DESIGN OPTIMIZATION OF THE BEAGLE II MARS LANDER AIRBAGS THROUGH EXPLICIT FINITE ELEMENT ANALYSIS – AN UPDATE

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ABBREVIATIONS USED IN THIS DOCUMENT

AIAA	American Institute of Aeronautics and Astronautics
ESA	European Space Agency
FEA	Finite Element Analysis
FEMB	KBS-2 pre-processor
KG	Kilogram
M/S	Millisecond
MBA	Martin Baker Aerospace
PC	Personal Computer
PREP7	ANSYS preprocessor
PSIG	Pounds per square inch gauge
RF	Radio Frequency
ROD	Rate of Descent

KEYWORDS

Airbags
Beagle II
Mars Landing

ABSTRACT

The Beagle II Mars Lander is a portion of the European Space Agency (ESA) Mars Express program. Irvin Aerospace Limited, on contract to Martin Baker Aerospace Ltd., will provide the parachutes and airbags for the probe's landing system. The purpose of the Beagle II Lander is to deliver scientific equipment, which will perform atmospheric and soil experiments focused on identifying signs of life on the Red Planet.

To reduce development costs, the parachute system will be identical to the Huygens probe parachute, which is currently enroute to the Saturn moon Titan. This parachute has been the subject of previous papers. The parachute system, lander mass, and landing atmospheric conditions therefore define the conditions for the airbag first impact.

This paper presents the results of concept development analysis for the Beagle II mission. Airbag design requirements, including the somewhat challenging impact velocity of 30.0 m/sec are presented. Several design iterations explored using the Explicit Finite Element Analysis (FEA) code LS-DYNA are presented.

Figure 1. Huygens Probe Landing Event and Airbag Release Depiction

INTRODUCTION

The Beagle II Mars Lander is a portion of the European Space Agency (ESA) Mars Express program. Irvin Aerospace Limited, on contract to Martin Baker Aerospace (MBA) Ltd., will provide the parachutes and airbags for the probes landing system. To reduce development costs, the parachute will be identical to the Huygens probe parachute, which is currently enroute to the Saturn moon Titan. This parachute has been the subject of previous papers, including References 2, 4 and 6.

This paper presents the results of concept development analysis for the Beagle II mission. Airbag design requirements, including the somewhat challenging impact velocity of 30.0 m/sec are presented. Several design iterations were explored using the Explicit Finite Element Analysis (FEA) code LS-DYNA are presented.

The initial airbag concept, as presented by MBA, was a pair of spherical airbags, which are secured around the lander to provide a spherical enclosure around the lander. Following vehicle impact, once the lander has come to rest, airbag ties are released, and the lander is dropped a short distance to the Martian soil. The airbags spring out in opposite directions, providing a clear area for the surface sampler. Figure 1 provides a depiction of the landing event and airbag release.

Given the 'off the shelf' nature of the parachute design, the airbag impact parameters were also clearly defined. Basic landing bag design requirements are presented in Table 1.

Table 1. Basic Landing Bag Design Requirements

• Use Previously Developed Parachute (Huygens)
• Lander Weight: 33 kg
• Terminal ROD: 30 m/s
• Horizontal Velocity: 30 m/s
• Maximum Deceleration: 200 g's
• Airbag Separation Plane for Airbag Release

The initial design requirement of 100 gees acceleration was later relaxed to 200 gees, as the airbag size (and mass) continued to grow in order to meet this requirement. The discussion section will present more data on this trade and other configuration optimizations/trades which were made during the initial study phase.

APPROACH

Description of Modeling Approach

The airbag modeling approach applied to this project has been presented in previous papers (in part), including References 1, 3, and 5 and include some validation information through comparison to test data.

In general, the LS-DYNA Explicit FEA code is applied. Irvin utilizes the KBS-2 version of the code, which is suited to analysis on PC type workstations. The Version 950 Beta release and 950c release were used throughout the analysis because of some specific features in that release, including an element contact algorithm which was favorable to the task at hand.

The modeling approach includes several key features:

1) Simulation of the lander as a rigid body
2) LS-DYNA fabric model for the airbag fabric elements (Mat 34)
3) LS-DYNA airbag model for the airbag control volumes
4) LS-DYNA Discrete spring elements to model the airbag ties
5) LS-DYNA Rigid wall to model the impact plane
6) Contact definition between lander and airbag faces
7) Contact definition between airbag portions
8) Airbag to Airbag venting to maximize impact attenuation
9) Dynamic Relaxation to initialize model geometry
    - Airbag Geometry requiring pre-inflation ties
    - Stabilization of Geometry prior to impact

Several versions of the basic model have been employed, exploring variations in airbag geometry and size. Figure 2 presents a view of the most widely used model. In this model, the airbag elements are split into upper and lower segments, which has been one of the geometry trades. The 'baffle' was found to improve airbag damping and geometry distortion during impact. Additionally, Figure 2 features a lander position with a vertical offset. This configuration was investigated as an approach to optimize airbag performance. Currently, a lander centered airbag configuration is the baseline, due to the implications of second impact dynamics.

