Use of LS DYNA to Simulate the Airbag Landing Impact Attenuation of the Kistler K1 Reusable Launch Vehicle

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Introduction

LS DYNA has been used to simulate the landing of a reusable launch vehicle returning to earth. In order to reduce the costs of putting many satellites in orbit, Kistler Aerospace is designing a two-stage launch vehicle to deliver payloads to orbit, figure 1.

Figure 1. Kistler K1 Reusable Launch Vehicle

Both stages of the vehicle, after performing their mission are parachuted back to earth where an airbag impact attenuation system is used for the landing touchdown event, figures 2 and 3.

Figure 2. 1st Stage Parachute Descent

Figure 3. 2nd Stage Airbag Landing

LS-DYNA has been used to assist in the design and validation of the Kistler launch vehicle by being able to accurately predict the performance and dynamics of the Irvin Industries built airbag system. Based on DYNA's proven ability to accurately predict the behavior of the Mars Pathfinder Spacecraft landing under un-testable conditions, the computer program is again being used under similar testing constraints. On the Kistler project, DYNA is being used to simulate very large heavy launch stages undergoing landing dynamic events that would be difficult and costly to test under full-scale conditions. The use of DYNA to support the K1 design has been integrated into the airbag development project to support many different tasks. DYNA's involvement in the project consists of four different phases. Phase 1 uses the modeling approach validated against test data to develop a "theoretical" model. The theoretical model does not have the complexity of the more detailed "design" model so that the theoretical model may be used for system level trade studies to support overall airbag design decisions. Phase 2 correlates ¼ scale dynamic math models against a range of test conditions performed with a scaled model drop test article. At a later point in the project, a phase 3 is implemented where a design model representing the final airbag design configuration is developed and more in depth simulations are performed. The requirements for the design model are to help in the design of the airbags themselves, where bag stresses, attachment flap stresses and launch vehicle landing interface loads are investigated. Design what ifs pertaining to structural sizing are trade studied to arrive at an optimum shape and size. The fourth and final phase validates the airbag system under the complete range of impact conditions where the entire landing event and environmental conditions are simulated. This phase incorporates into the model initial impact conditions resulting from terminal parachute velocity, horizontal winds, parachute swing and yaw, and terrain conditions such as, soils, obstacles and slopes.

Development of the LAP and OV Theoretical Models

An LS-DYNA airbag simulation model of both the Kistler 1st Stage or LAP and 2nd stage or OV have been completed. The "theoretical" models were made by first constructing a three dimensional solid model of the stage and its attached airbags. The 3-D solid models were built using the Kistler drawings provided for the project. A finite element mesh of approximately 11,000 nodes and 14,000 elements was then constructed for the LAP model, figures 4 and 5.

Figure 4. LAP Side View FEM

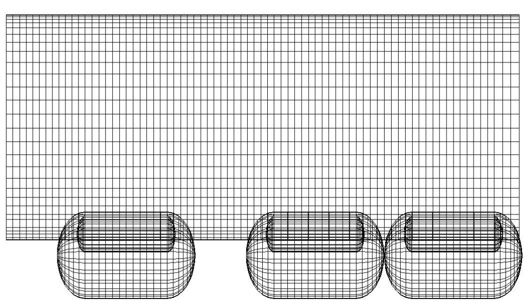
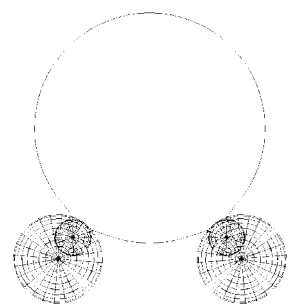


Figure 5. LAP Front View FEM



The model developed for the OV contains 6,149 nodes and 8,896 elements and is shown in figures 6 and 7. The most difficult part of the finite element modeling (FEM) was with respect to the airbags themselves. A so-called bag within a bag had to be constructed to represent the primary (vented) and secondary (non-vented) airbags. The secondary bags are inside the primary bags and act as bumpers after the primary bags vent and blowdown. The construction of the theoretical models did not address the details of the actual bag construction and stage attachment actually used in the design. However, they were modeled at a level sufficient to get a general understanding of the basic dynamic behavior of the vehicle and its airbags. The idea was to build as simple a model as possible, that would run quickly, but still have a reasonable level of accuracy. The bags were modeled as thin shells using an isotropic linear stress-strain material model and were attached to the sides of the vehicle in a rather random fashion, not representative of the real design. In the actual design the bags deploy from a stowage compartment and are attached to the inside of the compartment walls using flaps. After the basic finite element model was created, many other model parameters were developed to complete the model.

