_{cg} - x_n)\,P_{en}\Delta A_n\,\cos\alpha_n \\ f_{yn} &= sig(\,y_{cg} - y_n\,)\,P_{en}\,\Delta A_n\,\cos\beta_n \\ f_{zn} &= sig(\,z_{cg} - z_n\,)\,P_{en}\,\Delta A_n\,\cos\gamma_n \end{aligned}\right\}. \tag{61}$$

5.5.2 Summation of Forces vs. Time

The force components are summed together for each time step for each x, y, z direction, as shown in equation 41. The form used for the summations requires much less storage space.

$$\left.\begin{aligned} Fx_m &= \textstyle\sum_1^{n-1} f_{xn} + f_{xn} \\ Fy_m &= \textstyle\sum_1^{n-1} f_{yn} + f_{yn} \\ Fz_m &= \textstyle\sum_1^{n-1} f_{zn} + f_{zn} \end{aligned}\right\}. \qquad (62)$$

5.5.3 Global Moment Components

The instantaneous components of moment about the CG are given in equation 42; L_n is the lever arm from the CG to the force.

$$\left.\begin{aligned} M_n &= \overline{L_n F_n} \\ \mu_{xn} &= (y_n - y_{cg}) f_{zn} \\ \mu_{yn} &= (z_n - z_{cg}) f_{xn} \\ \mu_{zn} &= (x_n - x_{cg}) f_{yn} \end{aligned}\right\}. \qquad (63)$$

5.5.4 Summation of Moments vs. Time

The global moment components are summed together for each time step for each x, y, z direction, as shown in equation 41. The form used for the summations requires much less storage space.

$$\left.\begin{aligned} Mx_m &= \textstyle\sum_1^{n-1} \mu_{xmn} + \mu_{xmn} \\ My_m &= \textstyle\sum_1^{n-1} \mu_{ymn} + \mu_{ymn} \\ Mz_m &= \textstyle\sum_1^{n-1} \mu_{zmn} + \mu_{zmn} \end{aligned}\right\}. \qquad (64)$$

5.5.5 Six Degrees of Freedom Global Blast Loads

The analyses discussed thus far bring us to the point where we can summarize the global forces and moments at the CG of the vehicle at an instance in time. The three forces calculated by equation 41 and the three moments calculated by equation 43 summarize the global 6DOF environment at the CG. This summarization is only applicable to the CG and not to a point in or on any other position of the vehicle. As soon as the position of interest is displaced from the CG, the loading changes in both magnitudes and direction as a function of the global loadings and the dimensions of displacement relative to the CG. These loadings, referred to as "local" loadings, are specific to particular location. Examples of global loadings on a vehicle are shown in Figure 5-4. The loadings are given in acceleration units, where the forces and moments were divided by the vehicle mass and moments of inertia.

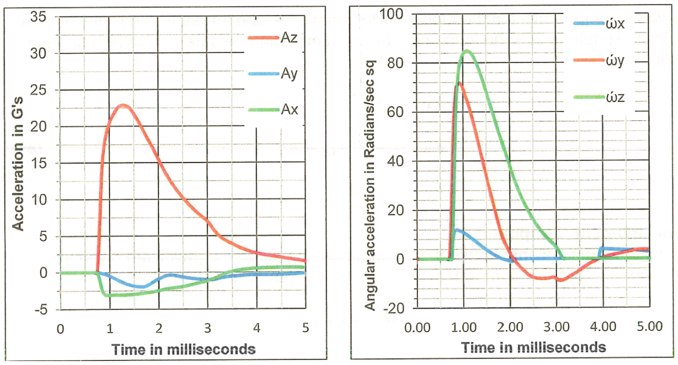

Figure 5-4. Six Degrees of Freedom Loadings at the CG of a Vehicle.

Chapter 6 discusses the analysis of local loads and the structural response at vehicle crewmember positions.

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CHAPTER 6. CALCULATION OF LOCAL AND STRUCTURAL RESPONSES

6.1 INTRODUCTION

To proceed with the analysis beyond the 6DOF force and moment descriptions of vehicle load environment, the loads need to be transformed from forces and moments to linear and angular accelerations, respectfully. Once the transformation is achieved, the local linear and angular acceleration environments may be analyzed to determine the 6DOF environment at the location of interest.

6.1.1 Global Linear Accelerations

From Newton's Second Law, it can be shown that the linear accelerations are

$$\left.\begin{aligned} A_x &= {}^{F_x}\!/_{m} \\ A_y &= {}^{F_y}\!/_{m} \\ A_z &= {}^{F_z}\!/_{m} \end{aligned}\right\}. \tag{65}$$

Note that the mass is the same in all three directions.

6.1.2 Global Linear Velocities

The global linear velocities are the integral of the accelerations with respect to time approximately as the difference of time approaches zero

$$\left.\begin{aligned} V_{xm} &= \sum_{1}^{m-1} A_{xm}\,\Delta T + A_{xm}\,\Delta T \\ V_{ym} &= \sum_{1}^{m-1} A_{ym}\,\Delta T + A_{ym}\,\Delta T \\ V_{zm} &= \sum_{1}^{m-1} A_{zm}\,\Delta T + A_{zm}\,\Delta T \end{aligned}\right\}. \tag{66}$$

6.1.3 Global Angular Accelerations

From Newton's Second Law, it can be shown that the angular accelerations are

$$\left.\begin{aligned} \dot{\omega}_x &= {}^{M_x}\!/_{I_x} \\ \dot{\omega}_y &= {}^{M_y}\!/_{I_y} \\ \dot{\omega}_z &= {}^{M_z}\!/_{z} \end{aligned}\right\}. \tag{67}$$

Note that the moment of inertia is specific for each axis.

6.1.4 Global Angular Velocities

The global angular velocities are the integral of the angular accelerations with respect to time approximately as the difference of time, ΔT, approaches zero:

$$\left.\begin{aligned} \omega_{xn} &= \sum_{1}^{m-1} \dot{\omega}_{xm}\,\Delta T + \dot{\omega}_{xm}\,\Delta T \\ \omega_{yn} &= \sum_{1}^{m-1} \dot{\omega}_{ym}\,\Delta T + \dot{\omega}_{ym}\,\Delta T \\ \omega_{zm} &= \sum_{1}^{m-1} \dot{\omega}_{zm}\,\Delta T + \dot{\omega}_{zm}\,\Delta T \end{aligned}\right\}. \tag{68}$$

6.2 LOCAL ACCELERATIONS

The relative motion of a position within the vehicle that is displaced from the CG of the vehicle is dependent on the distance from the CG and the rates of the pitch, yaw, and roll of the vehicle. These rates of motion generate accelerations that are additional to the global linear motion and significantly change the local environmental from the CG.

6.2.1 Linear Accelerations

The absolute linear accelerations at the displace position are the combination of the global linear accelerations, the local tangential accelerations, and the components of the Coriolis accelerations. The derivations of the Coriolis components are lucidly discussed by Den Hartog [1].

$$\left.\begin{aligned} \bar{A}_x &= {}^{F_x}\!/_{m} + r_z\dot{\omega}_y - r_y\dot{\omega}_z - r_x\,\omega_y^2 - r_x\,\omega_z^2 + \omega_x\,\omega_z\,r_z + \omega_x\,\omega_y\,r_y + 2\omega_y\,V_z + 2\omega_z\,V_y \\ \bar{A}_y &= {}^{F_y}\!/_{m} + r_x\,\dot{\omega}_z - r_z\,\dot{\omega}_x - r_y\,\omega_z^2 - r_y\,\omega_x^2 + \omega_y\,\omega_x\,r_x + \omega_y\,\omega_z\,r_z + 2\omega_z\,V_x + 2\omega_x\,V_z \\ \underbrace{\bar{A}_z}_{\text{Local}} &= \underbrace{{}^{F_z}\!/_{m}}_{\text{Global}} + \underbrace{r_y\,\dot{\omega}_x - r_x\,\dot{\omega}_y}_{\substack{\text{Tangential}\\ \text{Accelerations}}} \underbrace{- r_z\,\omega_x^2 - r_z\,\omega_y^2 + \omega_z\,\omega_y\,r_y + \omega_z\,\omega_x\,r_x + 2\omega_x\,V_y + 2\omega_y\,V_x}_{\text{Coriolis Components Accelerations}} \end{aligned}\right\}, \tag{69}$$

where r_x, r_y, and r_z are the orthogonal distances from the displaced position to the CG. These three equations combine to form a vector of acceleration of magnitude:

$$\ddot{U} = \sqrt{A_x^2 + A_y^2 + A_z^2}. \tag{70}$$

The three direction cosines are

$$cos\alpha_1 = {}^{A_x}\!/_{\ddot{U}},\ cos\beta_1 = {}^{A_y}\!/_{\ddot{U}},\ and\ cos\gamma_1 = {}^{A_z}\!/_{\ddot{U}}, \tag{71}$$

and where $cos\alpha_1$, $cos\beta_2$, and $cos\gamma_2$ are the direction cosines for the normal to the surface at the location. The cosine of the angle between the acceleration vector and the normal vector is

$$cos\varphi = cos\alpha_1\ cos\alpha_2 + cos\beta_1\ co\beta_2 + cos\gamma_1\ cos\gamma_2. \tag{72}$$

The resulting magnitude of the total acceleration parallel to the normal to surface is

$$\ddot{U}_\varphi = \ddot{U}cos\varphi. \tag{73}$$

When the angle φ is zero, the acceleration vector is parallel to the normal and the cosine is 1 and $\ddot{U}_\varphi = \ddot{U}$.

6.2.2 Angular Accelerations

The angular accelerations at a point in the vehicle remote from the CG are identical to the angular accelerations at the CG. The formulations are shown in equation 66.

6.3 LOCAL STRUCTURAL RESPONSE

The vehicle is made of a combination of structural parts that, when excited by an external impulsive force or acceleration, they respond by vibrating at vibration frequencies or modes specific to that part. Each part has several modes of vibration; generally, in engineering practice, the first three modes are considered to be significant. Test measurements indicate higher modes but with much lower magnitudes than the first three modes. The structural response is assumed to be a set of three sinusoidal accelerations whose amplitudes decay with time. Equation 74 shows the coupling between the structural and local response to be expected at a surface of a structural component.

$$\ddot{U}_{tr}(T_v) = \ddot{f}_1(\ddot{U}_\varphi,\omega_1,T_v) + \ddot{f}_2(\ddot{U}_\varphi,\omega_2,T_v) + \ddot{f}_3(\ddot{U}_\varphi,\omega_3,T_v) + \ddot{U}_\varphi(T_v). \tag{74}$$

The term $\ddot{f}_1(\ddot{U}_\varphi,\ \omega_1,\ T_v)$ is a function of the global response and a mode frequency, ω_1, at the location of interest. $\ddot{U}_\varphi$ is the local response as a function of time based on Duhamel's integrals [2]. The method relies on three aspects of structural dynamics: (1) all structural are complex oscillators that have responses in specific frequencies unique to the particular system, (2) the response of the structure is deterministic and repeatable for any given pulse shape, and (3) the response of the structure can be obtained by calculating the response of the discrete frequencies of the system using Duhamel's integral. The acceleration response for mode μ is $\ddot{f}_\mu$, which is determined by the numerical evaluation of Duhamel's integral in equation 75, derived from Crede and Harris [3] and Timoshenko et al. [4].

$$\ddot{f}_\mu = \frac{e^{-c\omega_\mu T_v}}{\omega_\mu} \left\{ \begin{aligned} &\left[\left(\sum_1^n \ddot{U}_n(T_v)\,sin(\omega_\mu T_v)\Delta T\right) cos(\omega_\mu T)\right. \\ &\left. + \left(\sum_1^n \ddot{U}_n(T_v)\,cos(\omega_\mu T_v)\Delta T\right) sin(\omega_\mu T)\right] \end{aligned} \right\}, \tag{75}$$

where $T_v = \sum_1^n n\Delta T - {}^{\Delta T}\!/_2$, $T = \sum_1^n n\Delta T$, μ = mode number, and ω_μ = is the mode frequency in radians/second.

6.3.1 Estimation of Structural Modes

The structural modes can be estimated by the following three different methodologies:

1. Estimations based on calculated static deflections are useful when estimating the dynamic panel responses during and the initial phases of vehicle design and when considering alternative designs of the external design. Equation 76 is derived from the equation in "Roark's Formulas for Stress and Strain" [5]. For flat plates, such as triangles, rectangles, and squares, with all edges constrained either fixed, simple, clamped, or a combination and with evenly distributed weight (including the weight of the plate), we have the following:

$$\omega_1 = 1.2769 \sqrt{g/\dot{\delta}}\,, \qquad (76)$$

where ω = radians/s, g = 386.4 in/s, and $\dot{\delta}$ = static deflection at the centroid in inches.

The static deflection is the y_{max} formulation shown in Table 11.4 of Young and Budynas [5] for the specific plate shape and conditions examined. Examining the constant multipliers for the different mode frequencies in references 2–4, the following coefficients were developed for modes 2 and 3. The estimated error in frequency is expected to be within 4% for each of the three modes.

$$\omega_2 = 2.17\omega_1;\ \omega_3 = 2.87_1. \qquad (77)$$

2. Estimations based on finite-element calculations can be used to determine static deformations; a simple finite-element model of the panel with fixed edges can be used for initial calculations in support of analysis of alternatives (AOA). These calculations can be supplanted prior to testing by a more detailed model of the final design, including the dynamic loading and more concise definition of the edge constraints.

3. Measurements of vibration are surveyed on the full-up vehicle prior to test. The most trustworthy method to obtain the modes of frequency response of the different parts of a structure is to excite the structure with either impulsive or periodic loadings. These processes are described in Crede and Harris [6].

6.3.2 Estimation of Damping

The response of a particular mode for excitation is dependent on the damping characteristics of the structure and material of the structure. In the case of excitation pulses, the damping governs the amplitude of the vibration during excitation and extends the vibration long after excitation has ended (Figure 6-1).

In the figure, the red curve is the excitation pulse, and the pink area indicates the time duration of the pulse; the blue

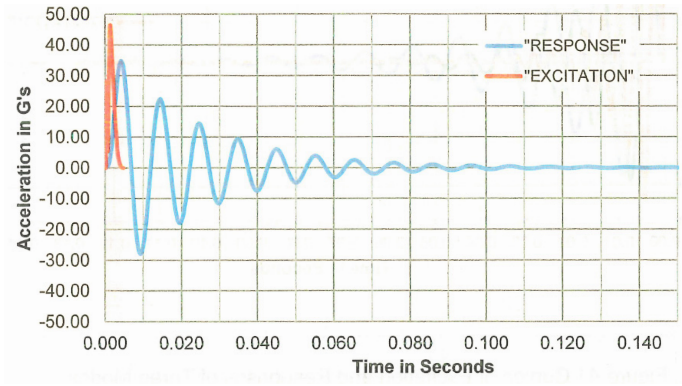

Figure 6-1. Damped Frequency Responses to Excitation.

curve is the response of a moderately damped 100 cycles/second mode frequency. The response during the excitation period is forced damped vibration; the remaining response after duration of the pulse is free damped vibration. The time length of the free vibration depends on the damping. The responses of three modes of vibration and the local linear acceleration are shown in Figure 6-2; each curve represents a term on the right side of equation 75.

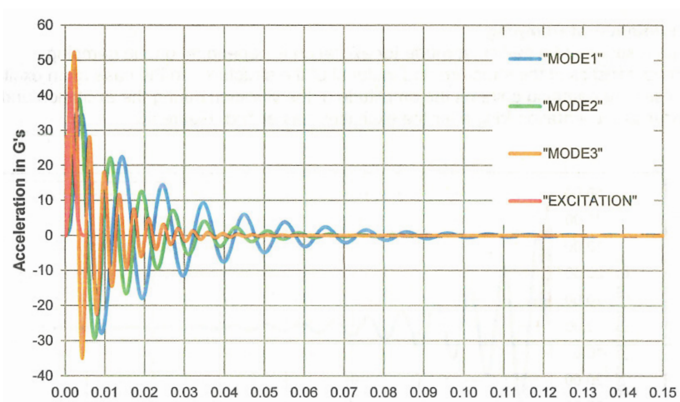

Figure 6-2. Curves of Excitation and Responses of Three Modes.

Figure 6-3 shows the results of equation 75; it should be noted that the maximum acceleration for the combined effect is nearly 120 G's, where the maximum of the separate effects is ~53 G's. The panel for this case was an interior floor panel where the structural responses were excited by the vertical components of the local responses.

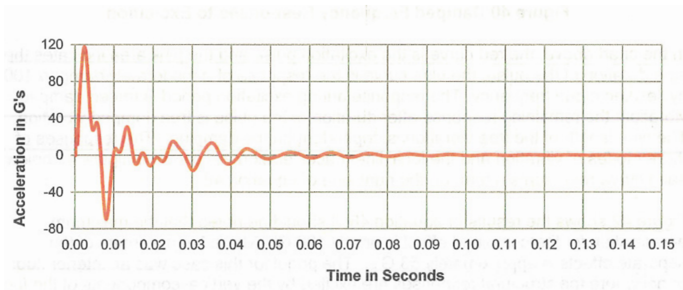

Figure 6-3. Combined Effect of Local Structural Response.