Airbag geometry was generated through several sources, including the KBS-2 pre-processor (FEMB), for initial models and the ANSYS preprocessor (PREP7), as the airbag geometry and mesh became more complex. A simple node, element translator was created (FORTRAN program) to move data between ANSYS (node and element archive format) and FEMB (NASTRAN Bulk Data Format). The current technique involves solid modeling of the airbag and lander in Solid Edge, Meshing of this geometry in ANSYS PREP7, final meshing discrete elements, etc. in FEMB, and text modification of the output deck to insert the airbag and other special cards.

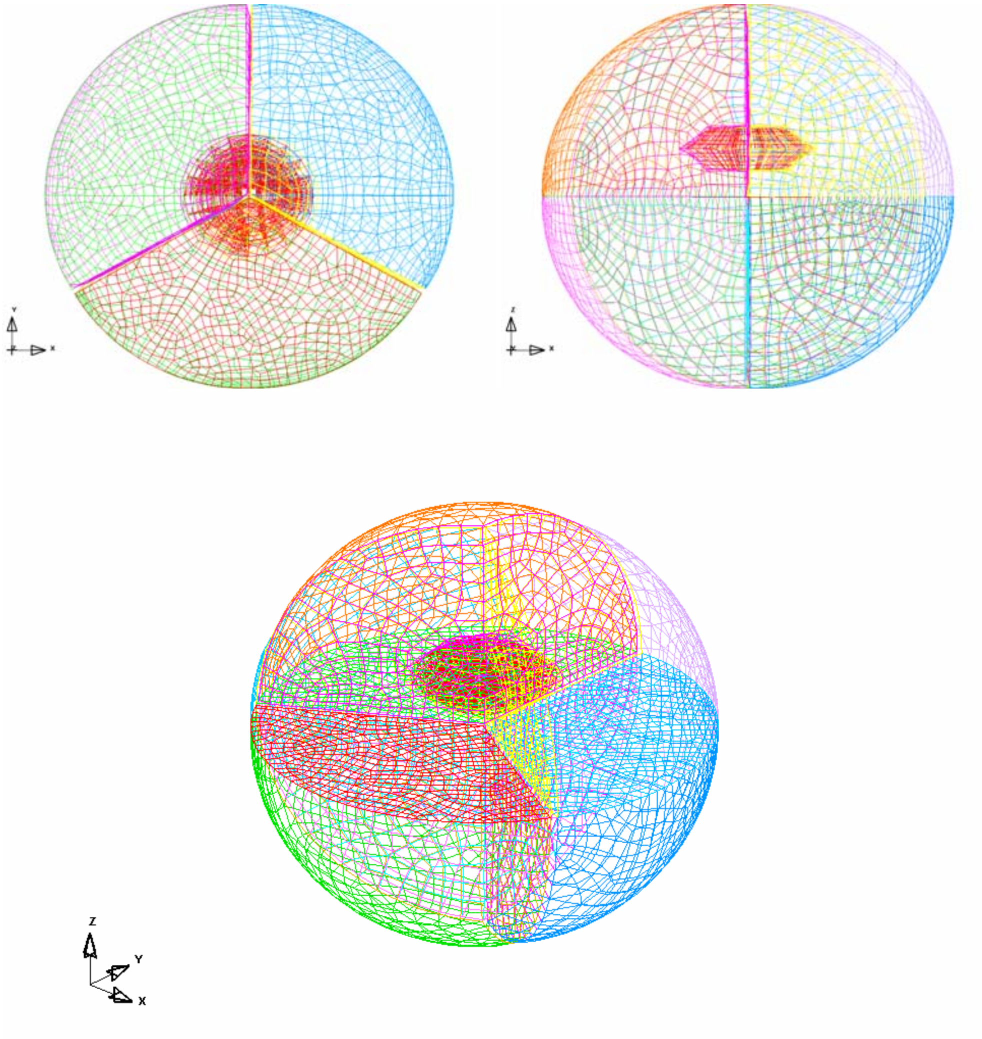

Figure 2. Airbag Models

Model Validation

All of the key modeling techniques listed above, with the exception of the discrete elements (item 4) and the dynamic relaxation (item 9) and bag to bag venting are employed in the work presented in References 1 and 3. We therefore feel that early model validation – in terms of technique - is provided by the test data correlation presented in these previous works.

The Dynamic Relaxation approach has also been applied to the work in References 1 and 3 since that work was published. Our experience is that while we pay a certain computational overhead, the resulting simulation has improved validity through reduced airbag pressure oscillation.

Analysis Approach

The approach for this analysis transitioned from a proof of concept phase, to a preliminary design optimization and finally to the current configuration definition phase. The first task, the proof of concept, involved several key steps, these included:

1) Development of simulation techniques which addressed the unique geometry of the concept presented
    - Geometry Initialization through Dynamic Relaxation
    - Simple Representation of tied sections
    - Model Reduction through symmetry
2) Initial Simulations which demonstrated that the concept was 'In the Ballpark'
3) Exploration of Airbag concepts which might improve performance
    - Simulations to sufficient detail to provide parametric data
    - Effect of 'Spokes'
    - Effect of Upper to Lower Baffle
    - Effect of Venting through the Baffle
    - Lander vertical offset

Finally, the analysis program has transitioned into a design definition phase. In this phase, we are concerned with several topics, including the following:

1) Definition of airbag fabric stresses
    - All portions of pressure vessel
    - Tie elements modeled
2) Validation of lander performance – first impact
3) Determination of second impact conditions – are these more or less energy than first impact
    - What is lander orientation at second impact
4) Parametric effect of variation in airbag pressure, as might be provided from various gas supply systems and impact timelines
5) Qualified evaluation of fabric requirements and stresses due to impact abrasion
6) The effect of horizontal orientation spokes as related to the up slope landing case

This paper concentrates on the issues presented directly above, as the earlier issues are the subject of Reference 5.