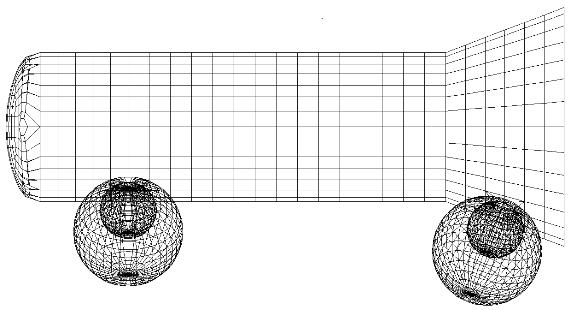


Figure 6. OV Side View FEM

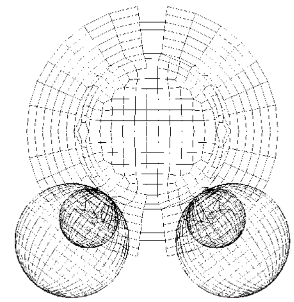


Figure 7. OV Front View FEM

Table 1 is a summary of the LAP vehicle mass properties, airbag gas constants, material properties, initial conditions, etc., used in the LS-DYNA model. Many checkout runs were made prior to the actual simulation of the LAP and OV landings to verify the airbag volumes, initial gas density, mass, temperature, etc. Runs to establish fill rates to make up for bag stretch and equivalent pop pressure initiations at 2.5 g's deceleration were also done.

1. Stage length of 600 inches.
2. Stage mass of 124.0 slugs or lbf-s2/in.
3. Roll Moment of Inertia of 1,600,000 lbf-s2-in.
4. Pitch and Yaw moment of Inertia of 5,700,000 lbf-s2-in.
5. Center of Gravity at 198 inches from the heavy end and 0,0 in the y,z-plane.
6. Primary (vented) airbag volume at 0 psig of 973,000 in3 or 563 ft3.
7. Secondary (non-vented) airbag volume at 0 psig of 151,000 in3 or 87 ft3.
8. Primary (vented) airbag volume at 3.5 psig of 1,070,000 in3 or 619 ft3.
9. Secondary (non-vented) airbag volume at 3.5 psig of 150,500 in3 or 87 ft3.
10. Airbag fill gas of 100% nitrogen (assumed) at –20 deg F or 440 deg R.
11. Airbag gas (N2) specific heat at constant volume of 1,643 in-lbf/lbm-deg R, or 634,855 in2/s2 R.
12. Airbag gas (N2) specific heat at constant pressure of 2,306 in-lbf/lbm-deg R, or 891,038 in2/s2 R.
13. Airbag gas density calculated by Dyna.
14. Ambient air density at 70 deg F of .00000011 lbf-s2/in4.
15. Airbag vent area of zero for the non-vented airbag.
16. Airbag vent area of 314 in2 and a .95 discharge coeff. for the primary bags.
17. Initial gage pressure of 3.5 psi for the primary airbags.
18. Additional gas added to the primary airbags to compensate for bag stretch of 006 lbf s2/in.
19. Initial gage pressure of 3.5 psi for the secondary airbags.
20. Note; interaction of initial pressures in both bags plus the added gas in the primary bag result in all bags being at 3.5 psig, at impact.
21. Pop pressure of 4.4 psig for the vented airbags. Note; individual bags do not vent until reaching their pop-pressure.
22. Initial vertical velocity at impact of –264 in/s, no horizontal velocity.
23. Airbag material modulus equal to 1,000,000 psi with thickness of .010 in.