The point on the panel is a mounting point for the seating structure for a crewmember. The total 6DOF description of the accelerations for the point is local x-axis and y-axis local accelerations and all three global angular accelerations and the local and structural response in the z-axis direction.

6.3.3 Environmental Description

The seat structure and crewmember's body are considered to be an articulated, lumped mass system. The degree of articulation depends on the amount of linear constraints between masses, the allowable range of angular motion between masses, and the inherent spring and damping constraints required to describe the assemblage.

The current practice is to calculate the total response at the center of the mounting pattern (Figure 6-4). The assumption is that the effect at the center of the pattern is approximately the average of the effects at the mounting points. The angular accelerations are most affected by the differences in the vertical components at the mounting points. These differences are very difficult to measure and subsequently separate them from the other dynamic effects in the measurement data. In Chapter 9, the vagaries and vicissitudes of measurements will be discussed. Chapters 7 and 8 discuss the visual basic for applications (VBA) implementations of Chapters 4–6.

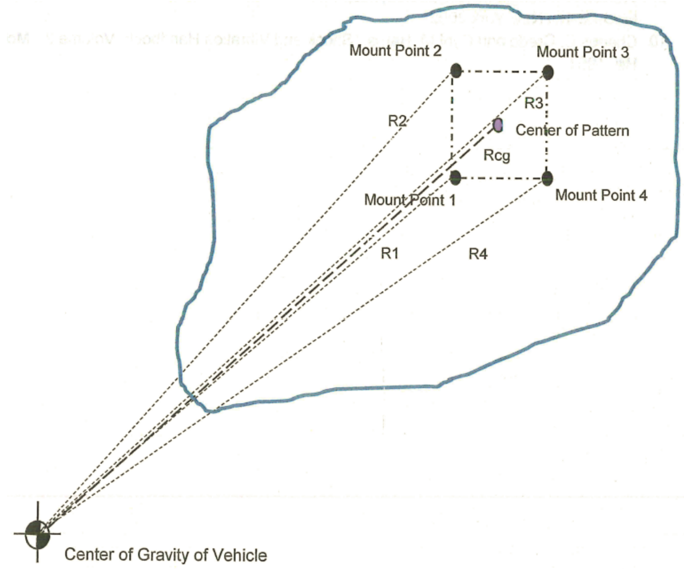

Figure 6-4. Position of a Seat Mounting Pattern Relative to the Vehicle's CG.

REFERENCES

1. Den Hartog, J. P. *Mechanics*. New York: Dover Publications, Inc., 1961.
2. Henry, C. L. "Analysis of Shocks by Numerical Solution of Duhamel's Integral." BRL-MR-3726, U.S. Army Ballistics Research Laboratory, Aberdeen Proving Ground, MD, December 1988.
3. Crede, C. C., and C. M. Harris. *Shock and Vibration Handbook*. New York: McGraw Hill, vol. 1, p. 8-4, 1961.
4. Timoshenko, S., D. H. Young, and W. Weaver, Jr. "Vibration Problems in Engineering." New York: John Wiley & Sons, 4th Ed., p. 98, 1974.
5. Young, W. C., and R. G. Budynas. "*Roark's Formulas for Stress and Strain*." New York: McGraw-Hill, 7th Ed., 2002.
6. Crede, C. C., and C. M. Harris. *Shock and Vibration Handbook*. New York: McGraw-Hill, vol. 2, 1961.

CHAPTER 7. IMPLEMENTATION OF THE CALCULATIONS OF GLOBAL RESPONSE

7.1 INTRODUCTION

This chapter is an annotated presentation of the VBA subroutine "GenVbotTranHouseGlobalResp" to estimate the global blast effects discussed in Chapter 4. The program is implemented on Microsoft Excel 2010. The Excel application is chosen because of its general availability and familiarity with analysts throughout the DoD community. The subroutine elements are written in black font, with the comments in green, as they will not appear in the Macro window. The table of declarations (required for execution of the subroutine) for this and other modules, along with the input tables for this subroutine, is given in the Appendix.

7.2 IMPLEMENTATION

The objective of implementing the equations in Chapters 4 and 5 is to provide estimates of the blast loads on a vehicle hull. The following subroutine calculates the 6DOF global accelerations on a generic vehicle that is exposed to the blast from an explosive charge located on the surface of the ground under the vehicle. The inputs to the subroutine are based on the desired test scenario and the vehicle's surface geometry. This particular implementation is to examine the effects of hull geometry and is appropriate for use in the early design phase for AOA and determining pressure distribution infinite element stress analyses. This implementation does not consider the constraints and reactions of the undercarriage; consequently, the velocity terms are not calculated.

7.2.1 Scenarios

The layout of the test scenarios is shown in Figure 7-1. The intersections of dashed lines show the possible charge positions for analyses; the first and tenth rows are numbered. The layout shows the horizontal position of the charge (red and yellow star), the crewmembers (yellow ovals), the CG (black and white segmented circle), the floor panels (double-lined rectangles), and the transmission housing (gray crosshatched area). The various input tables are in the Appendix. Prior to testing, various scenarios are examined to determine worst-case conditions and estimate the loads for specific test conditions. Not shown in Figure 6-4 in Chapter 6 are the positions of test instrumentation that will be discussed in Chapters 8 and 9.

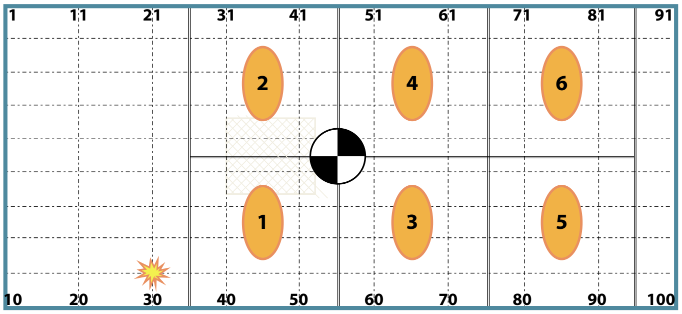

Figure 7-1. Charge Layouts for Scenario 29.

7.2.2 Vehicle Geometry

The primary geometry for this series of calculations is the armored hull and salient features, such as transmission housing. The geometry used in this discussion is a generic v-bottomed hull, with a transmission cover emulating an mine-resistant, ambush-protected type of vehicle. The running gear is not depicted based on the assumption that the free space between the hull and major components of the running gear is sufficient to nullify shadowing effect. The generic vehicle body (vehicle hull with transmission housing) is shown, along with charge position and CG in Figure 7-1.

The vehicle's minimum road clearance is assumed to be 0.4572 m. The charge position with respect to the vehicle reflects the geometry for a contact-activated mine located on the driver's side of the road.

7.3 FLOW CHART

The sequence of calculations and logic of the subroutine and logic of the subroutine "GenVbotTranHouseGlobalResp" is shown in Figure 7-2.

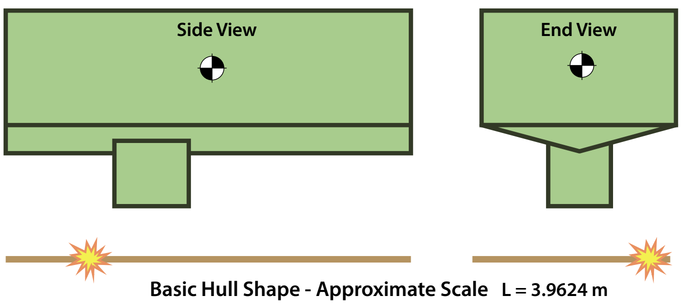

Figure 7-2. Generic Vehicle Body.

The following list describes the steps diagrammed in Figure 7-3.

1. Input
   a) Charge mass
   b) Test geometry, location of the charge with respect to the vehicle
   c) Vehicle geometry, including mass, moments of inertia, and CG
2. Start and increment time of observation
   a) Select first hull panel
   b) Determine incremental area
   c) Determine range to charge
   d) Determine cosines for the normal to the panel
   e) Direction cosines for ray from charge
   f) Determine sine and cosine for angle of obliquity
   g) Determine side-on pressure
   h) Determine normal reflected pressure
   i) Determine reflected pressure
   j) Determine time of arrival
   k) Determine pulse duration
   l) Determine time window
   m) Determine scaled parameters
   n) Accumulate global forces
   o) Accumulate global moments
3. Next panel, perform determinations 2.a–2.q
   a) If last panel, tabulate 6DOF forces and moments
   b) Calculate 6DOF accelerations
   c) Tabulate 6DOF accelerations
   d) Return to step 2
4. If last time step, STOP

Figure 7-3. Flow Charts for "GenericVehicle_GlobalResponse."

7.4 SUBROUTINE

The following pages show the initial portion of the subroutine "GenericVehicle_GlobalResponse." The global response and time duration of the blast are depicted in Figure 7-1. The commands that calculate the forces and accelerations on the first of a series of six illuminated panels are listed; the complete subroutine is not shown. The green fonts are comments and nonfunctioning elements of the procedure. This procedure is based on a 13.636-kg charge mass (~30 lb) in a surface-mounted configuration. The entire subroutine is shown in the Appendix. The pages following the listed code discuss the output of the subroutine.

7.4.1 Output

The following charts, Figures 7-4–7-7, show the global accelerations of the generic vehicle hull for scenario 29 and charge mass of 13.636 kg. These outputs are the inputs to the calculations used to determine the combined local and structural accelerations at different positions in the vehicle, which is the subject of the discussions in Chapter 8. The magnitude of time is determined by using the Hopkinson scaling factor; the ordinal calculated pressures are for a charge of 13.636 kg. The data (forces and moments) can be scaled to represent different masses of charge against the same vehicle geometry and scenario.

```
' GenericVehicle_GlobalResponse Macro.
' Macro recorded 1/24/2015 by James O. Pilcher II.

' Updated 1/24/2015 by James O. Pilcher II.
' This subroutine calculates the 6DOF forces and moments generated by blast on a generic vehicle over the time duration of the blast. The charge is assumed to be under the vehicle mounted in the ground within the footprint of the hull and wheels. The charge mass is 13.636 kg. Only the directly illuminated panels for scenario 29 are implemented in this subroutine. Panels are 2, 3, 4, 7, 8, and 9.

'IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII INITIALIZATION IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII

    CM = 13.636 'Charge mass in kilograms
    S = 29
    TC = 20
    SCF = 2.389
    Xc = 2.2351
    Yc = 1.1176
    Zc = 0
    Xcg = 1.524
    Ycg = 2.134
    Zcg = 1.638
    DelLl = 0.02
    DelL2 = 0.02
    mm = 13636
    Ix = 140233
    Iy = 21622
```

```
    Iz = 139948
    DelTv = 0.005 'time increment in milliseconds
For k = 1 To 3000 'Tv = 0.005 msec to 15 msec
    Tv = I / 200 'time in msec
    Ts = 0.4186 * Tv 'scaled time in milliseconds
    Pe = 0 'Effective pressure
    TFx = 0 'Running total of force in the x direction
    TFy = 0 'Running total of force in the y direction
    TFz = 0 'Running total of force in the z direction
    TMx = 0 'Running total of moment about the x direction
    TMy = 0 'Running total of moment about the y direction
    TMz = 0 'Running total of moment about the z direction
    Po = 18.658 'MPa or K Newtons/square millimeter
    Ro = 0.2043 'meters

'IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII CALCULATIONS IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII
'IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII Hull Panel 2 IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII

    x1 = 0.6096 'the values for x1 through z4 are read from the dimension table in the "Dimensions" spreadsheet.
    y1 = 0.3048 'From dimension tables
    z1 = 1.0866 'From dimension tables
    x2 = 0.6096 'From dimension tables
    y2 = 3.9624 'From dimension tables
    z2 = 1.0866 'From dimension tables
    x3 = 1.4478 'From dimension tables
    y3 = 3.9624 'From dimension tables
    z3 = 0.9144 'From dimension tables
    x4 = 1.4478 'From dimension tables
    y4 = 0.3048 'From dimension tables
    z4 = 0.9144 'From dimension tables

'IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII Rectangular Panel, Length, and Area Increments IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII

    L1 = ((x2 - x1) ^ 2 + (y2 - y1) ^ 2 + (z2 - z1) ^ 2) ^ 0.5
    L1 = ((x2 - x1) ^ 2 + (y2 - y1) ^ 2 + (z2 - z1) ^ 2) ^ 0.5
    L2 = ((x4 - x1) ^ 2 + (y4 - y1) ^ 2 + (z4 - z1) ^ 2) ^ 0.5
    m = L1 / DelL1
    n = L2 / DelL2
    DelA = DelL1 * DelL2 'square meters or 1,000,000 square millimeters
    DelX = (x4 – x1) / n
    DelY = (y2 – y1) / m
    DelZ = (z4 – z1) / n
```

```
'|||||||||||||||||||||||||||||||||||||||| Range to Charge ||||||||||||||||||||||||||||||||||||||||
For j = 1 To m
  For i = 1 To n
     X = x1 + (i - 1 / 2) * DelX
     Y = y1 + (j - 1 / 2) * DelY
     Z = z1 + (i -1 / 2) * DelZ
     R = ((X - Xc) ^ 2 + (Y - Yc) ^ 2 + (Z - Zc) ^ 2) ^ 0.5
     RS = loge * Log(R) 'In VBA 2010, the function Log() is actually the natural logarithm not the Log base 10.

'|||||||||||||||||||||||||||||||||||||||| The Direction Cosines for the Normal to the Panel ||||||||||||||||||||||||||||||||||||||||

     CSALN = 0.179
     CSBTN = 0
     CSGAMN = 0.984

'|||||||||||||||||||||||||||||||||||||||| Direction Cosines for Ray From Charge ||||||||||||||||||||||||||||||||||||||||

     CSALC = (X - Xc) / R
     CSBTC = (Y - Yc) / R
     CSGAMC = (Z - Zc) / R

'|||||||||||||||||||||||||||||||||||||||| Sine and Cosine for Angle of Obliquity ||||||||||||||||||||||||||||||||||||||||

     CSZETA = CSALC * CSALN + CSBTC * CSBTN + CSGAMC * CSGAMN
If CSZETA > 0.999 Then CSZETA = 1
     SIZETA = (1 - CSZETA ^ 2) ^ 0.5

'|||||||||||||||||||||||||||||||||||||||| Side-on Pressure ||||||||||||||||||||||||||||||||||||||||

Pso = Po * (R / Ro) ^ -1.55

'|||||||||||||||||||||||||||||||||||||||| Normal Reflected Pressure ||||||||||||||||||||||||||||||||||||||||

Pnr = Pso * 22 * (R / Ro) ^ -0.45

'|||||||||||||||||||||||||||||||||||||||| Reflected Pressure ||||||||||||||||||||||||||||||||||||||||

Pr = Pnr * CSZETA ^ 2 + Pso * SIZETA ^ 2

'|||||||||||||||||||||||||||||||||||||||| Pulse Duration ||||||||||||||||||||||||||||||||||||||||

If 0.178 < R <= 1.01 Then
     U = 1.92946154068 + 5.25099193925 * RS
     LGTD = -0.614227603559 + 0.130143717675 * U + 0.134872511954 * U ^ 2 _
     + 0.0391574276906 * U ^ 3 - 0.00475933664702 * U ^ 4 - 0.00428144598008 * U ^ 5
```

```
End If
If 1.01 <= R <= 2.78 Then
    U = -2.12492525216 + 9.2996288611 * RS
    LGTD = 0.315409245784 - 0.0297944268976 * U + 0.030632954288 * U ^ 2 _
    + 0.0183405574086 * U ^ 3 - 0.0173964666211 * U ^ 4 - 0.00106321963633 * U ^ 5 _
    + 0.0056206003977 * U ^ 6 + 0.0001618217499 * U ^ 7 - 0.0006860188944 * U ^ 8
End If
If 2.78 <= R <= 40 Then
    U = -3.53626218091 + 3.46349745571 * RS
    LGTD = 0.686906642409 + 0.0933035304009 * U - 0.0005849420883 * U ^ 2
    - 0.00226884995013 * U ^ 3 - 0.00295908591505 * U ^ 4 + 0.00148029868929 * U ^ 5
End If
    Td = 10 ^ LGTD

'||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||| Time Window |||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||

If (Ta < Tv And Tv < (Ta + Td)) Then
    Pe = Pr * Exp(-TC * (Tv - Ta) / Td) * 10 ^ 6 'Newtons/meter squared
Else
    Pe = 0
End If

'||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||| Scaled Parameters |||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||

    Ts = Tv / SCF
    DelTs = DelTv / SCF

'||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||| Global Forces |||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||

    Fx = Pe * DelA * CSALN 'Newtons
If Xcg > X Then
    Fx = Fx
Else
    Fx = -Fx
End If
    Fy = Pe * DelA * CSBTN 'Newtons
If Ycg > Y Then
    Fy = Fy
Else
    Fy = -Fy
End If
    Fz = Pe * DelA * CSGAMN 'Newtons
If Zcg > Z Then
```

```
    Fz = Fz
Else
    Fz = -Fz
End If
    TFx = TFx + Fx
    TFy = TFy + Fy
    TFz = TFz + Fz

'|||||||||||||||||||||||||||||||||||||||||||||| Global Moments ||||||||||||||||||||||||||||||||||||||||||||||

    Mx = (Y - Ycg) * Fz - (Z - Zcg) * Fy 'Newton-meters
    My = (Z - Zcg) * Fx - (X - Xcg) * Fz 'Newton-meters
    Mz = (X - Xcg) * Fy - (Y -Ycg) * Fx 'Newton-meters
    TMx = TMx + Mx
    TMy = TMy + My
    TMz = TMz + Mz

    Next i
Next j

'|||||||||||||||||||||||||||||||||||||||||||||| Hull Panel 3 ||||||||||||||||||||||||||||||||||||||||||||||

    x1 = 1.4478
    y1 = 0.3048
    z1 = 0.9144
      ---
      ---
      ---
```

Figure 7-4. Initial Portion of Subroutine "GenericVehicle_GlobalResponse."