DISCUSSION

Analysis Discussion - General Approach

In general, the models employed for the analysis presented are similar to the general model discussed above, however, several significant variations were either explored or imposed, depending on significance. These variations include:

1) Dynamic relaxation prior to all simulations. This was required to initialize the airbag to airbag interfaces.
2) Airbag to Airbag vent area was the subject of some trade studies
3) Additional 'special runs' were required to explore interface unique results
4) Airbag initial pressure was varied
5) Impact condition, including horizontal and vertical velocity, and ground slope are modeled
6) Airbag to ground friction are varied to investigate abrasion
7) 'Spoke' Elements are added
8) Rock models are added to ground plane simulation for initial assessment of rock impacts

Definition of Airbag Fabric Stresses

Early definition of airbag stresses is of key importance to the airbag designers. Even before final configuration definition, preliminary indication of required fabric strength, airbag pressure, cord element forces, and the effects of airbag constructed geometry are critical to program advancement.

Key questions include, can we use high elongation fabric (nylon) or is low elongation fabric (Kevlar, Vectran, Zylon) required? What level of seam strength is required. An early approximation can dictate the difference between chemical bonding, RF welding, or sew and tape? Currently, RF Welding appears to be the preferred approach. This decision can affect not only the final planetary airbags, but even early program aspects such as developmental models.

Additionally, early definition of fabric strength, can feedback fabric weight to the analyst, improving the fidelity of early simulation models. Early definition of fabric weight or density has improved the accuracy of early LS-DYNA simulations.

Figure 3 presents a result for peak airbag loading for one impact simulation. Several impact cases are reviewed to define the peak stress for any airbag section, however, the data in Figure 3 is representative. Figure 4 presents stress data for another portion of the airbag. Due to the space weight requirements for minimum mass, segment by segment definition of fabric strength is required. For the stresses in Figure 4, local reinforcement is indicated.

Figure 5 presents the same data plotted on the un-deformed airbag shape. This presentation is particularly useful for defining stress regions to the airbag design engineer.

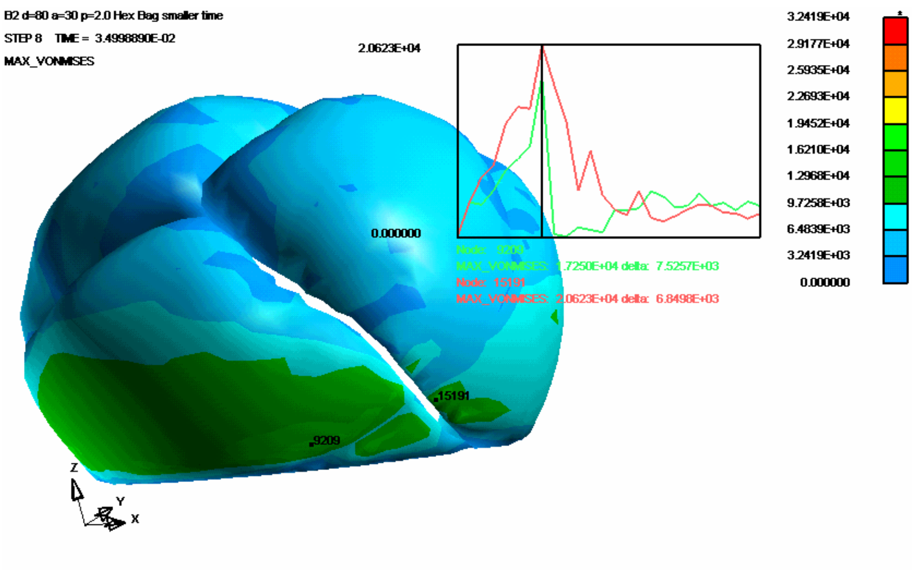

Figure 3. View of Peak Airbag Stress – Outer Shell Portion of Airbag

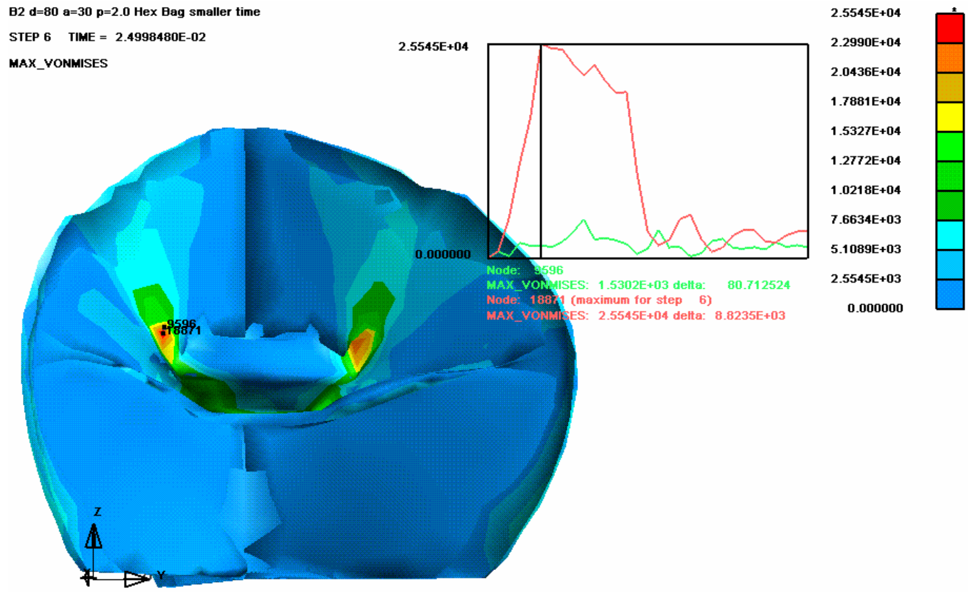

Figure 4. View of Peak Fabric Stress – Face Region of the Airbag

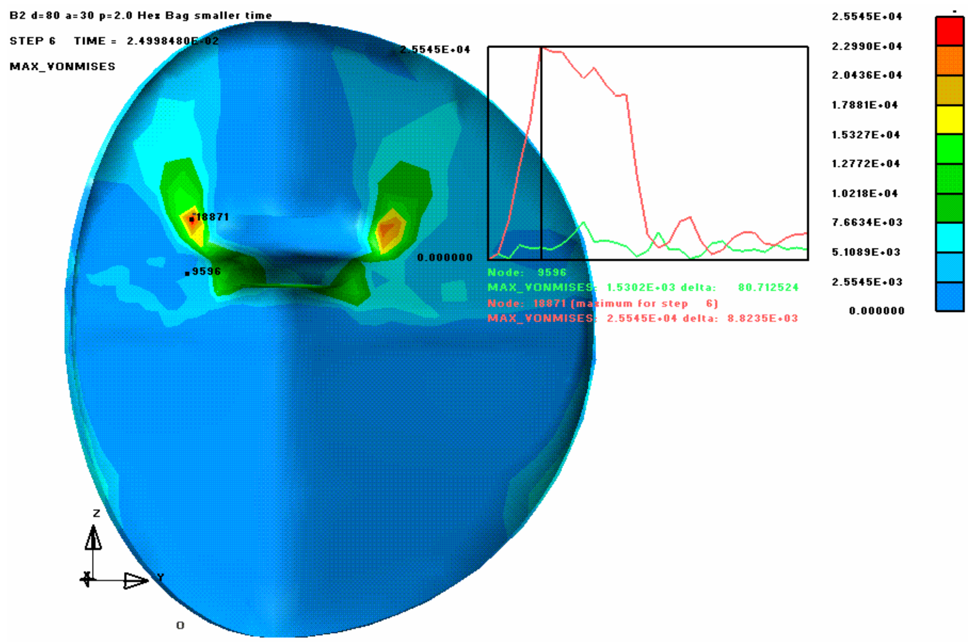

Figure 5. Face Region of the Airbag – Un-deformed Geometry

Validation of Lander Performance – First Impact

Assessment of overall lander performance includes compliance with the peak landing acceleration (200 terrestrial gees), maintenance of a minimum rock clearance (approximately 8.0 inches), and compliance for several impact conditions, including horizontal velocity and ground slope for impact. As the maximum ground slope is 15.0 degrees, this slope, combined with the maximum horizontal velocity (and nominal to maximum vertical velocity) can greatly increase initial impact energy.

Figure 6 presents a plot of resultant acceleration (in terrestrial gees) for four impact cases. The airbag configuration is the vertical offset of the lander, as presented in Figure 2. The four impact cases are summarized in Table 2.

Table 2 – Impact Case Summarization

Vvertical	**Vhorizontal**	**Ground Slope**
1200 in/sec	0 in/sec	0 degrees
1200 in/sec	1200 in/sec	0 degrees
1200 in/sec	1200 in/sec	15 degrees
1200 in/sec	-12 in/sec	-15 degrees

Impact Case Summary from Previous Report

The data in Figure 6 indicates that all cases meet the peak landing acceleration specification of 200 terrestrial gees. However, Figure 7 presents the minimum ground clearance for the up-slope landing case. This case clearly indicates that clearance for the maximum rock is not met. The minimum clearance presented in the Figure is approximately 3.0 inches. This conclusion, and revelations relative to second impact conditions, as presented in sections below, have pushed the status airbag configuration back to a lander centered configuration. These simulations are on-going at the time of this writing.