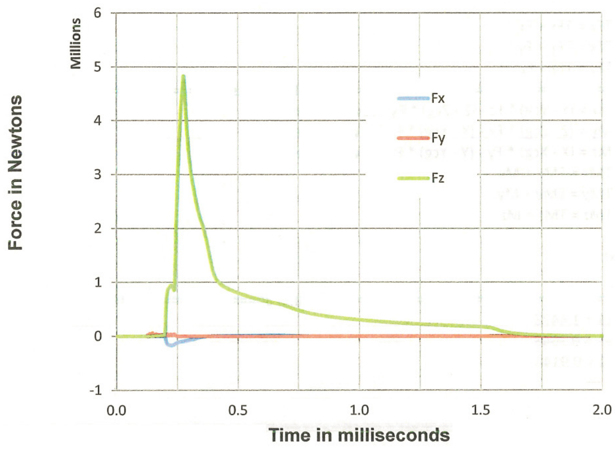

Figure 7-5. Global Linear Forces.

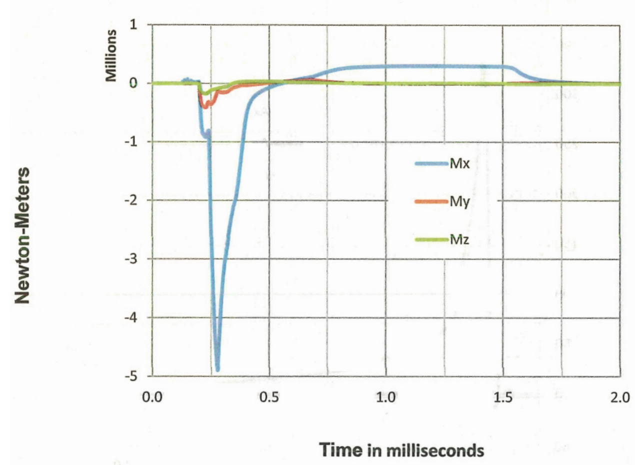

Figure 7-6. Global Moments.

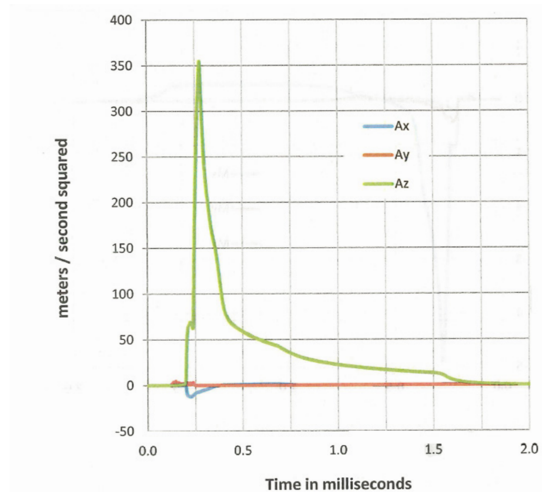

Figure 7-7. Global Linear Accelerations.

The output from these calculations is for a 13.636-kg charge of TNT. The data is shown in 6DOF components to facilitate the calculation of vehicle local response, structural response, and crewmember environments. The scenario examined in this calculation may seem rather survivable, but there are scenarios that, with the same vehicle geometry and charge energy, can increase severity by a factor of 3 or more.

7.4.2 Global Linear Forces

The graph in Figure 7-5 shows the 6DOF components of the linear forces in the three coordinate directions X, Y, and Z relative to time. **Fx** (blue curve) is force that moves the vehicle toward the driver's side when the magnitude is positive or to the passenger's side when the magnitude is negative. **Fy** (red curve) is the force that moves the vehicle backward when the magnitude is positive or forward when the magnitude is negative. **Fz** (light-green curve) is the force that moves the vehicle upward when that magnitude is positive or downward when the magnitude is negative.

The shapes of three curves are governed by the geometry of the vehicle surfaces and the position of the charge with respect to the vehicle. If either the vehicle geometry or charge position or both are changed, the shapes of the curve will change. The magnitude of the curves will change linearly proportional to the Hopkinson scaling factor, but the shapes will not be affected.

7.4.3 Global Moments

The graph in Figure 7-6 shows the 6DOF components of the moments about the three coordinate directions X, Y, and Z relative to time. **Mx** (blue curve) is the pitch moment that rotates the vehicle nose down when the magnitude is positive or nose up when the magnitude is negative. **My** (red curve) is the roll moment that rotates the vehicle driver side up when the magnitude is negative or driver side down when the magnitude is positive. **Mz** (light-green curve) is the yaw moment that rotates the vehicle left when that magnitude is positive or right when the magnitude is negative.

The shapes of three curves are governed by the geometry of the vehicle surfaces and the position of the charge with respect to the vehicle. Again, if either the vehicle geometry or charge position or both are changed, then the shapes of the curves will change. The magnitude of the curves will change linearly proportional to the Hopkinson scaling factor, but the shapes will not be affected.

7.4.4 Global Linear Acceleration

The acceleration curves in Figure 7-7 are the same shapes as the respective force curves in Figure 7-5 but different magnitudes because each force is divided by the mass of the vehicle to determine the accelerations. The relative magnitudes of the three curves remain the same because the mass of the vehicle is the same in all directions.

7.4.5 Global Angular Accelerations

The relative order of magnitudes of the angular accelerations in Figure 7-8 appears to be in different order than that of the global moments in Figure 7-6. This effect is due to the fact that the moments of inertia about the X and Z axes are approximately 6 × the magnitude of the moment of inertia about the Y axis.

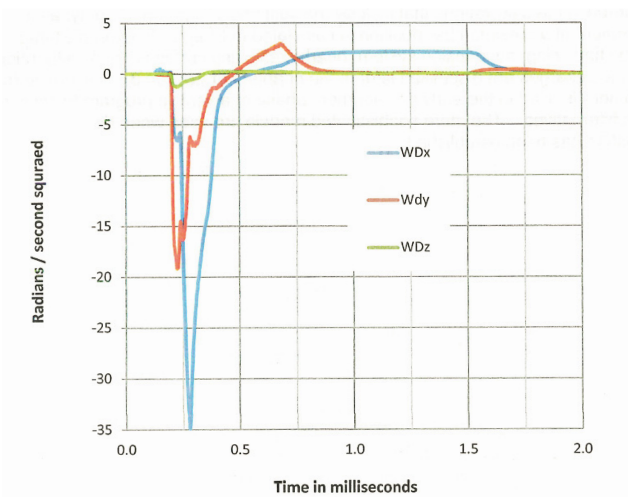

Figure 7-8. Global Angular Accelerations.

7.5 SUMMARY

The subroutine "GenericVehicle_GlobalResponse" calculates the global response over the time duration of the blast against a generic vehicle under the conditions of a specific scenario. The results of the calculation are often called the "global" or "rigid-body" response. These quasistatic calculations are required as a first step in determining the dynamic environments imposed on personnel and structures.

The data from these calculations are used for the AOA for vehicle geometry and structural design, survivability analysis, and lethality analysis. The calculations for determining the dynamic environment at a crewmember position in a generic vehicle are discussed in Chapter 8.

At this point in the analysis process, the effects of gravity are ignored and are to be considered in the calculations that include the suspension system. The dynamic environment at a crewmember position is calculated in Chapter 8. The simple model shown here is used in the early development phase of a vehicle program to access design alternatives. The more sophisticated models are used when detailed design information has been established.

CHAPTER 8. IMPLEMENTATION OF CALCULATIONS FOR CREWMEMBER ENVIRONMENT

8.1 INTRODUCTION

This chapter is an annotated presentation of the VBA subroutine "CrewmemberEnvironment" to estimate the blast environment at crewmember position 1, as discussed in Chapter 6. This computation is implemented on Microsoft Excel 2010. The subroutine elements are written in Arial font, size 10, with the comments in green as they would appear in the Macro window. The table of declarations (required for execution of the subroutine) for this and other modules, along with the input tables for this subroutine, is given in the Appendix.

8.2 IMPLEMENTATION

The objective of the implementation of the equations in Chapter 6 is to provide estimates of the effects of the blast loads at a position within a vehicle. The following subroutine calculates the 6DOF local and structural accelerations at a position inside a generic vehicle exposed to the blast from an explosive charge located on the surface of the ground under the vehicle. The inputs to the subroutine are based on the global response from the specific test scenario and surface geometry of the vehicle discussed in Chapter 7. The position in this example is the driver's position (position 1) in Figure 8-1. The inputs to the subroutine are the global responses calculated in Chapter 7. The suspension system is not in the calculation; thus, velocities are ignored. Consequently, the Coriolis accelerations are not calculated. This type of calculation is used as a first estimate of blast effects for assessing vehicle geometry, personnel survivability, and other design issues. The calculation is extended to account for velocity effects as design details are finalized.

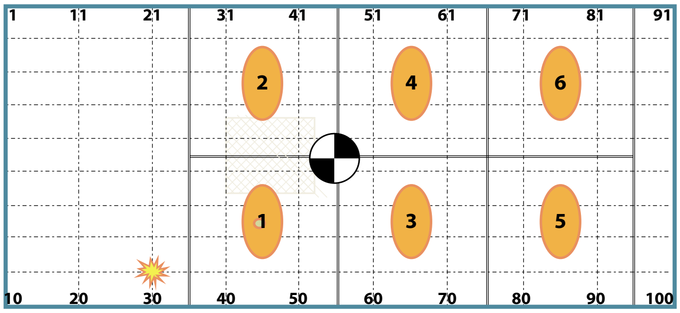

Figure 8-1. Test Layouts for Crewmember Position 1, Scenario 29.

The intersections of dashed lines show the possible charge positions for analyses. The layout shows the horizontal positions of the charge (red and yellow star), the crewmembers (yellow ovals), the CG (black and white segmented circle), the floor panels (double-lined rectangles), and the transmission housing (gray crosshatched area). The crewmember position for following implementation is shown in the figure as the center of crewmember position 1. The position of test instrumentation is assumed to be on the floor of the vehicle at that position. The measurements for that position will be discussed in Chapter 9. Since the significant portion of the global accelerations is ~5 ms, the structural response is calculated over a period of 150 ms after time of arrival to account for the residual vibration environment imposed on the crewmember.

8.3 FLOW CHART

The sequence of calculations and logic of the subroutine "CrewmemberEnvironment" is shown in Figure 8-2. The following list describes the diagrammed steps:

1. Input physical parameters
    a) Location of CG, vehicle mass, and moments of inertia
    b) Location of crewmember position
    c) The three modes of structural frequency response
2. Initialize variables
3. Start and increment time of observation to cover a period of 150 ms

4. Start and increment time
5. Input global accelerations
6. Calculate local accelerations
7. Calculate structural response during the time increment
8. Determine the total 6DOF crewmember acceleration environment
9. Tabulate 6DOF environment
10. Increment time step
11. If last time step, STOP

8.4 SUBROUTINE

Figure 8-3 lists the subroutine "CrewmemberEnvironment" that calculates the acceleration environment over the time duration of the blast against the generic vehicle depicted in Figure 7-3 in Chapter 7. The green fonts are the comments and nonfunctioning elements of the procedure. This procedure uses the results of the calculation for the global 6DOF response calculations to generate the acceleration environment at a crewmember position. The output from these calculations is used to estimate the survivability of a crewmember subjected to the environment.

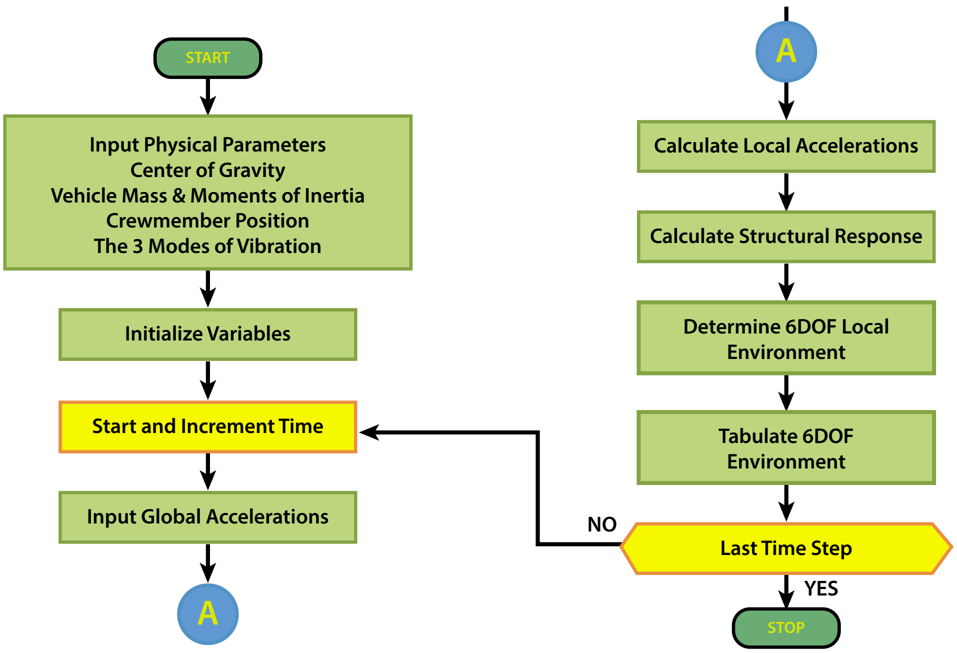

Figure 8-2. Flow Charts for Subroutine "CrewmemberEnvironment."

Sub CrewmemberEnvironment ()

'CrewmemberEnvironment Macro recorded by James O. Pilcher II, 10/11/2014.
'Updated 12/2014 by James O. Pilcher II. This Macro calculates the local and structural response of the floor panel of a generic ground vehicle given the global vertical acceleration response of the vehicle to mine blast from a 13.636-kg mine located approximately at the front tire on the driver's side. Three vibration modes of the panel are calculated. The total acceleration environment is estimated for position 1 (driver). This version calculates over a time period 50× longer than the pulse duration. The problem does not include the effects of the suspension system and does not consider external rigid or flexible constraints to motion. These calculations are first-time estimates for initial design considerations. Consequently, angular and linear velocities are not considered.

```
'IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII INITIALIZATION IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII

    Sheets("Environment").Select
    Xcg = 1.524
    Ycg = 2.134
    Zcg = 1.948
    CPx = 1.952
    CPy = 1.751
    CPz = 1.216
    F1 = 278
    F2 = 603
    F3 = 798
    W1 = 2 * pi * F1
    W2 = 2 * pi * F2
    W3 = 2 * pi * F3
    DAMP1 = 0.01
    DAMP2 = 0.01
    DAMP3 = 0.01
    INT11 = 0
    INT21 = 0
    INT12 = 0
    INT22 = 0
    INT13 = 0
    INT23 = 0

'IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII CALCULATIONS IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII

'The calculations are in three phases.  First phase is the acquisition of the local 6DOF accelerations, the second phase is the calculation of structural response, and the third phase is the assembly of the total 6DOF acceleration environment at the crewmember position.

'IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII Inputs IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII

For k = 1 To 4438
    Sheets("Environment").Select
    Ts = Cells(2 + k, 2) / 1000
    Ax = Cells(k + 2, 4)
    Ay = Cells(k + 2, 5)
    Az = Cells(k + 2, 6)
    WDx = Cells(k + 2, 8)
    WDy = Cells(k + 2, 9)
    WDz = Cells(k + 2, 10)

'IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII Local Angular Accelerations IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII

'The angular accelerations are the same as those at the CG and do not change with position.

'IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII Local Linear Accelerations IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII

    CPRx = CPx - Xcg
    CPRy = CPy - Ycg
```

```
CPRz = CPz - Zcg
LAx = Ax + CPRz * WDy - CPRy * WDz
LAy = Ay + CPRx * WDz - CPRz * WDx
LAz = Az + CPRy * WDx - CPRx * WDy
LA = (LAx ^ 2 + LAy ^ 2 + LAz ^ 2) ^ 0.5
```

‘IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII Structural Response IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII

‘ This segment of the subroutine incorporates the element of the subroutine titled “FreqResponse_3Freqs()” included in the Appendix. This section calculates the structural response of the floor panel of the generic ground vehicle given the vertical acceleration of the vehicle from mine blast and the first three vibration modes of the panel. The total acceleration is calculated. This version calculates over a time period 50× longer than the pulse duration.

‘IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII Initialization IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII

```
If k < 3001 Then
   dT = 0.00000209
Else
   dT = 0.0001
End If
```

‘IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII Calculation IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII

```
W1T = W1 *Ts
CW1T = Cos(W1T)
SW1T = Sin(W1T)
W2T = W2 * Ts
CW2T = Cos(W2T)
SW2T = Sin(W2T)
W3T = W3 * Ts
CW3T = Cos(W3T)
SW3T = Sin(W3T)
EL11 = LAz * SW1T * dT
EL21 = LAz * CW1T * dT
EL12 = LAz * SW2T * dT
EL22 = LAz * CW2T * dT
EL13 = LAz * SW3T * dT
EL23 = LAz * CW3T * dT
INT11 = INT11 + EL11
INT21 = INT21 + EL21
DMP1 = Exp(-DAMP1 * W1T)
INT12 = INT12 + EL12
INT22 = INT22 + EL22
DMP2 = Exp(-DAMP2 * W2T)
INT13 = INT13 + EL13
INT23 = INT23 + EL23
DMP3 = Exp(-DAMP3 * W3T)
SA1 = DMP1 * W1 * (SW1T * INT21 - CW1T * INT11)
SA2 = DMP2 * W2 * (SW2T * INT22 - CW2T * INT12)
SA3 = DMP3 * W3 * (SW3T * INT23 - CW3T * INT13)
SAC = SA1 + SA2 + SA3
```

```
'|||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||| Combined Environment ||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||

' This analysis assumes that the crewmember has direct contact (through seating arrangement) only with the floor
of the vehicle; only the floor response is significant, and there is no structural response in the horizontal directions
considered.

'||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||| Tabulation |||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||

    Cells(2 + k, 14) = LAz
    Cells(2 + k, 15) = LA
    Cells(2 + k, 17) = SA1
    Cells(2 + k, 18) = SA2
    Cells(2 + k, 19) = SA3
    Cells(2 + k, 20) = SAC
    Cells(2 + k, 22) = CPAx
    Cells(2 + k, 23) = CPAy
    Cells(2 + k, 24) = CPAz
    Cells(2 + k, 25) = CPA
    Cells(1, 12) = "LAx"
    Cells(1, 13) = "LAy"
    Cells(1, 14) = "LAz"
    Cells(1, 15) = "LA"
    Cells(1, 17) = "SA1"
    Cells(1, 18) = "SA2"
    Cells(1, 19) = "SA3"
    Cells(1, 20) = "SAC"
    Cells(1, 22) = "CPAx"
    Cells(1, 23) = "CPAy"
    Cells(1, 24) = "CPAz"
    Cells(1, 25) = "CPA"
Next I
End Sub
```

Figure 8-3. Listing of Subroutine "CrewmemberEnvironment."

8.5 OUTPUT

Figures 8-4 and 8-5 show the linear and angular acceleration environments at crew position 1 of the generic vehicle for scenario 29 and charge mass of 13.636 kg. These are the outputs of the calculations used to determine the local accelerations that drive the structural responses at crewmember position 1. The linear accelerations are significantly different in magnitude due to the offset of position 1 from the CG. The magnitude of the vertical component of the linear acceleration at crew position is 35% greater than that at the CG.

8.5.1 Local Linear Accelerations

The graph in Figure 8-4 shows the 6DOF components of the linear accelerations in the three coordinate directions X, Y, and Z relative to the passage of time. $\mathbf{A_x}$ (blue curve) is the acceleration that moves the vehicle toward the driver's side when the magnitude is positive or to the passenger's side when the magnitude is negative. $\mathbf{A_y}$ (red curve) is the acceleration that moves the vehicle backward when the magnitude is positive or forward when the magnitude is negative. $\mathbf{A_z}$ (light-green curve) is the acceleration that moves the

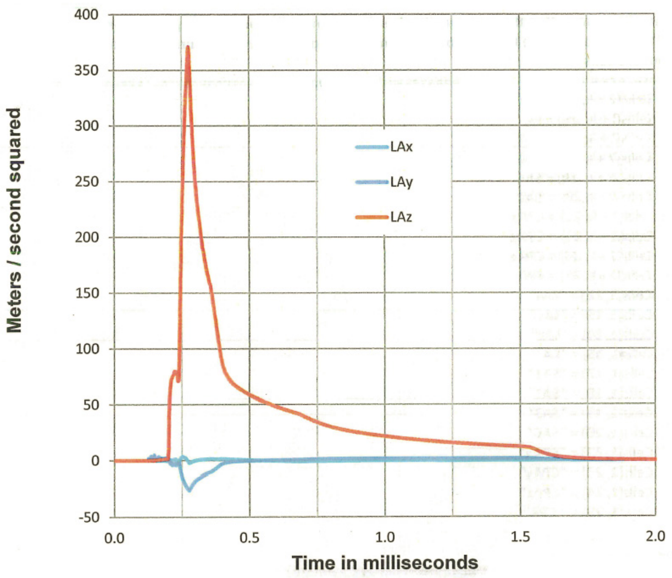

Figure 8-4. Local Linear Accelerations at Crewmember Position 1.

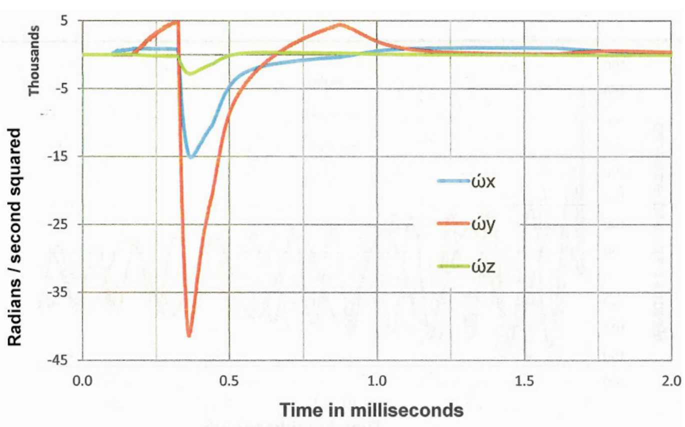

Figure 8-5. The Local Angular Accelerations at Crew Position 1.

vehicle upward when that magnitude is positive or downward when the magnitude is negative. The shapes of the three curves are governed by the geometry of the vehicle surfaces and the position of the charge with respect to the vehicle. If the vehicle geometry, charge position, and crew position are changed, both the shapes and magnitudes of the curves will change. The magnitude of the curves will change linearly proportional to the Hopkinson scaling factor, but the shapes will not be affected.

8.5.2 Local Angular Accelerations

The graph in Figure 8-5 shows the 6DOF components of the angular accelerations about the three coordinate directions X, Y, and Z relative to the passage of time. $\acute{\omega}_x$ (blue curve) is the acceleration that rotates the vehicle nose down when the magnitude is negative. ω_y (red curve) is the acceleration that rotates the vehicle driver side up when the magnitude is positive or driver side down when the magnitude is negative. $\acute{\omega}_z$ (light-green curve) is the acceleration that rotates the vehicle left when that magnitude is positive or right when the magnitude is negative.

The shapes of three curves are governed by the geometry of the vehicle surfaces and the position of the charge with respect to the vehicle. If the vehicle geometry, charge position, and crew position are changed, both the shapes and magnitudes of the curves will change. The magnitude of the curves will change linearly proportional to the mass and moments of inertia of the vehicle. The magnitude is proportional to the cube root of the ratio of the desired charge mass to the reference charge mass; the shapes of the pulse will not be affected.

At this point in the analysis process, the effects of gravity and suspension constraints are ignored; consequently, velocity is not considered in the calculations. Velocity terms included are considered in the calculations of the local dynamic environments in later chapters.

8.5.3 Structural Accelerations

There are three properties of structures that make it possible to estimate their responses to acceleration and force environments. They are as follows:

1. All structures are complex oscillators that have specific response frequencies unique to a particular structure.
2. The relative response of a structure is deterministic and repeatable for any given pulse shape.

3. The response of structure is a set of specific frequencies that can be forced by a pulse and ring free after the pulse.

These properties of structures allow the estimation of structural response frequencies by empirical equations and non-destructive testing. Response to the various frequencies is obtained by Duhamel's integral [1]. Figure 8-6 shows the responses to the local vertical acceleration for first three modes (SA1, SA2, and SA3) of vibration of the floor panel at crew position 1 superimposed over the local driving pulse, LARz. The driving pulse (the purple curve) lasts about 1.5 ms, while the vibratory response of the structure lasts, in this case, 150 ms. Only the first 25 ms of the vent are shown for clarity. The actual vertical acceleration will look like Figure 8-7.

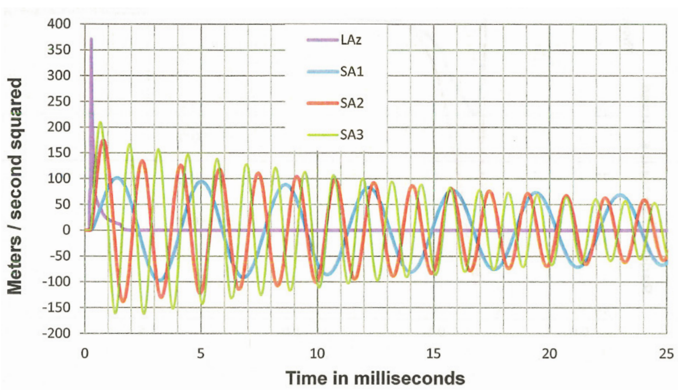

Figure 8-6. Three Modes of Structural Response at Crew Position 1.

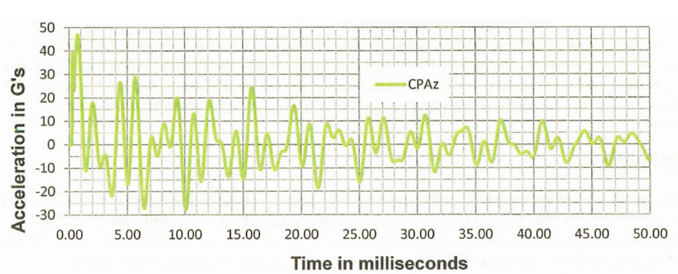

Figure 8-7. Vertical Linear Acceleration at Position 1.

8.6 CREWMEMBER ENVIRONMENT

8.6.1 Vertical Linear Environment

The crewmember environment depends on the summation of the structural and local response at the specific crewmember location; different crewmember locations have different environments. The curve in Figure 8-8 shows this composite acceleration of the three modes and vertical excitation pulse shown in Figure 8-6. This is the principal linear acceleration at position 1. Calculations and testing experience indicate the significant accelerations can be expected as late in time as 150 ms. The major physical damage to personnel is attributed to the vibrations that linger long after the excitation pulse.

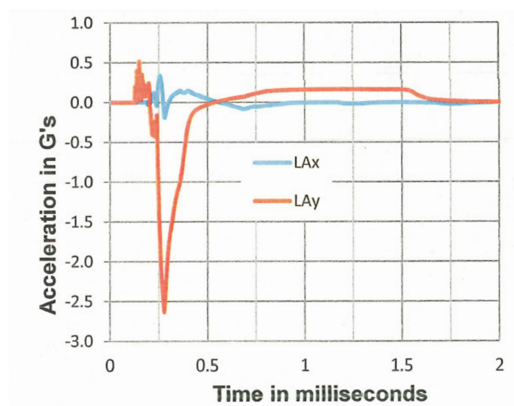

Figure 8-8. Horizontal Linear Accelerations at Position 1.

8.6.2 Crewmember's Angular Acceleration Environment

The generic vehicle is considered to be a rigid body without articulations; as such, rotation dynamics do not change with position. The angular quantities do not change with position on the vehicle. The angular accelerations at crew position 1 are the same as those at the CG; they are the same as the global angular accelerations. Figure 8-5 shows the angular acceleration for any position in the vehicle.

8.7 SUMMARY

The subroutine "GenericVehicle_GlobalResponse" in Chapter 7 calculates the global responses over the time duration of the blast against a generic vehicle under the conditions of a specific scenario. The results of these quasi-static calculations are required as inputs in determining the dynamic environments imposed on personnel and structures. The data from these calculations are used for AOA for vehicle geometry and structural design, survivability analysis, and lethality analysis.

REFERENCES

1. Henry, C. L. "Analysis of Shocks by Numerical Solution of Duhamel's Integral." BRL-MR-3726, U.S. Army Ballistics Research Laboratory, Aberdeen Proving Ground, MD, December 1988.

CHAPTER 9. VERIFYING ANALYSIS BY EXPERIMENT

9.1 INTRODUCTION

All of the analyses in the world cannot guarantee the accuracy or truthfulness of the results without some experimental verification. One cannot blindly expect agreement between analysis and experiment of a dynamic event. The approach is to minimize the errors in target description, blast analysis, target response, and measurement technique. It takes cooperation among analysts, testers, and designers throughout the development cycle to successfully implement and verify the accuracy of the estimate of blast effects from a planned test event.

9.2 THE PROBLEM

The problem is that analysis is basically an educated guess based on using the proper mathematics to manipulate what is understood of the physics of blast, the geometry of the event, and the responsive behavior of the target to obtain some significant measure of the event. Further, the problem is acerbated by the limitations of the measuring device or process—does measuring device respond to the dynamic parameter of choice or does it respond to multiple parameters? Is the measuring device adequately calibrated? Where and when do the assumptions violate the truth? Do the analyses answer the questions?

9.2.1 The Approach to the Solution

The approach accurately models the blast event as it is to be tested and verifies its accuracy and precision by comparing the modeling and test results. The following conditions must be met to achieve this goal:

1. Accurate description of the physical parameters of the target
   a) Mass and moments of inertia, as tested
   b) External geometry
   c) Vibration modes at points of measurement
2. Accurate description of charge
   a) Mass, TNT equivalent
   b) Type, free-air, surface-mounted, buried
3. Accurate description of test scenario
   a) Location and orientation of charge
   b) Location and orientation of target
   c) Calibration, location, and orientation of measuring instrument
4. Determine the most readily identifiable characteristic common to the results of both analysis and measurement.

9.2.2 Target Description

The primary parameters that change over the development are the mass and moments of inertia; these parameters are affected by the load of the target and must be measured when under the loading conditions prescribed for the test. The same can be said for modes of vibration, but the structural components need to be loaded as they would be loaded during the test. These characteristics can be measured through standardized automotive tests and vibration sine sweep techniques. The vibration sweep tests can be performed any time after the test item has been released for testing. The measurements for these tests should be taken at each proposed test measurement position. The diagram in Figure 9-1 illustrates the sine sweep technique.

Figure 9-1 shows the side view of the relative positions of the vehicle, crew position 1 loaded with a dummy, and the measurement position of the accelerometer for the test and the analysis [1, 2]. The position of the vibration exciter is also shown. To determine the first three modes of vibration of the structure at the position of the accelerometer, a sinusoidal force is imposed on the vehicle by the exciter. The excitation force is varied in frequency over a range of frequencies sufficient to excite any of the response frequencies at the point of the accelerometer. The signals from the accelerometer and the exciter are monitored, recorded, and analyzed to determine the first three modes of vibration at the accelerometer

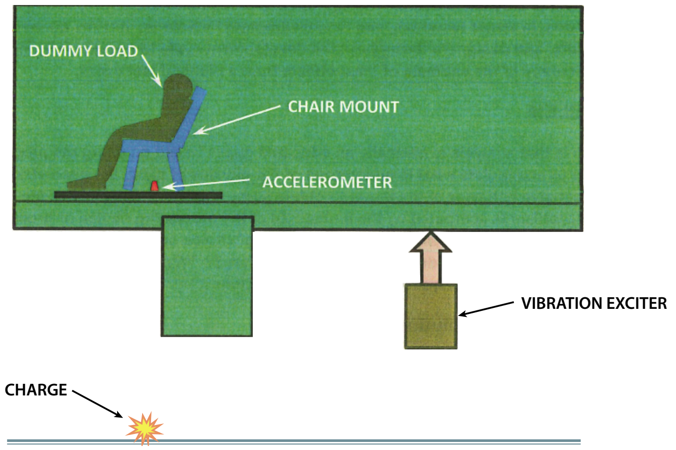

Figure 9-1. Sine Sweep Technique.

and their damping coefficient. This information is then used to update the analysis prior to the major test event and later used in the test data analysis procedures. The position of the exciter is varied during the test to get good energy transfer to the measurement site.

9.2.3 Charge Characteristics

Like all explosives, the explosives used to assemble the charge deteriorate with time and are susceptible to variations in moisture, temperature, and handling. Because of this, testers using explosives incorporate instrumentation to monitor and record the general performance of the explosives from test to test as they are used. This information is highly useful to the analyst to keep his or her analysis current.

9.2.4 Scenario Dimensions

The precision of the calculation of effective blast pressure at a point of contact on the target depends on the precision of the dimensions defining the position of the charge with respect to the vehicle. These dimensions are generally determined when the charge is emplaced. To enhance the ability to readily measure these dimensions, readily recognizable reference points should be provided on the exterior surface of the vehicle within reach of test personnel and observable by optical surveying instrumentation.