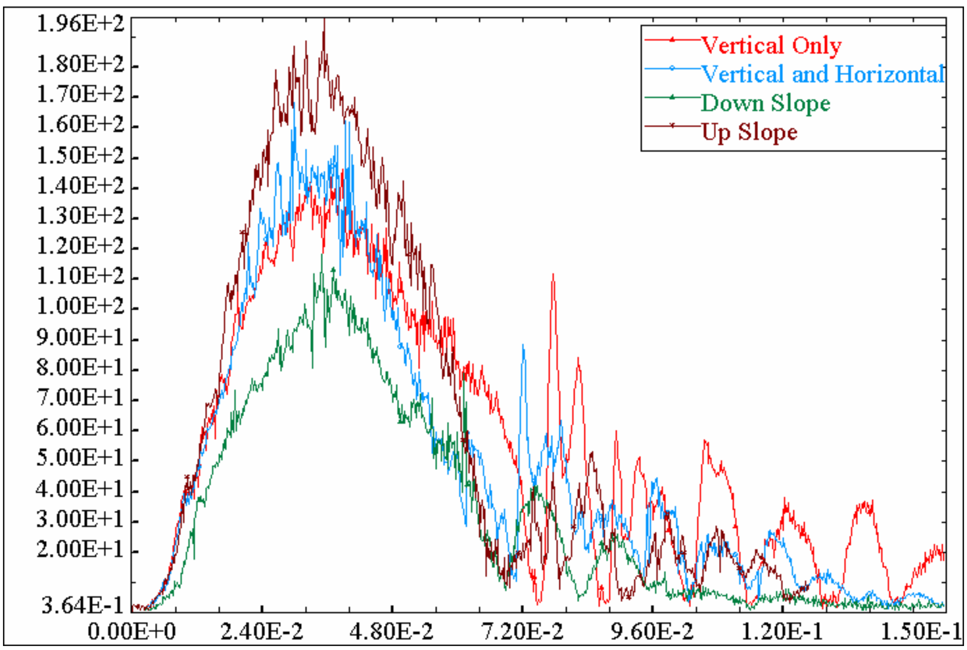

Figure 6. Lander Resultant Acceleration – Four Key Impact Cases

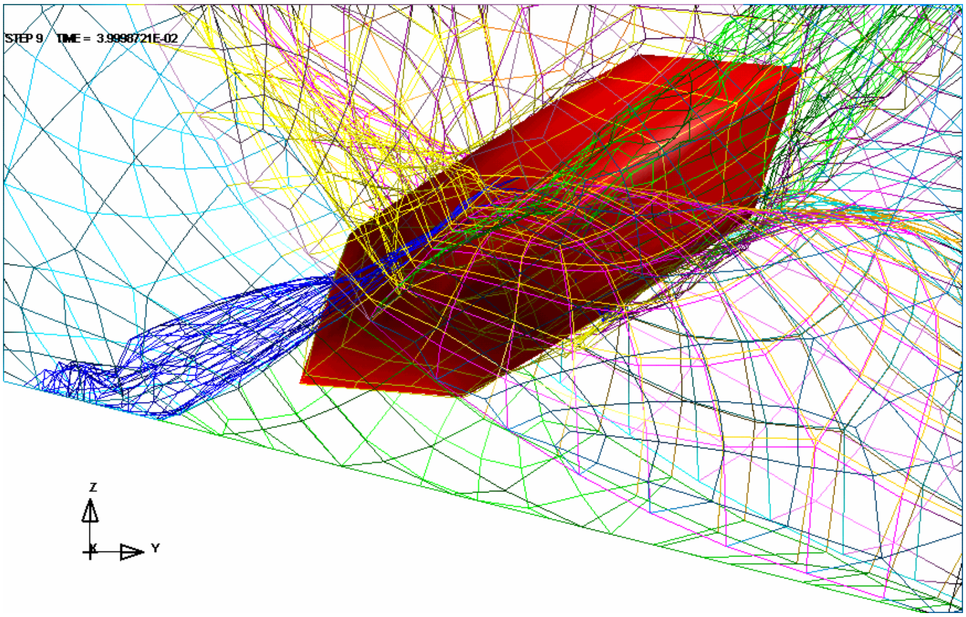

Figure 7. Minimum Lander Clearance – Up-Slope Landing Case

Determination Of Second Impact Conditions – Are These More Or Less Energy Than First Impact

Inherent in the vertical offset airbag design, is an assumption that the airbag system second impact will be of lower energy than the first impact. The first impact orientation is determined by the presence of a parachute, which is released during that first impact. Therefore the second impact, whose angular orientation is assumed to be random, must be of lower energy, due to the position of the lander.

To assure this lower impact energy (for the second bounce), we have tried to maximize the damping provided by the basic airbag configuration – which seems like a good idea generally. One tool to control this damping is a defined specified vent area in the airbag baffle (Figure 2) between the upper and lower airbag segments.

Having optimized the bag to bag vent size for the vertical impact case, we assessed four (4) impacts which tend to represent the corners of the landing envelope. For all of these cases, the maximum vertical velocity was simulated. The four cases then included; 1) no horizontal velocity, 2) maximum horizontal velocity, level impact, 3) maximum horizontal velocity, 15 degree down slope landing, 4) maximum horizontal velocity, 15 degree up slope landing.

Figure 6 presents the resultant acceleration time history for these cases. As expected, the maximum normal impact velocity (the up slope case) provides the peak acceleration. All acceleration traces meet the lander requirement of 200 gees.

Figures 9 and 10 present velocity time histories for the lander vertical and horizontal velocities, respectively. Of particular interest are the down slope landing case horizontal velocity following impact (Figure 10), and the lander vertical velocity for the up slope landing case (Figure 9).

For the down slope landing case, the rebound vertical velocity is low, but our concern was that the horizontal velocity, combine with a constant 15.0 degree down slope, would increase the systems vertical height, and thus the second impact vertical velocity. Trajectory simulations indicate that for this case, the second impact vertical energy is somewhat less than that of the first impact. However, vertical velocity is high enough, that success of an inverted (lander low) impact is unlikely, when rock clearance is considered. This case does however, illustrate the need for maximum damping during impact. Should the landing system continue to ‘bounce down hill’, without sufficient damping, impact energy would continue to increase.

Probably more decisive, is the vertical rebound velocity for the up slope landing case. Having resolved that maximum vertical velocity, horizontal velocity, and ground slope, combined with the maximum rock (first or second impact) are included in the landing envelope, the second impact challenges the lander offset configuration. Assuming no change in potential energy, the second impact has nearly the same energy as the first impact. Given a nearly random second impact orientation (with a slight tendency to lander down), we must consider the lander down, and maximum rock case. Previous analysis has indicated that this configuration cannot maintain rock clearance for vertical energies near the initial energy.

Having concluded that the vertical offset configuration is not the final configuration, a lander centered configuration in now the primary focus of study.

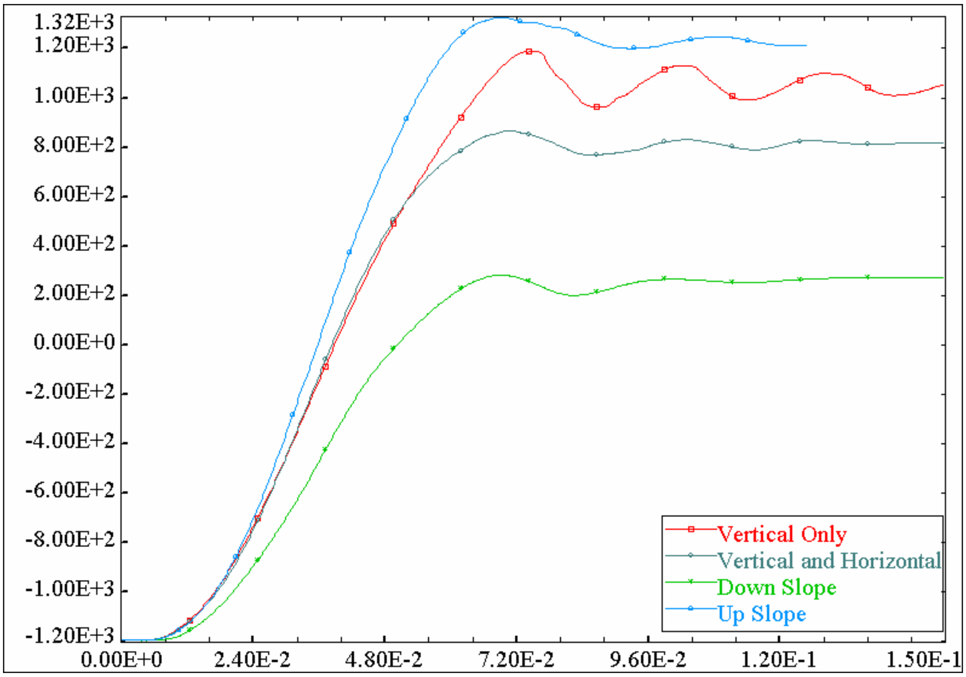

Figure 9. Vertical Velocity Time History – Corners of the Landing Envelope

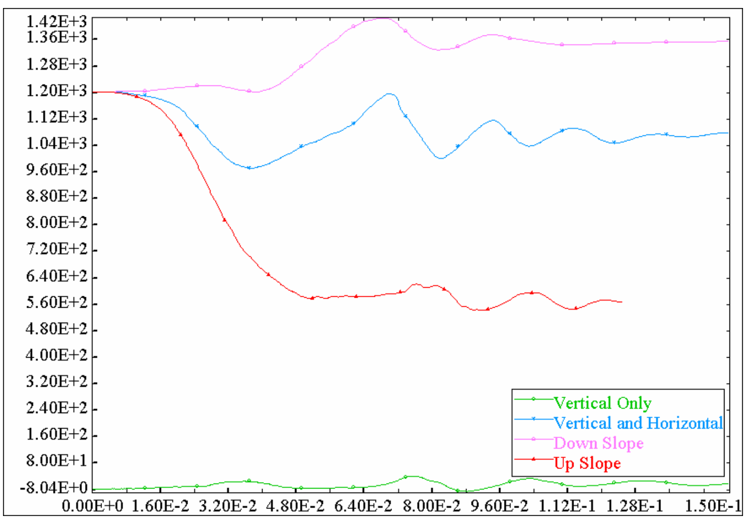

Figure 10. Horizontal Velocity Time History – Corners of the Landing Envelope

Parametric Effect of Variation In Airbag Pressure, As Might Be Provided From Various Gas Supply Systems And Impact Timelines

Another area of parametric evaluation was the impact of changes in airbag pressure for the initial impact. Motivation for this analysis include effects of gassing system and thermal variations during the initial impact, airbag cooling (and pressure loss) for subsequent bounces, and to provide parametric guidance relative to future configuration changes.