9.2.5 Identifiable Characteristics

Comparing the output of a blast model and test measurement of the same event is like trying to sort out the common elements from two different pots of chili made by two different cooks. First, the most readily identifiable characteristics common to the results of both the analysis and measurement must be determined.

Second, the characteristics must be a function of the structure and independent of external forces and influences other than an extreme change in the physical characteristics of the structure, such as permanent deformation or damage.

There are two characteristics that satisfy both conditions—namely, response frequencies and their damping. They are both functions of structural geometry and material properties. Another feature is that neither the frequency nor the damping change with the magnitude of the excitation forces as long as no permanent damage occurs to the structure. This means that in the absence of permanent damage, frequency and damping do not change from one test event to another. The magnitude of the three modes of vibration forms a basis for comparing results. The ratio of peak local accelerations, analytical to measured, is equal to the ratio of the peak amplitudes of each mode. If the three ratios are the same, equation 79 is true. Then the pulse shapes are the same and can be used to correct the analysis. If the three ratios are nearly equal to one (within some allowable error), then the analysis stands as is. If the equation is false, then the initial conditions of the analysis are in error in each aspect. Target, charge, and scenario must be reexamined to discern discrepancies with the test's initial conditions.

$$\frac{A_a}{A_m} = \frac{A_{a1}}{A_{m1}}, \frac{A_{a2}}{A_{m2}}, \frac{A_{a3}}{A_{m3}}, \tag{78}$$

$$\frac{A_{a1}}{A_{m1}} = \frac{A_{a2}}{A_{m2}}, \frac{A_{a3}}{A_{m3}}, \tag{79}$$

where A = amplitude, a and m = subscripts indicating analysis or measurement, and $1, 2, 3$ = subscripts indicating mode of vibration.

The expected time histories of the three modes, including their respective damping used in the response, are calculated, recorded, and set aside for use in comparing estimated results with measured test results.

9.2.6 Calibration of Instrumentation

In the days leading up to the test event, many hours are spent in preparing the instrumentation for the test. At the test range, this time is spent verifying that the data collection system faithfully captures and records the output from the measuring devices. The system response and data rate must be sufficient to capture the rise times and frequency content of the dynamic events to be encountered. Great care is taken to ensure that the system does not alias the output measuring devices and otherwise introduce spurious data. The analyst should specify to the project engineer the predicted expected rise time and significant frequencies (identifiable characteristics) and pointing direction for the cross-axis sensitivity for each position to be measured.

9.2.7 Calibration of Accelerometers

Given a perfectly performing instrumentation system, measurement results are governed by the performance of the accelerometer or device that makes the measurement.

To maintain accuracy and precision, accelerometers should meet the following criteria:

1. Withstand accelerations in excess of 50% greater than expected maximum.
2. Maintain specified linearity over useful range.
3. Calibrate useful range, including principal axis and cross axes sensitivities.
4. Establish directions of the principal and cross axis.

The upper limit in criterion 1 should be below the point where the gage suffers permanent deformation, otherwise criterion 2 cannot be met. Figure 9-2 diagrammatically shows the positions of the primary response axes.

The red arrows show the locations and positive directions of the sensitivity vectors. In addition, an angle θ indicates direction of the cross-axis sensitivity vector with respect to the central axis or the connector that is an identifiable feature

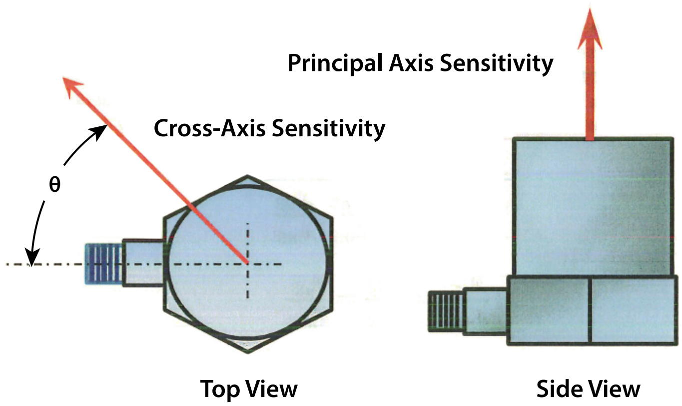

Figure 9-2. Typical Axes of Sensitivity on a Base-Mounted Accelerometer.

of the accelerometer. The calibration results should include the following:

1. The sensitivity factors
2. The cross-axis pointing angle, θ
3. Linearity
4. Maximum range

The calibration data for each accelerometer should be given to the analysts and tester.

9.2.8 Test Data Analysis

Figures 9-3–9-5 show how the modes are separated from the data by digital filtering to determine the first three modes of vibration and then combined to compare with the raw data and verify if the data analysis is reasonable and suitable for validating the estimates from the blast model. These data analyses are products of time series analysis techniques, which are described in detail by Dr. James N. Walbert in his monograph "Time Series Analysis and Its Application to Ballistic Data" [3].

Figure 9-3 shows the raw data (this is very clean data) from a particular accelerometer on a specific position on the target structure.

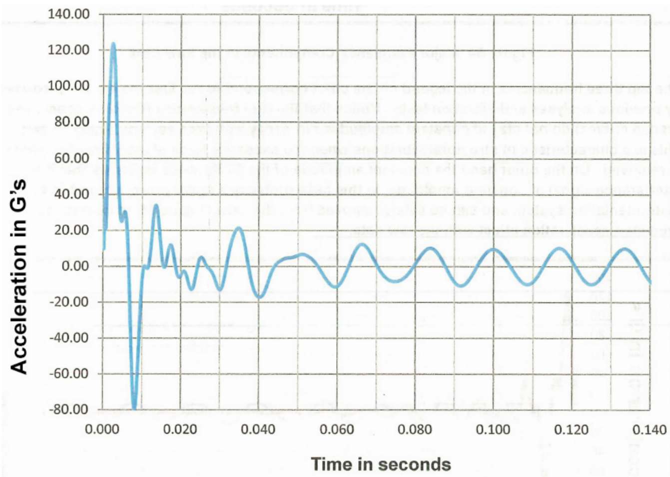

Figure 9-3. Cleaned-Up Raw Data.

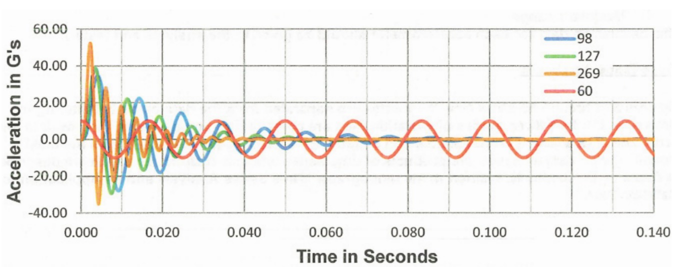

Figure 9-4. Major Frequency Components in the Raw Data.

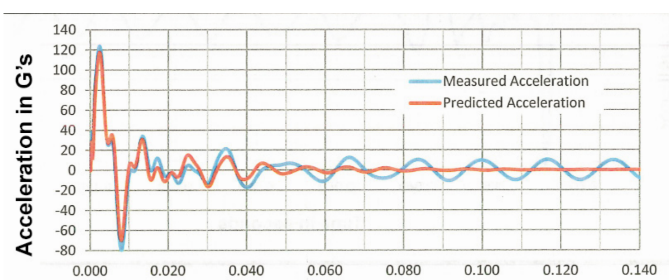

Figure 9-5. Comparison of Predicted and Measured Results.

The power spectrum of the data was generated to determine the significant frequency content. The raw data has been passed through a low-pass filter to eliminate identifiable spurious signals. In this case, the four frequencies showed significant power. The frequencies were compared with the results of the predictive analysis and the results of any sine-survey testing. Figure 9-4 shows plots of the four frequencies.

The top three frequencies in the legend on the chart correspond to the first the modes predicted by previous analyses and vibration tests. Notice that the first frequencies (the blue, green, and orange curves) do not stay at constant amplitudes but decay with time asymptotically to zero. This is a characteristic of structural vibrations when the causative force of the vibration ceases or is removed. On the other hand, the constant amplitude of the 60-Hz mode indicates that it is an interference signal of constant amplitude—in this case, probably a faulty power ground in the instrumentation system that can be safely removed from the data. Figure 9-5 compares the predicted acceleration effect with the raw data.

Examination of the measured and computed data showed that equation 79 is satisfied; this allows direct comparison of the early time portions of the results to be used as a measure of the reasonableness of the predicted test results. Using the difference of the first peaks, it was determined that the maximum acceleration of the test results was 5.3% higher than predicted (considered better than most results). In the absence of additional data from other tests, the model is considered good until shown to be otherwise.

9.3 SUMMARY

The main factor in achieving a successful verification of an estimate of the result of the outcome of a dynamic event is the communication and cooperation amongst the major actors in the verification process. Critical information must be readily available to all the major actors in the process.

REFERENCES

1. Pilcher, J. O., II. "Theoretical Considerations in Measuring Six-Degree-of-Freedom Motion of Gun Tubes by Accelerometers." ARBRL-TR-02474, U.S. Army Ballistics Research Laboratory, Aberdeen Proving Ground, MD, February 1983.
2. Pilcher, J. O., II. "Acceleration Measurements in High G Environments." BRL-TR 2610, U.S. Army Ballistics Research Laboratory, Aberdeen Proving Ground, MD, November 1984.
3. Walbert, J. N., Ph.D. "Time Series Analysis and Its Application to Ballistic Data." SURVICE Engineering Company, December 2012.

APPENDIX: SUBROUTINES

"GenericVehicle_GlobalResponse"

```
Option Explicit
Public X As Double 'X coordinate at surface in meters
Public Y As Double 'Y coordinate at surface in meters
Public Z As Double 'Z coordinate at surface in meters
Public x1 As Double 'x coordinate of panel in meters
Public y1 As Double 'y coordinate of panel in meters
Public z1 As Double 'z coordinate of in meters
Public x2 As Double 'x coordinate of panel in meters
Public y2 As Double 'y coordinate of panel in meters
Public z2 As Double 'z coordinate of panel in meters
Public x3 As Double 'x coordinate of panel in meters
Public y3 As Double 'y coordinate of panel in meters
Public z3 As Double 'z coordinate of panel in meters
Public x4 As Double 'x coordinate of panel in meters
Public y4 As Double 'y coordinate of panel in meters
Public z4 As Double 'z coordinate of panel in meters
Public Xc As Double 'X coordinate of Charge in meters
Public Yc As Double 'Y coordinate of Charge in meters
Public Zc As Double 'Z coordinate of Charge in meters
Public CSALN As Double 'Direction cosine ALFAn for the normal to the panel (dimensionless)
Public CSBTN As Double 'Direction cosine BETAn for the normal to the panel (dimensionless)
Public CSGAMN As Double 'Direction cosine GAMMAn for the normal to the panel (dimensionless)
Public CSALC As Double 'Direction cosine ALFAc for the ray from the charge (dimensionless)
Public CSBTC As Double 'Direction cosine BETAc for the ray from the charge (dimensionless)
Public CSGAMC As Double 'Direction cosine GAMMAc for the ray from the charge (dimensionless)
Public CSTHN As Double 'Direction cosine for angle of normal (dimensionless)
Public SITHN As Double 'Direction sine for angle of normal (dimensionless)
Public CSZETA As Double 'Direction cosine of obliquity (dimensionless)
Public SIZETA As Double 'Direction sine of obliquity (dimensionless)
Public Pso As Double 'Initial side-on Pressure in kpa
Public LGPSO As Double 'Log of side-on pressure. (dimensionless)
Public mm As Double 'mass of vehicle in kilograms
Public A As Double 'size of charge in kilograms
Public B As Double 'count for for-next statement (dimensionless)
Public C As Double 'time constant for pressure exponent (dimensionless)
```

```
Public CM As Double ‘Charge mass in kilograms
Public SCF As Double ‘Hopkinson Scale Factor (dimensionless)
Public Xcg As Double ‘X coordinate of center of gravity in meters
Public Ycg As Double ‘Y coordinate of center of gravity in meters
Public Zcg As Double ‘Z coordinate of center of gravity in meters
Public Ix As Double ‘polar moment of inertia about x in kilonewtons-meters squared
Public Iy As Double ‘polar moment of inertia about y in kilonewtons-meters squared
Public Iz As Double ‘polar moment of inertia about z in kilonewtons-meters squared
Public n As Integer ‘number of Increments (dimensionless)
Public m As Integer ‘number of Increments (dimensionless)
Public i As Integer ‘Increment (dimensionless)
Public j As Integer ‘Increment (dimensionless)
Public S As Double ‘Scenario number (dimensionless)
Public k As Integer ‘Increment (dimensionless)
Public l As Integer ‘Increment (dimensionless)
Public R As Double ‘Distance from center of charge to a point on the surface in meters
Public Ro As Double ‘Reference distance
Public Po As Double ‘Reference pressure
Public RS As Double ‘Hopkinson Scale Factor (dimensionless)
Public Pr As Double ‘Reflected Pressure at surface in kpa
Public Pe As Double ‘Effective Pressure at surface in kpa
Public PM As Double ‘Maximum Pressure at surface kpa
Public Pnr As Double ‘Normal Reflective Pressure in kpa
Public Theta As Double ‘angle of parallelepiped in radians
Public ZETA As Double ‘angle of obliquity in radians
Public Td As Double ‘time duration of pulse in seconds
Public Ta As Double ‘time of arrival of pulse in seconds
Public Tv As Double ‘time of observation in seconds
Public Ts As Double ‘scaled time of observation in seconds
Public DelTs As Double ‘scaled time of observation differential in seconds
Public DelL1 As Double ‘increment of line defining edge of panel in meters
Public DelL2 As Double ‘increment of line defining edge of panel in meters
Public DelH As Double ‘increment of line defining height of panel in meters
Public H As Double ‘line defining height of panel in meters
Public L1 As Double ‘line defining edge of panel in meters
Public L2 As Double ‘line defining edge of panel in meters
Public DelTv As Double ‘increment of time of observation in seconds
Public Fx As Double ‘Force in x direction in kilonewtons
Public Fy As Double ‘Force in y direction in kilonewtons
Public Fz As Double ‘Force in z direction in kilonewtons
Public Mx As Double ‘Moment in x direction in kilonewtons meters
Public My As Double ‘Moment in y direction in kilonewtons meters
```

```
Public Mz As Double 'Moment in z direction in kilonewtons meters
Public TFx As Double 'Summation of Fx in kilonewtons
Public TFy As Double 'Summation of Fy in kilonewtons
Public TFz As Double 'Summation of Fz in kilonewtons
Public TMx As Double 'Summation of Mx in kilonewtons meters
Public TMy As Double 'Summation of My in kilonewtons meters
Public TMz As Double 'Summation of Mz in kilonewtons meters
Public Ax As Double 'Acceleration in x direction in meters/second squared
Public Ay As Double 'Acceleration in y direction In meters/second squared
Public Az As Double 'Acceleration in z direction in meters/second squared
Public WDx As Double 'Angular acceleration about x in radians/second squared
Public WDy As Double 'Angular acceleration about y axis in radians/second squared
Public WDz As Double 'Angular acceleration about zx axis In radians/second squared
Public LGTA As Double 'intermediate variable from TM5-855-1
Public LGTD As Double 'intermediate variable from TM5-855-1
Public DelA As Double 'Area of element of panel in square meters
Public DelX As Double 'Length of element of panel In meters
Public DelY As Double 'Length of element of panel in meters
Public DelZ As Double 'Length of element of panel in meters
Public U As Double 'Dummy variable
Public TC As Double 'Time constant
Public Const gc As Double = 9.802 'meters/second squared
Public Const pi As Double = 3.142 'radians
Public Const MC As Double = 1 'kg default charge mass
Public Const loge As Double = 0.43429 'common log of e
```

```
Sub GenericVehicle_GlobalResponse()
' Macro recorded 1/24/2015 by James O. Pilcher II.
' Updated 1/24/2015 by James O. Pilcher II.
' This subroutine calculates the six degrees of freedom (6DOF) forces and moments generated by blast on a generic vehicle over the time duration of the blast. The charge is assumed to be under the vehicle mounted in the ground within the footprint of the hull and wheels. The charge mass is 13.636 kg. Only the directly illuminated panels for scenario 29 are implemented in this subroutine. Panels are 2, 3, 4, 7, 8, and 9.

'|||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||| INITIALIZATION ||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
    CM = 13.636 'Charge mass in kilograms
    S = 29
    TC = 20
    SCF = 2.389
    Xc = 2.2351
    Yc = 1.1176
    Zc = 0
```

```
    Xcg = 1.524
    Ycg = 2.134
    Zcg = 1.638
    DelLl = 0.02
    DelL2 = 0.02
    mm = 13636 'vehicle mass in kilograms
    Ix = 140233 'vehicle moment of inertia about X axis
    Iy = 21622 'vehicle moment of inertia about Y axis
    Iz = 139948 'vehicle moment of inertia about Z axis
    DelTv = 0.005 'time increment in milliseconds
For k = 1 To 3000 'Tv = 0.005 msec to 15 msec
    Tv = k/ 200 'time in msec
    Ts = 0.4186 * Tv 'scaled time
    Pe = 0 'Effective pressure
    TFx = 0 'Running total of force in the x direction
    TFy = 0 'Running total of force in the y direction
    TFz = 0 'Running total of force in the z direction
    TMx = 0 'Running total of moment about the x direction
    TMy = 0 'Running total of moment about the y direction
    TMz = 0 'Running total of moment about the z direction
    Po = 18.658 'MPa or KNewtons/square millimeter
    Ro = 0.2043 'meters

'|||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||| CALCULATIONS ||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
'|||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||| Hull Panel 2 ||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
    x1 = 0.6096
    y1 = 0.3048
    z1 = 1.0866
    x2 = 0.6096
    y2 = 3.9624
    z2 = 1.0866
    x3 = 1.4478
    y3 = 3.9624
    z3 = 0.9144
    x4 = 1.4478
    y4 = 0.3048
    z4 = 0.9144

'||||||||||||||||||||||||||||||||||||||||||||||||||||||| Rectangular Panel, Length, and Area Increments ||||||||||||||||||||||||||||||||||||||||||||||||||||
    L1 = ((x2 - x1) ^ 2 + (y2 - y1) ^ 2 + (z2 - z1) ^ 2) ^ 0.5
    L2 = ((x4 - x1) ^ 2 + (y4 - y1) ^ 2 + (z4 - z1) ^ 2) ^ 0.5
```

```
    m = L1 / DelL1
    n = L2 / DelL2
    DelA = DelL1 * DelL2 'square meters or 1,000,000 square millimeters
    DelX = (x4 - x1) / n
    DelY = (y2 - y1) / m
    DelZ = (z4 - z1) / n
'|||||||||||||||||||||||||||||||||||||||| Range to Charge ||||||||||||||||||||||||||||||||||||||||
    For j = 1 To m
      For i = 1 To n
        X = x1 + (i - 1 / 2) * DelX
        Y = y1 + (j - 1 / 2) * DelY
        Z = z1 + (i -1 / 2) * DelZ
        R = ((X - Xc) ^ 2 + (Y - Yc) ^ 2 + (Z - Zc) ^ 2) ^ 0.5
        RS = loge * Log(R)
'|||||||||||||||||||||||||||||||||||||||| The Direction Cosines for the Normal to the Panel ||||||||||||||||||||||||||||||||||||||||
    CSALN = 0.179
    CSBTN = 0
    CSGAMN = 0.984
'|||||||||||||||||||||||||||||||||||||||| Direction Cosines for Ray From Charge ||||||||||||||||||||||||||||||||||||||||
    CSALC = (X - Xc) / R
    CSBTC = (Y - Yc) / R
    CSGAMC = (Z - Zc) / R
'|||||||||||||||||||||||||||||||||||||||| Sine and Cosine for Angle of Obliquity ||||||||||||||||||||||||||||||||||||||||
    CSZETA = CSALC * CSALN + CSBTC * CSBTN + CSGAMC * CSGAMN
  If CSZETA > 0.999 Then CSZETA = 1
    SIZETA = (1 - CSZETA ^ 2) ^ 0.5
'|||||||||||||||||||||||||||||||||||||||| Side-on Pressure ||||||||||||||||||||||||||||||||||||||||
    Pso = Po * (R / Ro) ^ -1.55
'|||||||||||||||||||||||||||||||||||||||| Normal Reflected Pressure ||||||||||||||||||||||||||||||||||||||||
    Pnr = Pso * 22 * (R / Ro) ^ -0.45
'|||||||||||||||||||||||||||||||||||||||| Reflected Pressure ||||||||||||||||||||||||||||||||||||||||
    Pr = Pnr * CSZETA ^ 2 + Pso * SIZETA ^ 2
'|||||||||||||||||||||||||||||||||||||||| Time of Arrival ||||||||||||||||||||||||||||||||||||||||
    If 0.0674 <= R <= 40 Then
        U = -0.202425716178 + 1.37784223635 * RS
        LGTA = -0.0591634288046 + 1.35706496258 * U + 0.052492798645 * U ^ 2 _
        - 0.196563954086 * U ^ 3 - 0.0601770052288 * U ^ 4 + 0.0696360270891 * U ^ 5 _
        + 0.0215297490092 * U ^ 6 - 0.0161658930785 * U ^ 7 - 0.00232531970294 * U ^ 8 _
```

```
        + 0.00147752067524 * U ^ 9
        Ta = 10 ^ (LGTA)
End If
'||||||||||||||||||||||||||||| Pulse Duration |||||||||||||||||||||||||||||
    If 0.178 < R <= 1.01 Then
        U = 1.92946154068 + 5.25099193925 * RS
        LGTD = -0.614227603559 + 0.130143717675 * U + 0.134872511954 * U ^ 2
        + 0.0391574276906 * U ^ 3 - 0.00475933664702 * U ^ 4 - 0.00428144598008 * U ^ 5
    End If
    If 1.01 <= R <= 2.78 Then
        U = -2.12492525216 + 9.2996288611 * RS
        LGTD = 0.315409245784 - 0.0297944268976 * U + 0.030632954288 * U ^ 2
        + 0.0183405574086 * U ^ 3 - 0.0173964666211 * U ^ 4 - 0.00106321963633 * U ^ 5
        + 0.0056206003977 * U ^ 6 + 0.0001618217499 * U ^ 7 - 0.0006860188944 * U ^ 8
    End If
    If 2.78 <= R <= 40 Then
        U = -3.53626218091 + 3.46349745571 * RS
        LGTD = 0.686906642409 + 0.0933035304009 * U - 0.0005849420883 * U ^ 2
        - 0.00226884995013 * U ^ 3 - 0.00295908591505 * U ^ 4 + 0.00148029868929 * U ^ 5
    End If
        Td = 10 ^ LGTD
'||||||||||||||||||||||||||||| Time Window |||||||||||||||||||||||||||||
    If (Ta < Tv And Tv < (Ta + Td)) Then
        Pe = Pr * Exp(-TC * (Tv - Ta) / Td) * 10 ^ 6 'Newtons/meter squared
    Else
        Pe = 0
    End If
'||||||||||||||||||||||||||||| Scaled Parameters |||||||||||||||||||||||||||||
    Ts = Tv / SCF
    DelTs = DelTv / SCF
'||||||||||||||||||||||||||||| Global Forces |||||||||||||||||||||||||||||
        Fx = Pe * DelA * CSALN 'Newtons
    If Xcg > X Then
        Fx = Fx
    Else
        Fx = -Fx
    End If
        Fy = Pe * DelA * CSBTN 'Newtons
    If Ycg > Y Then
        Fy = Fy
```

```
Else
    Fy = -Fy
End If
    Fz = Pe * DelA * CSGAMN 'Newtons
If Zcg > Z Then
    Fz = Fz
Else
    Fz = -Fz
End If
    TFx = TFx + Fx
    TFy = TFy + Fy
    TFz = TFz + Fz
'||||||||||||||||||||||||||||||||||||||||||||||| Global Moments |||||||||||||||||||||||||||||||||||||||||||||||
    Mx = (Y - Ycg) * Fz - (Z - Zcg) * Fy 'Newton-meters
    My = (Z - Zcg) * Fx - (X - Xcg) * Fz 'Newton-meters
    Mz = (X -Xcg) * Fy - (Y -Ycg) * Fx 'Newton-meters
    TMx = TMx + Mx
    TMy = TMy + My
    TMz = TMz + Mz
  Next i
Next j
'||||||||||||||||||||||||||||||||||||||||||||||| Hull Panel 3 |||||||||||||||||||||||||||||||||||||||||||||||
    x1 = 1.4478
    y1 = 0.3048
    z1 = 0.9144
    x2 = 1.4478
    y2 = 3.9624
    z2 = 0.9144
    x3 = 1.6002
    y3 = 0.3048
    z3 = 0.9144
    x4 = 1.6002
    y4 = 3.9624
    z4 = 0.9144
'||||||||||||||||||||||||||| Rectangular Panel, Length, and Area Increments |||||||||||||||||||||||||||
    L1 = ((x2 - x1) ^ 2 + (y2 - y1) ^ 2 + (z2 - z1) ^ 2) ^ 0.5
    L2 = ((x4 - x1) ^ 2 + (y4 - y1) ^ 2 + (z4 - z1) ^ 2) ^ 0.5
    m = L1 / DelL1
    n = L2 / DelL2
    DelA = DelL1 ^ DelL2
```

```
        DelX = (x4 - x1) / n
        DelY = (y2 - y1) / m
        DelZ = (z4 - z1) / n
'''''''''''''''''''''''''''''' Coordinates and Range to Charge ''''''''''''''''''''''''''''''
For j = 1 To m
    For i = 1 To n
        X = x1 + (i - 1 / 2) * DelX
        Y = y1 + (j - 1 / 2) * DelY
        Z = z1 + (i - 1 / 2) * DelZ
        R = ((X - Xc) ^ 2 + (Y - Yc) ^ 2 + (Z - Zc) ^ 2) ^ 0.5
        RS = loge * Log(R)
'''''''''''''''''''''''''''''' Direction Cosines for Normal to a Panel ''''''''''''''''''''''''''''''
        CSALN = 0
        CSBTN = 0
        CSGAMN = 1
'''''''''''''''''''''''''''''' Direction Cosines for Ray From Charge ''''''''''''''''''''''''''''''
        CSALC = (X - Xc) / R
        CSBTC = (Y - Yc) / R
        CSGAMC = (Z - Zc) / R
'''''''''''''''''''''''''''''' Sine and Cosine for Angle of Obliquity ''''''''''''''''''''''''''''''
        CSZETA = CSALC * CSALN + CSBTC * CSBTN + CSGAMC * CSGAMN
    If CSZETA > 0.999 Then CSZETA = 1
        SIZETA = (1 – CSZETA ^ 2) ^ 0.5
'''''''''''''''''''''''''''''' Side-on Pressure ''''''''''''''''''''''''''''''
        Pso = Po * (R / Ro) ^ -1.55
'''''''''''''''''''''''''''''' Normal Reflected Pressure ''''''''''''''''''''''''''''''
        Pnr = Pso * 22 * (R / Ro) ^ -0.45
'''''''''''''''''''''''''''''' Reflected Pressure ''''''''''''''''''''''''''''''
        Pr = Pnr * CSZETA ^ 2 + Pso * SIZETA ^ 2
'''''''''''''''''''''''''''''' Time of Arrival ''''''''''''''''''''''''''''''
    If 0.0674 <= R <= 40 Then
        U = -0.202425716178 + 1.37784223635 * RS
        LGTA = -0.0591634288046 + 1.35706496258 * U + 0.052492798645 * U ^ 2
        - 0.196563954086 * U ^ 3 - 0.0601770052288 * U ^ 4 + 0.0696360270891 * U ^ 5
        + 0.0215297490092 * U ^ 6 - 0.0161658930785 * U ^ 7 - 0.00232531970294 * U ^ 8
        + 0.00147752067524 * U ^ 9
        Ta = 10 ^ (LGTA)
    End If
```

```
'''''''''''''''''''''''''''''''''''''''''''''''''''''''' Pulse Duration ''''''''''''''''''''''''''''''''''''''''''''''''''''''''
    If 0.178 < R <= 1.01 Then
        U = 1.92946154068 + 5.25099193925 * RS
        LGTD = -0.614227603559 + 0.130143717675 * U + 0.134872511954 * U ^ 2
        + 0.0391574276906 * U ^ 3 - 0.00475933664702 * U ^ 4
        - 0.00428144598008 * U ^ 5
    End If
    If 1.01 <= R <= 2.78 Then
        U = -2.12492525216 + 9.2996288611 * RS
        LGTD = 0.315409245784 - 0.0297944268976 * U + 0.030632954288 * U ^ 2
        + 0.0183405574086 * U ^ 3 - 0.0173964666211 * U ^ 4
        - 0.00106321963633 * U ^ 5 + 0.0056206003977 * U ^ 6 + 0.0001618217499 * U ^ 7
        - 0.0006860188944 * U ^ 8
    End If
    If 2.78 <= R <= 40 Then
        U = -3.53626218091 + 3.46349745571 * RS
        LGTD = 0.686906642409 + 0.0933035304009 * U - 0.0005849420883 * U ^ 2
        - 0.00226884995013 * U ^ 3 - 0.00295908591505 * U ^ 4
        + 0.00148029868929 * U ^ 5
    End If
        Td = 10 ^ LGTD
'''''''''''''''''''''''''''''''''''''''''''''''''''''''' Time Window ''''''''''''''''''''''''''''''''''''''''''''''''''''''''
    If (Ta < Tv And Tv < (Ta + Td)) Then
        Pe = Pr * Exp(-TC * (Tv - Ta) / Td) * 10 ^ 6
    Else
        Pe = 0
    End If
'''''''''''''''''''''''''''''''''''''''''''''''''''''''' Scaled Parameters ''''''''''''''''''''''''''''''''''''''''''''''''''''''''
        Ts = Tv /SCF
        DelTs = DelTv / SCF
'''''''''''''''''''''''''''''''''''''''''''''''''''''''' Global Forces ''''''''''''''''''''''''''''''''''''''''''''''''''''''''
        Fx = Pe * DelA * CSALN
    If Xcg > X Then
        Fx = Fx
    Else
        Fx = -Fx
    End If
        Fy = Pe * DelA * CSBTN
    If Ycg > Y Then
        Fy = Fy
    Else
```

```
        Fy = - Fy
    End If
        Fz = Pe * DelA * CSGAMN
    If Zcg > Z Then
        Fz = Fz
    Else
        Fz = -Fz
    End If
        T Fx = T Fx + Fx
        T Fy = T Fy + Fy
        T Fz = T Fz + Fz
'||||||||||||||||||||||||||||||||| Global Moments |||||||||||||||||||||||||||||||||
        Mx = (Y - Ycg) * Fz - (Z - Zcg) * Fy
        My = (Z- Zcg) * Fx - (X - Xcg) * Fz
        Mz = (X - Xcg) * Fy - (Y - Ycg)* Fx
        TMx = TMx + Mx
        TMy = TMy + My
        TMz = TMz + Mz
      Next i
    Next j
'||||||||||||||||||||||||||||||||| Hull Panel 4 |||||||||||||||||||||||||||||||||
        x1 = 1.6002
        y1 = 0.3048
        z1 = 0.9144
        x2 = 1.6002
        y2 = 3.9624
        z2 = 0.9144
        x3 = 2.4384
        y3 = 3.9624
        z3 = 1.0668
        x4 = 2.4384
        y4 = 0.3048
        z4 = 1.0668
'||||||||||||||||||||| Rectangular Panel, Length, and Area Increments |||||||||||||||||||||
        L1 = ((x2 - x1) ^ 2 + (y2 - y1) ^ 2 + (z2 - z1) ^ 2) ^ 0.5
        L2 = ((x4 - x1) ^ 2 + (y4 - y1) ^ 2 + (z4 - z1) ^ 2) ^ 0.5
        m = L1 / DelL1
        n = L2 / DelL2
        DelA = DelL1 * DelL2
        DelX = (x4 - x1) / n
```

```
        DelY = (y2 - y1) / m
        DelZ = (z4 - z1) / n
'||||||||||||||||||||||||||||||||||| Range to Charge |||||||||||||||||||||||||||||||||||
  For j = 1 To m
    For i = 1 To n
        X = x1 + (i - 1 / 2) * DelX
        Y = y1 + (j - 1 / 2) * DelY
        Z = z1 + (i - 1 / 2) * DelZ
        R = ((X - Xc) ^ 2 + (Y - Yc) ^ 2 + (Z - Zc) ^ 2) ^ 0.5
        RS = loge * Log(R)
'||||||||||||||||||||||| The Direction Cosines for the Normal to the Panel |||||||||||||||||||||||