Figure 11 presents peak lander acceleration for several initial airbag pressures. Clearly, for this case, several airbag pressures are consistent with the peak acceleration limit. Lessons learned from these simulations include that, 1) Airbag pressure variations of +/- 0.1 psig – due to the gassing system – are very acceptable, and 2) tailoring of the final airbag pressure can provide adjustment of airbag performance – as opposed to geometry changes. Further to the second point, Figure 12 presents lander to ground plane clearance (as a function of time) for the various initial pressure cases. Lander/Ground contact occurs at a Lander location of –32.0 inches.

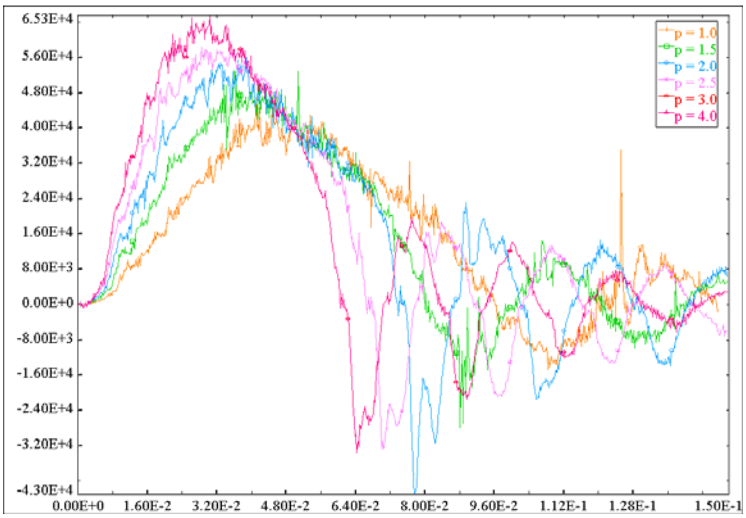

Figure 11. Lander Acceleration Time History – Various Initial Airbag Pressures

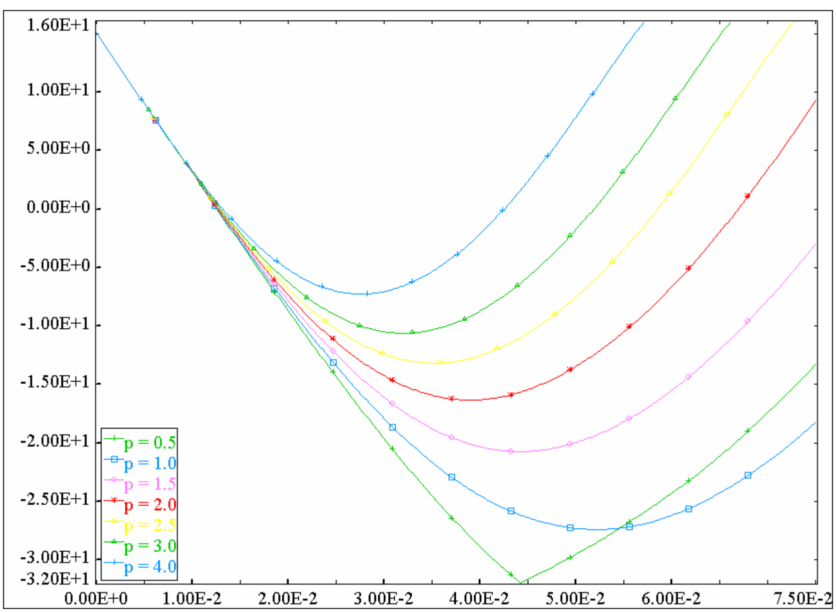

Figure 12. Lander Vertical Coordinate – Various Initial Airbag Pressures

The Effect of Horizontal Orientation Spokes As Related To the Up Slope Landing Case

The effect of horizontal ‘spoke’ elements was explore through the addition of discrete elements to the model. The spoke elements, presented in Figure 13, were assigned the properties of internal cords, including a slight (1.0 inch) pre-load. The addition of spokes was explored to improve lander ground clearance for the up slope landing case. Figure 15 presents minimum lander clearance for the up slope landing, with spokes.

The addition of spokes provides a great improvement in lander clearance, with an acceptable change in resultant acceleration. Figure 15 presents an acceleration time history comparison.

Additionally, simulation results indicate that the spokes have minimal impact for the vertical only landing case. Also, predicted spoke loads and fabric stresses are consistent with the design and available materials.

A variant of the spoke configuration, incorporating a fabric plane, rather than discrete cord elements is currently under review.