        CSALN = 0.179
        CSBTN = 0
        CSGAMN = 0.984
'||||||||||||||||||||||||||||| Direction Cosines for Ray From Charge |||||||||||||||||||||||||||||
        CSALC = (X - Xc) / R
        CSBTC = (Y - Yc) / R
        CSGAMC = (Z - Zc) / R
'||||||||||||||||||||||||||||| Sine and Cosine for Angle of Obliquity |||||||||||||||||||||||||||||
        CSZETA = CSALC * CSALN + CSBTC * CSBTN + CSGAMC * CSGAMN
    If CSZETA > 0.999 Then CSZETA = 1
        SIZETA = (1 - CSZETA ^ 2) ^ 0.5
'||||||||||||||||||||||||||||||||||| Side-on Pressure |||||||||||||||||||||||||||||||||||
        Pso = Po * (R / Ro) ^ -1.55
'||||||||||||||||||||||||||||||| Normal Reflected Pressure |||||||||||||||||||||||||||||||
        Pnr = Pso * 22 * (R / Ro) ^ -0.45
'|||||||||||||||||||||||||||||||||| Reflected Pressure ||||||||||||||||||||||||||||||||||
        Pr = Pnr * CSZETA ^ 2 + Pso * SIZETA ^ 2
'||||||||||||||||||||||||||||||||||| Time of Arrival |||||||||||||||||||||||||||||||||||
    If 0.0674 <= R <= 40 Then
        U = -0.202425716178 + 1.37784223635 * RS
        LGTA = -0.0591634288046 + 1.35706496258 * U + 0.052492798645 * U ^ 2 _
        - 0.196563954086 * U ^ 3 - 0.0601770052288 * U ^ 4 + 0.0696360270891 * U ^ 5 _
        + 0.0215297490092 * U ^ 6 - 0.0161658930785 * U ^ 7 - 0.00232531970294 * U ^ 8 _
        + 0.00147752067524 * U ^ 9
        Ta = 10 ^ (LGTA)
    End If
```

```
'''''''''''''''''''''''''''''''''''' Pulse Duration ''''''''''''''''''''''''''''''''''''
    If 0.178 < R <= 1.01 Then
        U = 1.92946154068 + 5.25099193925 * RS
        LGTD = -0.614227603559 + 0.130143717675 * U + 0.134872511954 * U ^ 2 _
        + 0.0391574276906 * U ^ 3 - 0.00475933664702 * U ^ 4 - 0.00428144598008 * U ^ 5
    End If
    If 1.01 <= R <= 2.78 Then
        U = -2.12492525216 + 9.2996288611 * RS
        LGTD = 0.315409245784 - 0.0297944268976 * U + 0.030632954288 * U ^ 2 _
        + 0.0183405574086 * U ^ 3 - 0.0173964666211 * U ^ 4 - 0.00106321963633 * U ^ 5 _
        + 0.0056206003977 * U ^ 6 + 0.0001618217499 * U ^ 7 - 0.0006860188944 * U ^ 8
    End If
        If 2.78 <= R <= 40 Then
        U = -3.53626218091 + 3.46349745571 * RS
        LGTD = 0.686906642409 + 0.0933035304009 ^ U - 0.0005849420883 * U ^ 2 _
        - 0.00226884995013 * U ^ 3 - 0.00295908591505 * U ^ 4 + 0.00148029868929 * U ^ 5
    End If
        Td = 10 ^ LGTD
'''''''''''''''''''''''''''''''''''' Time Window ''''''''''''''''''''''''''''''''''''
    If (Ta < Tv And Tv < (Ta + Td)) Then
        Pe = Pr * Exp (-TC * (Tv - Ta) / Td) * 10 ^ 6
    Else
        Pe = 0
    End If
'''''''''''''''''''''''''''''''''''' Scaled Parameters ''''''''''''''''''''''''''''''''''''
        Ts = Tv / SCF
        DelTs = DelTv / SCF
'''''''''''''''''''''''''''''''''''' Global Forces ''''''''''''''''''''''''''''''''''''
        Fx = Pe * DelA * CSALN
    If Xcg > X Then
        Fx = Fx
    Else
        Fx = -Fx
    End If
        Fy = Pe * DelA * CSBTN
    If Ycg > Y Then
        Fy = Fy
    Else
        Fy = -Fy
    End If
        Fz = Pe * DelA * CSGAMN
```

```
If Zcg > Z Then
    Fz = Fz
Else
    Fz = -Fz
End If
    TFx = TFx + Fx
    TFy = TFy + Fy
    TFz = TFz + Fz
'IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII Global Moments IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII
    Mx = (Y - Ycg*) Fz - (Z - Zcg) * Fy
    My = (Z - Zcg*) Fx - (X - Xcg) * Fz
    Mz = (X - Xcg*) Fy - (Y - Ycg) * Fx
    TMx = TMx + Mx
    TMy = TMy + My
    TMz = TMz + Mz
  Next i
Next j

'IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII Hull Panel 7 IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII
    x1 = 1.2954
    y1 = 1.524
    z1 = 0.4572
    x2 = 1.2954
    y2 = 2.1336
    z2 = 0.4572
    x3 = 1.7526
    y3 = 2.1336
    z3 = 0.4572
    x4 = 1.7526
    y4 = 1.524
    z4 = 0.4572
'IIIIIIIIIIIIIIIIIIIIIIIIII Rectangular Panel, Length, and Area Increments IIIIIIIIIIIIIIIIIIIIIIIIII
    L1 = ((x2 - x1) ^ 2 + (y2 - y1) ^ 2 + (z2 - z1) ^ 2) ^ 0.5
    L2 = ((x4 - x1) ^ 2 + (y4 - y1) ^ 2 + (z4 - z1) ^ 2) ^ 0.5
    m = L2 / DelL2
    n = L1 / DelL1
    DelA = DelL1 * DelL2
    DelX = (x4 - x1) / n
    DelY = (y2 - y1) / m
    DelZ = (z4 - z1) / n
```

```
'||||||||||||||||||||||||||||||||||||| Range to Charge |||||||||||||||||||||||||||||||||||||
        For j = 1 To m
        For i = 1 To n
        X = x1 + (i - 1 / 2) * DelX
        Y = y1 + (j - 1 / 2) * DelY
        Z = z1 + (i - 1 / 2) * DelZ
        R = ((X - Xc) ^ 2 + (Y - Yc) ^ 2 + (Z - Zc) ^ 2) ^ 0.5
        RS = loge * Log(R)
'||||||||||||||||||||||||| Special Case Direction Cosines for Normal to a Panel |||||||||||||||||||||||||
        CSALN = 0
        CSBTN = 0
        CSGAMN = 1
'||||||||||||||||||||||||||||| Direction Cosines for Ray From Charge |||||||||||||||||||||||||||||
        CSALC = (X - Xc) / R
        CSBTC = (Y - Yc) / R
        CSGAMC = (Z - Zc) / R
'||||||||||||||||||||||||||||| Sine and Cosine for Angle of Obliquity |||||||||||||||||||||||||||||
        CSZETA = CSALC * CSALN + CSBTC * CSBTN + CSGAMC * CSGAMN
    If CSZETA > 0.999 Then CSZETA = 1
        SIZETA = (1 - CSZETA ^ 2) ^ 0.5
'||||||||||||||||||||||||||||||||||||| Side-on Pressure |||||||||||||||||||||||||||||||||||||
        Pso = Po * (R / Ro) ^ -1.55
'||||||||||||||||||||||||||||||||| Normal Reflected Pressure |||||||||||||||||||||||||||||||||
        Pnr = Pso * 22 * (R / Ro) ^ -0.45
'|||||||||||||||||||||||||||||||||||| Reflected Pressure ||||||||||||||||||||||||||||||||||||
        Pr = Pnr * CSZETA ^ 2 + Pso * SIZETA ^ 2


'||||||||||||||||||||||||||||||||||||| Time of Arrival |||||||||||||||||||||||||||||||||||||
    If 0.0674 <= R <= 40 Then
        U = -0.202425716178 + 1.37784223635 * RS
        LGTA = -0.0591634288046 + 1.35706496258 * U + 0.052492798645 * U ^ 2 _
        - 0.196563954086 * U ^ 3 - 0.0601770052288 * U ^ 4 + 0.0696360270891 * U ^ 5 _
        + 0.0215297490092 * U ^ 6 - 0.0161658930785 * U ^ 7 - 0.00232531970294 * U ^ 8 _
        + 0.00147752067524 * U ^ 9
        Ta = 10 ^ (LGTA)
    End If
'||||||||||||||||||||||||||||||||||||| Pulse Duration |||||||||||||||||||||||||||||||||||||
    If 0.178 < R <= 1.01 Then
        U = 1.92946154068 + 5.25099193925 * RS
```

```
        LGTD = -0.614227603559 + 0.130143717675 * U + 0.134872511954 * U ^ 2
        + 0.0391574276906 * U ^ 3 - 0.00475933664702 * U ^ 4 - 0.00428144598008 * U ^ 5
    End If
    If 1.01 <= R <= 2.78 Then
        U = -2.12492525216 + 9.2996288611 * RS
        LGTD = 0.315409245784 - 0.0297944268976 * U + 0.030632954288 * U ^ 2
        + 0.0183405574086 * U ^ 3 - 0.0173964666211 * U ^ 4 - 0.00106321963633 * U ^ 5
        + 0.0056206003977 * U ^ 6 + 0.0001618217499 * U ^ 7 - 0.0006860188944 * U ^ 8
    End If
    If 2.78 <= R <= 40 Then
        U = -3.53626218091 + 3.46349745571 * RS
        LGTD = 0.686906642409 + 0.0933035304009 * U - 0.0005849420883 * U ^ 2
        - 0.00226884995013 * U ^ 3 - 0.00295908591505 * U ^ 4 + 0.00148029868929 * U ^ 5
    End If
        Td = 10 ^ LGTD
'|||||||||||||||||||||||||||||||||||||||| Time Window ||||||||||||||||||||||||||||||||||||||||
    If (Ta < Tv And Tv < (Ta + Td)) Then
        Pe = Pr * Exp(-TC * (Tv - Ta) / Td) * 10 ^ 6
    Else
        Pe = 0
    End If
'|||||||||||||||||||||||||||||||||||||||| Scaled Parameters ||||||||||||||||||||||||||||||||||||||||
        Ts = Tv / SCF
        DelTs = DelTv / SCF
'|||||||||||||||||||||||||||||||||||||||| Global Forces ||||||||||||||||||||||||||||||||||||||||
        Fx = Pe * DelA * CSALN
    If Xcg > X Then
        Fx = Fx
    Else
        Fx = -Fx
    End If
        Fy = Pe * DelA * CSBTN
    If Ycg > Y Then
        Fy = Fy
    Else
        Fy = -Fy
    End If
        Fz = Pe * DelA * CSGAMN
    If Zcg > Z Then
        Fz = Fz
```

```
    Else
        Fz = -Fz
    End If
        TFx = TFx + Fx
        TFy = TFy + Fy
        TFz = TFz + Fz
'''''''''''''''''''''''''''''''' Global Moments ''''''''''''''''''''''''''''''''
        Mx = (Y - Ycg) * Fz - (Z - Zcg) * Fy
        My = (Z - Zcg) * Fx - (X - Xcg) * Fz
        Mz = (X - Xcg) * Fy - (Y - Ycg) * Fx
        TMx = TMx + Mx
        TMy = TMy + My
        TMz = TMz + Mz
      Next i
    Next j
'''''''''''''''''''''''''''''''' Hull Panel 8 ''''''''''''''''''''''''''''''''
        x1 = 1.7526
        y1 = 1.524
        z1 = 0.4572
        x2 = 1.7526
        y2 = 2.1336
        z2 = 0.4572
        x3 = 1.7526
        y3 = 2.1336
        z3 = 1.0226
        x4 = 1.7526
        y4 = 1.524
        z4 = 1.0226
'''''''''''''''''''''''''''''''' Rectangular Panel, Length, and Area Increments ''''''''''''''''''''''''''''''''
        L1 = ((x2 - x1) ^ 2 + (y2 - y1) ^ 2 + (z2 - z1) ^ 2) ^ 0.5
        m = L2 / DelL2
        n = L1 / DelL1
        DelA = DelL1 * DelL2
        DelX = (x4 - x1) / n
        DelY = (y2 - y1)
        DelZ = (z4 - z1) / n
'''''''''''''''''''''''''''''''' Range to Charge ''''''''''''''''''''''''''''''''
        For j = 1 To m
        For i = 1 To n
        X = x1 + (i - 1 / 2) * DelX
```

```
        Y = y1 + (j - 1 / 2) * DelY
        Z = z1 + (i - 1 / 2) * DelZ
        R = ((X - Xc) ^ 2 + (Y - Yc) ^ 2 + (Z - Zc) ^ 2) ^ 0.5
        RS = loge* Log(R)
'''''''''''''''''''''''''''''''''''''''''''''''' Special Case Direction Cosines for Normal to a Panel ''''''''''''''''''''''''''''''''''''''''''''''''
        CSALN = 1
        CSBTN = 0
        CSGAMN = 0
'''''''''''''''''''''''''''''''''''''''''''''''' Direction Cosines for Ray From Charge ''''''''''''''''''''''''''''''''''''''''''''''''
        CSALC = (X - Xc)/ R
        CSBTC = (Y- Yc) / R
        CSGAMC = (Z - Zc) / R
'''''''''''''''''''''''''''''''''''''''''''''''' Sine and Cosine for Angle of Obliquity ''''''''''''''''''''''''''''''''''''''''''''''''
        CSZETA = CSALC * CSALN + CSBTC * CSBTN + CSGAMC * CSGAMN
    If CSZETA > 0.999 Then CSZETA = 1
        SIZETA = (1 - CSZETA ^ 2) ^ 0.5
'''''''''''''''''''''''''''''''''''''''''''''''' Side-on Pressure ''''''''''''''''''''''''''''''''''''''''''''''''
        Pso = Po* (R / Ro) ^ -1.55
'''''''''''''''''''''''''''''''''''''''''''''''' Normal Reflected Pressure ''''''''''''''''''''''''''''''''''''''''''''''''
        Pnr = Pso * 22 * (R / Ro) ^ -0.45
'''''''''''''''''''''''''''''''''''''''''''''''' Reflected Pressure ''''''''''''''''''''''''''''''''''''''''''''''''
        Pr = Pnr * CSZETA ^ 2 + Pso * SIZETA ^ 2
'''''''''''''''''''''''''''''''''''''''''''''''' Time of Arrival ''''''''''''''''''''''''''''''''''''''''''''''''
    If 0.0674 <= R <= 40 Then
        U = -0.202425716178 + 1.37784223635 * RS
        LGTA = -0.0591634288046 + 1.35706496258 * U + 0.052492798645 * U ^ 2 _
        - 0.196563954086 * U ^ 3 - 0.0601770052288 * U ^ 4 + 0.0696360270891 * U ^ 5 _
        + 0.0215297490092 * U ^ 6 - 0.0161658930785 *U ^ 7 - 0.00232531970294 * U ^ 8 _
        + 0.00147752067524 * U ^ 9
        Ta = 10 ^ (LGTA)
    End If
'''''''''''''''''''''''''''''''''''''''''''''''' Pulse Duration ''''''''''''''''''''''''''''''''''''''''''''''''
    If 0.178 < R <= 1.01 Then
        U = 1.92946154068 + 5.25099193925 * RS
        LGTD = -0.614227603559 + 0.130143717675 * U + 0.134872511954 * U ^ 2 _
        + 0.0391574276906 *U ^ 3 - 0.00475933664702 * U ^ 4 - 0.00428144598008 * U ^ 5
    End If
    If 1.01 <= R <= 2.78 Then
        U = -2.12492525216 + 9.2996288611 * RS
        LGTD = 0.315409245784 - 0.0297944268976 * U + 0.030632954288 * U ^ 2 _
```

```
        + 0.0183405574086 * U ^ 3 - 0.0173964666211 * U ^ 4 - 0.00106321963633 * U ^ 5 _
        + 0.0056206003977 * U ^ 6 + 0.0001618217499 * U ^ 7 - 0.0006860188944 * U ^ 8
    End If
    If 2.78 <= R <= 40 Then
        U = -3.53626218091 + 3.46349745571 * RS
        LGTD = 0.686906642409 + 0.0933035304009 * U - 0.0005849420883 * U ^ 2 _
        - 0.00226884995013 * U ^ 3 - 0.00295908591505 * U ^ 4 + 0.00148029868929 * U ^ 5
    End If
        Td = 10 ^ LGTD
'|||||||||||||||||||||||||||||||||||||||||||||| Time Window ||||||||||||||||||||||||||||||||||||||||||||||
    If (Ta < Tv And Tv < (Ta + Td)) Then
        Pe = Pr * Exp(-TC * (Tv - Ta) / Td) * 10 ^ 6
    Else
        Pe = 0
    End If
'|||||||||||||||||||||||||||||||||||||||||||||| Scaled Parameters ||||||||||||||||||||||||||||||||||||||||||||||
        Ts = Tv / SCF
        DelTs = DelTv / SCF
'|||||||||||||||||||||||||||||||||||||||||||||| Global Forces ||||||||||||||||||||||||||||||||||||||||||||||
        Fx = Pe * DelA * CSALN
    If Xcg > X Then
        Fx = Fx
    Else
        Fx = -Fx
    End If
        Fy = Pe * DelA * CSBTN
    If Ycg > Y Then
        Fy = Fy
    Else
        Fy = -Fy
    End If
        Fz = Pe * DelA * CSGAMN
    If Zcg > Z Then
        Fz = Fz
    Else
        Fz = -Fz
    End If
        TFx = TFx + Fx
        TFy = TFy + Fy
        TFz = TFz + Fz
```

```
'''''''''''''''''''''''''''''''''''''' Global Moments ''''''''''''''''''''''''''''''''''''''
            Mx = (Y - Ycg) * Fz - (Z - Zcg) * Fy
            My = (Z - Zcg) * Fx - (X - Xcg) * Fz
            Mz = (X - Xcg) * Fy - (Y - Ycg) * Fx
            TMx = TMx+ Mx
            TMy = TMy + My
            TMz = TMz + Mz
        Next i
    Next j
'''''''''''''''''''''''''''''''''''''' Hull Panel 9 ''''''''''''''''''''''''''''''''''''''
            x1 = 1.2954
            y1 = 1.524
            z1 = 0.4572
            x2 = 1.2954
            y2 = 1.524
            z2 = 1.0336
            x3 = 1.7526
            y3 = 1.524
            z3 = 1.0336
            x4 = 1.7526
            y4 = 1.524
            z4 = 0.4572
'''''''''''''''''''''''''''''''''''''' Rectangular Panel, Length, and Area Increments ''''''''''''''''''''''''''''''''''''''
            L1 = ((x2 - x1) ^ 2 + (y2 - y1) ^ 2 + (z2 - z1) ^ 2) ^ 0.5
            L2 = ((x4 - x1) ^ 2 + (y4 - y1) ^ 2 + (z4 - z1) ^ 2) ^ 0.5
            m = L2 / DelL2
            n = L1 / DelL1
            DelA = DelL1 * DelL2
            DelX = (x4 - x1) / n
            DelY = (y2 - y1) / m
            DelZ = (z4 - z1) / n
'''''''''''''''''''''''''''''''''''''' Range to Charge ''''''''''''''''''''''''''''''''''''''
  For j = 1 To m
    For i = 1 To n
            X = x1+ (i - 1/ 2) * DelX
            Y = y1+ (i - 1/ 2) * DelY
            Z = z 1+ (i - 1/ 2) * DelZ
            R = ((X - Xc) ^ 2 + (Y - Yc) ^ 2 + (Z - Zc) ^ 2) ^ 0. 5
            RS = loge * Log(R)
'''''''''''''''''''''''''''''''''''''' Special Case Direction Cosines for Normal to a Panel ''''''''''''''''''''''''''''''''''''''
```

```
        CSALN = 0
        CSBTN = 1
        CSGAMN = 0
'||||||||||||| Direction Cosines for Ray From Charge |||||||||||||
        CSALC = (X - Xc) / R
        CSBTC = (Y - Yc) / R
        CSGAMC = (Z - Zc) / R
'||||||||||||| Sine and Cosine for Angle of Obliquity |||||||||||||
        CSZETA = CSALC * CSALN + CSBTC * CSBTN + CSGAMC * CSGAMN
    If CSZETA > 0.999 Then CSZETA = 1
        SIZETA = (1 - CSZETA ^ 2) ^ 0.5
'||||||||||||| Side-on Pressure |||||||||||||
        Pso = Po * (R / Ro) ^ -1.55
'||||||||||||| Normal Reflected Pressure |||||||||||||
        Pnr = Pso * 22 * (R / Ro) ^ -0.45
'||||||||||||| Reflected Pressure |||||||||||||
        Pr = Pnr * CSZETA ^ 2 + Pso * SIZETA ^ 2
'||||||||||||| Time of Arrival |||||||||||||
    If 0.0674 <= R <= 40 Then
        U = - 0.202425716178 + 1.37784223635 * RS
        LGTA = - 0.0591634288046 + 1.35706496258 * U + 0.052492798645 * U ^ 2 _
        - 0.196563954086 * U ^ 3 - 0.0601770052288 * U ^ 4 + 0.0696360270891 * U ^ 5 _
        + 0.0215297490092 * U ^ 6 - 0.0161658930785 * U ^ 7 - 0.00232531970294 * U ^ 8 _
        + 0.00147752067524 * U ^ 9
        Ta = 10 ^ (LGTA)
    End If
'||||||||||||| Pulse Duration |||||||||||||
    If 0.178 < R <= 1.01 Then
        U = 1.92946154068 + 5.25099193925 * RS
        LGTD = -0.614227603559 + 0.130143717675 * U + 0.134872511954 * U ^ 2 _
        + 0.0391574276906 * U ^ 3 - 0.00475933664702 * U ^ 4 - 0.00428144598008 * U ^ 5
    End If
    If 1.01 <= R <= 2.78 Then
        U = -2.12492525216 + 9.2996288611 * RS
        LGTD = 0.315409245784 - 0.0297944268976 * U + 0.030632954288 * U ^ 2 _
        + 0.0183405574086 * U ^ 3 - 0.0173964666211 * U ^ 4 - 0.00106321963633 * U ^ 5 _
        + 0.0056206003977 * U ^ 6 + 0.0001618217499 * U ^ 7 - 0.0006860188944 * U ^ 8
    End If
    If 2.78 <= R <= 40 Then
```

```
        U = -3.53626218091 + 3.46349745571 * RS
        LGTD = 0.686906642409 + 0.0933035304009 * U - 0.0005849420883 * U ^ 2 _
        - 0.00226884995013 * U ^ 3 - 0.00295908591505 * U ^ 4 _
        + 0.00148029868929 * U ^ 5
    End If
        Td = 10 ^ LGTD
'IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII Time Window IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII
    If (Ta < Tv And Tv < (Ta + Td)) Then
        Pe = Pr * Exp(-TC * (Tv - Ta) / Td) * 10 ^ 6
    Else
        Pe = 0
    End If
'IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII Scaled Parameters IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII
        Ts = Tv I SCF
        DelTs = DelTv I SCF
'IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII Global Forces IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII
        Fx = Pe * DelA * CSALN
    If Xcg > X Then
        Fx = Fx
    Else
        Fx = -Fx
    End If
        Fy = Pe * DelA * CSBTN
    If Ycg > Y Then
        Fy = Fy
    Else
        Fy = -Fy
    End If
        Fz = Pe * DelA * CSGAMN
    If Zcg > Z Then
        Fz = Fz
    Else
        Fz = -Fz
    End If
        TFx = TFx + Fx 'Newtons
        TFy = TFy + Fy 'Newtons
        TFz = TFz + Fz 'Newtons
'IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII Global Moments IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII
        Mx = (Y - Ycg) * Fz - (Z - Zcg) * Fy 'Newton-meters
```

```
        My = (Z - Zcg) * Fx - (X - Xcg) * Fz 'Newton-meters
        Mz = (X - Xcg) * Fy - (Y - Ycg) * Fx 'Newton-meters
        TMx = TMx + Mx
        TMy = TMy + My
        TMz = TMz + Mz
      Next i
    Next j
        Ax = TFx / mm 'meters/second squared
        Ay = TFy / mm 'meters/second squared
        Az = TFz / mm 'meters/second squared
        WDx = TMx / Ix 'radians/second squared
        WDy = TMy / Iy 'radians/second squared
        WDz = TMz / Iz 'radians/second squared
'|||||||||||||||||||||||||||||||||||||||||||||||||||||||||||| Store Data ||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
        Sheets("GlobalResp").Select
        Cells(k + 2, 1) = k
        Cells(k + 2, 2) = Tv
        Cells(2 + k, 3) = Ts
        Cells(2 + k, 5) = TFx
        Cells(k + 2, 6) = TFy
        Cells(k + 2, 7) = TFz
        Cells(k + 2, 9) = TMx
        Cells(k + 2, 10) = TMy
        Cells(k + 2, 11) = TMz
        Cells(k + 2, 13) = Ax
        Cells(k + 2, 14) = Ay
        Cells(k + 2, 15) = Az
        Cells(k + 2, 17) = WDx
        Cells(k + 2, 18) = WDy
        Cells(k + 2, 19) = WDz
      Next k
    End Sub
```

"**CrewmemberEnvironment"**

```
Option Explicit
Public CP As Double 'Crewmember Position
Public CPx As Double 'Crewmember Position x axis
Public CPy As Double 'Crewmember Position y axis
Public CPz As Double 'Crewmember Position z axis
Public Md1 As Double 'First Mode of Vibration
```

Public Md2 As Double **'Second Mode of Vibration**
Public Md3 As Double **'Third Mode of Vibration**
Public LAy As Double **'Crewmember Position Acceleration**
Public LAx As Double **'Crewmember Position Acceleration**
Public LAz As Double **'Crewmember Position Acceleration**
Public LA As Double **'Crewmember Position Acceleration**
Public CPA As Double **'Crewmember Position Acceleration**
Public CPAx As Double **'Crewmember Position X axis Acceleration**
Public CPAy As Double **'Crewmember Position Y axis Acceleration**
Public CPAz As Double **'Crewmember Position Z axis Acceleration**
Public CPRx As Double **'Crewmember Radius X axis direction**
Public CPRy As Double **'Crewmember Radius Y axis direction**
Public CPRz As Double **'Crewmember Radius Z axis direction**
Public SAC As Double **'Combined Vibration Response**
Public SA1 As Double **'Mode 1 Vibration Response**
Public SA2 As Double **'Mode 2 Vibration Response**
Public SA3 As Double **'Mode 3 Vibration Response**
Public W As Double **'Angular frequency (omega) in radians/second**
Public WT As Double **'Angle, omega times Time in radians**
Public CWT As Double **'Cosine of WT (dimensionless)**
Public SWT As Double **'Sine of WT (dimensionless)**
Public W1 As Double **'Mode1-Angular frequency (omega) in radians/second**
Public W1T As Double **'Mode1-Angle, Omega times Time in radians**
Public CW1T As Double **'Mode1-Cosine of WT (dimensionless)**
Public SW1T As Double **'Mode1-Sine of WT (dimensionless)**
Public W2 As Double **'Mode2-Angular frequency (omega) in radians/second**
Public W2T As Double **'Mode2-Angle, Omega times Time in radians**
Public CW2T As Double **'Mode2-Cosine of WT (dimensionless)**
Public SW2T As Double **'Mode2-Sine of WT (dimensionless)**
Public W3 As Double **'Mode1-Angular frequency (omega) in radians/second**
Public W3T As Double **'Mode3-Angle, Omega times Time in radians**
Public CW3T As Double **'Mode1-Cosine of WT '(dimensionless)**
Public SW3T As Double **'Mode1-Sine of WT '(dimensionless)**
Public INT11 As Double **'1Integral1-Mode1**
Public INT21 As Double **'1Integral2-Mode1**
Public INT12 As Double **'1Integral1-Mode2**
Public INT22 As Double **'1Integral2-Mode2**
Public INT13 As Double **'1Integral1-Mode3**
Public INT23 As Double **'1Integral2-Mode3**

```
Public DAMP1 As Double 'Damping exponent mode1
Public DAMP2 As Double 'Damping exponent mode2
Public DAMP3 As Double 'Damping exponent mode3
Public DMP1, As Double 'Damping coefficient Mode1
Public DMP2 As Double 'Damping coefficient Mode2
Public DMP3 As Double 'Damping coefficient Mode3
Public T As Double 'time in seconds
Public dT As Double 'Differential time in seconds
Public EL11 As Double 'First time increment of acceleration Mode1 in meters/second squared
Public EL21 As Double 'Second time increment of acceleration Mode1 in meters/second squared
Public EL12 As Double 'First time increment of acceleration Mode2 in meters/second squared
Public EL22 As Double 'Second time increment of acceleration Mode2 in meters/second squared
Public EL13 As Double 'First time increment of acceleration Mode3 in meters/second squared
Public EL23 As Double 'Second time increment of acceleration Mode3 in meters/second squared
Public F1 As Double 'Mode1 frequency in cycles/second
Public F2 As Double 'Mode2 frequency in cycles/second
Public F3 As Double 'Mode2 frequency in cycles/second
```

```
Sub CrewmemberEnvironment ()
'CrewmemberEnvironment Macro recorded by James O. Pilcher II, 10/11/2014.
'Updated 2/27/2014 by James O. Pilcher II.  This Macro calculates the local and structural response of floor panel of a generic ground vehicle given the global vertical acceleration response of the vehicle to mine blast from a 13.636-kg mine located approximately at the front tire on the driver's side.  Three vibration modes of the panel are calculated. The total acceleration environment is estimated for position 1 (driver).  This version calculates over a time period 50× longer than the pulse duration.  Worksheet "Environment" is preloaded from "GlobalResp."
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''' INITIALIZATION ''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
    Sheets("Environment").Select
    Xcg = 1.524
    Ycg = 2.134
    Zcg = 1.948
    CPx = 1.952
    CPy = 1.751
    CPz = 1.216
    F1 = 278
    F2 = 603
    F3 = 798
    W1 = 2 * pi * F1
    W2 = 2 * pi * F2
    W3 = 2 * pi * F3
    DAMP1 = 0.01
    DAMP2 = 0.01
```

```
        DAMP3 = 0.01
        INT11 = 0
        INT21 = 0
        INT12 = 0
        INT22 = 0
        INT13 = 0
        INT23 = 0
'''''''''''''''''''''''''''''''''''''''''''''' CALCULATIONS ''''''''''''''''''''''''''''''''''''''''''''''
    'The calculations are in three phases.  First phase is the acquisition of the local 6DOF accelerations, the second phase is the calculation of structural response, and the third phase is the assembly of the total acceleration environment at the crewmember position.
'''''''''''''''''''''''''''''''''''''''''''''' Input Global Data ''''''''''''''''''''''''''''''''''''''''''''''
    For k = 1 To 4438
        Ts = Cells(2 + k, 2) / 1000
        Ax = Cells(k + 2, 4)
        Ay = Cells(k + 2, 5)
        Az = Cells(k + 2, 6)
        WDx = Cells(k + 2, 8)
        WDy = Cells(k + 2, 9)
        WDz = Cells(k + 2, 10)
'''''''''''''''''''''''''''''''''''''''''''''' Angular Accelerations ''''''''''''''''''''''''''''''''''''''''''''''
    'The angular accelerations are the same as those at the CG.  The equations below are without the velocity terms.
'''''''''''''''''''''''''''''''''''''''''''''' Linear Accelerations ''''''''''''''''''''''''''''''''''''''''''''''
        CPRx = CPx - Xcg
        CPRy = CPy - Ycg
        CPRz = CPz - Zcg
        LAx = Ax + CPRz * WDy - CPRy * WDz
        LAy = Ay + CPRx * WDz - CPRz * WDx
        LAz = Az + CPRy * WDx - CPRx * WDy
        LA = (LAx ^ 2 + LAy ^ 2· + LAz ^ 2) ^ 0.5
    If k < 3001 Then
        dT = 0.00000209
    Else
        dT = 0.0001
    End If
'''''''''''''''''''''''''''''''''''''''''''''' Calculation ''''''''''''''''''''''''''''''''''''''''''''''
        W1T = W1 * Ts
        CW1T = Cos(W1T)
        SW1T = Sin(W1T)
        W2T = W2 * Ts
        CW2T = Cos(W2T)
```

```
SW2T = Sin(W2T)
W3T=W3 * Ts
CW3T = Cos(W3T)
SW3T = Sin(W3T)
EL11 = LAz * SW1T * dT
EL21 = LAz * CW1T * dT
EL12 = LAz * SW2T * dT
EL22 = LAz * CW2T * dT
EL13 = LAz * SW3T * dT
EL23 = LAz * CW3T * dT
INT11 = INT11 + EL11
INT21 = INT21 + EL21
DMP1 = Exp(-DAMP1 * W1T)
INT12 = INT12 + EL 12
INT22 = INT22 + EL22
DMP2 = Exp(-DAMP2 * W2T)
INT13 = INT13 + EL 13
INT23 = INT23 + EL23
DMP3 = Exp(-DAMP3 * W3T)
SA1 = DMP1 * W1 * (SW1T * INT21 - CW1T * INT11)
SA2 = DMP2 * W2 * (SW2T * INT22 - CW2T * INT12)
SA3 = DMP3 * W3 * (SW3T * INT23 - CW3T * INT13)
SAC = SA1 + SA2 + SA3
'||||||||||||||||||||||||||||||||||||||||||||||||| Combined Environment |||||||||||||||||||||||||||||||||||||||||||||||||
'This analysis assumes that the crewmember has direct contact (through seating arrangement) only with the floor
of the vehicle; only the floor response is considered.
'||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
CPAx = LAx
CPAy = LAy
CPAz = LAz + SAC
CPA = (CPAx ^ 2 + CPAy ^ 2 + CPAz ^ 2) ^ 0.5
'||||||||||||||||||||||||||||||||||||||||||||||||||||||| Tabulation |||||||||||||||||||||||||||||||||||||||||||||||||||||
Cells(2 + k, 12) = LAx
Cells(2 + k, 13) = LAy
Cells(2 + k, 14) = LAz
Cells(2 + k, 15) = LA
Cells(2 + k, 17) = SA1
Cells(2 + k, 18) = SA2
Cells(2 + k, 19) = SA3
Cells(2 + k, 20) = SAC
```

```
        Cells(2 + k, 22) = CPAx
        Cells(2 + k, 23) = CPAy
        Cells(2 + k, 24) = CPAz
        Cells(2 + k, 25) = CPA
        Cells(1, 12) = "LAx"
        Cells(1, 13) = "LAy"
        Cells(1, 14) = "LAz"
        Cells(1, 15) = "LA"
        Cells(1, 17) = "SA1"
        Cells(1, 18) = "SA2"
        Cells(1, 19) = "SA3"
        Cells(1, 20) = "SAC"
        Cells(1, 22) = "CPAx"
        Cells(1, 23) = "CPAy"
        Cells(1, 24) = "CPAz"
        Cells(1, 25) = "CPA"
    Next k
End Sub
```

THE EFFECTS OF BLAST ON A COMBAT SYSTEM

By James O. Pilcher II

DSIAC PUBLICATION DSIAC-2021-1339

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