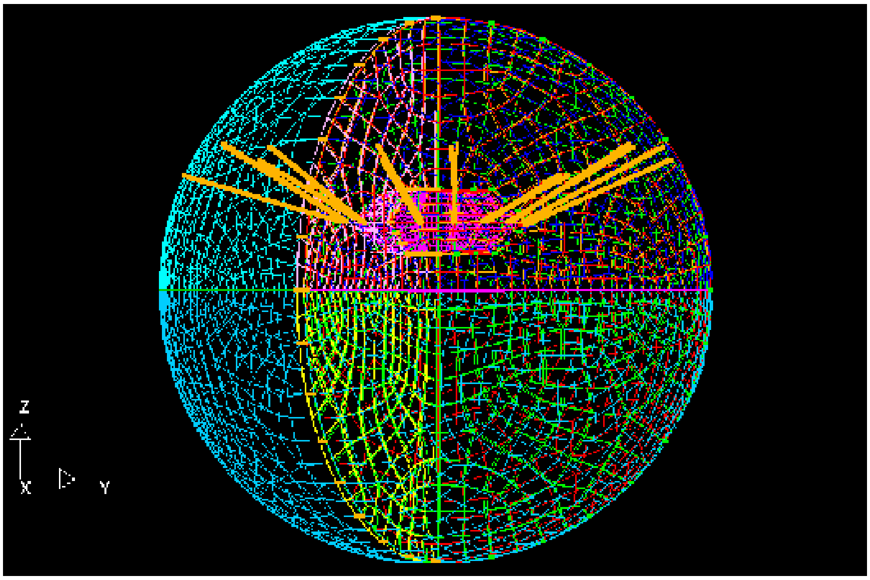

Figure 13. View of Spokes Configuration Added to Model

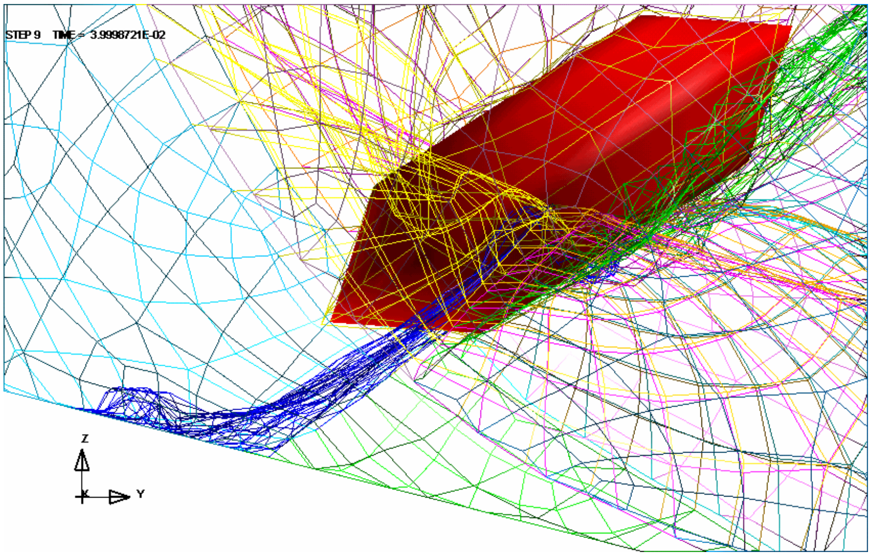

Figure 14. Minimum Lander Clearance – With Spokes – 7.1 inch Clearance

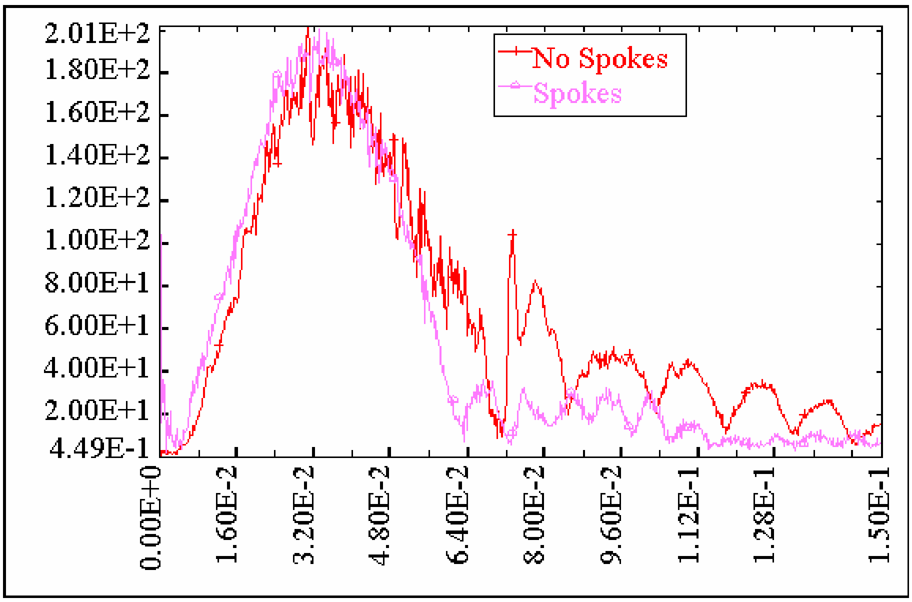

Figure 15. Acceleration Time Histories – With/Without Spokes

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