Table 1. LS-DYNA LAP Impact Model Input Parameters.

Model Correlation to ¼ Scale Experimental Drop Test Data

Part of the effort to help design and validate the airbag system involves DYNA results being crosschecked and correlated against available experimental test data. Correlation of simulation data to experimental test data helps to provide confidence in the mathematical modeling approach and assumptions made in construction and solution of the simulation model. Using the same correlated modeling approach as applied to the full-scale vehicle provides for greater confidence in numerically predicting the dynamics of the real vehicle. Therefore the DYNA data produced from the full scale simulations, can be used to assist in trade studies and design validation, in regards to airbag performance, fabric stresses, interface loads, etc. The approach used required correlating the test results obtained from ¼ scale, LAP drop tests to the DYNA simulation results made using a math model of the ¼ scale vehicle.

The LS-DYNA model developed for the ¼ scale test vehicle was based on the previously developed LAP "theoretical" model except for the substitution of an exact, but scaled finite element mesh of the stage and airbags and a reduction in the number of airbags from six down to four. Other test vehicle parameters such as mass properties, impact velocities, and bag pop pressure where also changed to reflect the ¼ scale test vehicle's experimental values. Otherwise the theoretical math model and ¼ scale test model where exactly alike. Only one other exception was updating of the material model, to a fabric material, in place of the earlier thin shell model. Based on successful correlation to the test data, the ¼ scale test model would therefore be the basis for further development of the full-scale LAP and OV "design" models. Figure 8 taken from the DYNA simulation results show the ¼ scale vehicle just after impact.

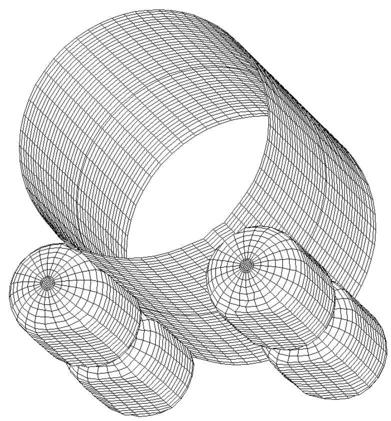


Figure 8. ¼ Scale DYNA Simulation at Impact

The test data used for the comparison was taken from an Irvin report, GIR 85-763 that contains data for a number of different drop tests. Test cases 2, 3, 4, 5, 7 and 8 were simulated using DYNA and compared to the test results contained in the report. In general, the six different tests represent variations in impact velocities, orifice size, and acceleration pop pressures. Correlating against a number of different test data points obviously gives greater confidence in the computer program's ability to accurately predict real world events. Table 2 summarizes the

Test No.	First impact acceleration g's		Second impact acceleration g's		Outer bag peak pressure psia	
	Test	Dyna	Test	Dyna	Test	Dyna
2	5.6	5.6	1.4	1.2	19.8	19.5
3	5.6	5.7	1.5	1.4	19.9	19.9
4	6.1	5.0	1.6	1.8	20.1	19.8
5	5.5	5.5	1.3	1.8	20.1	20.1
7	4.2	4.2	2.1	1.9	19.7	19.7
8	3.5	3.4	2.1	2.1	19.2	19.2

Table 2. Correlation of ¼ Scale Experimental Data to LS-DYNA Simulation Results

comparison between the simulation results and the test data. The results show a very close correlation to the test data across the board. Other than just a few points, the correlation is almost exact and this was achieved with no tweaking of model input parameters. These results were obtained by building an exact mathematical model of the individual test cases and directly presenting their results. It might be added that the use of a .70 discharge coefficient, as used in the Irvin Industries airbag4 computer simulations, helped produce these results.

The data in table 2 was developed from a careful comparison of the DYNA simulation results to the applicable test data contained in the Irvin report. As an example of the comparison only one test case will be described in detail. Figure 9, 10, and 11 plot comparisons of test data, DYNA results and the Irvin Airbag4 results for; impact g's, bag pressure and velocity.

Figure 9. Comparison of 1/4 Scale Test Data, DYNA and Airbag4 Simulations

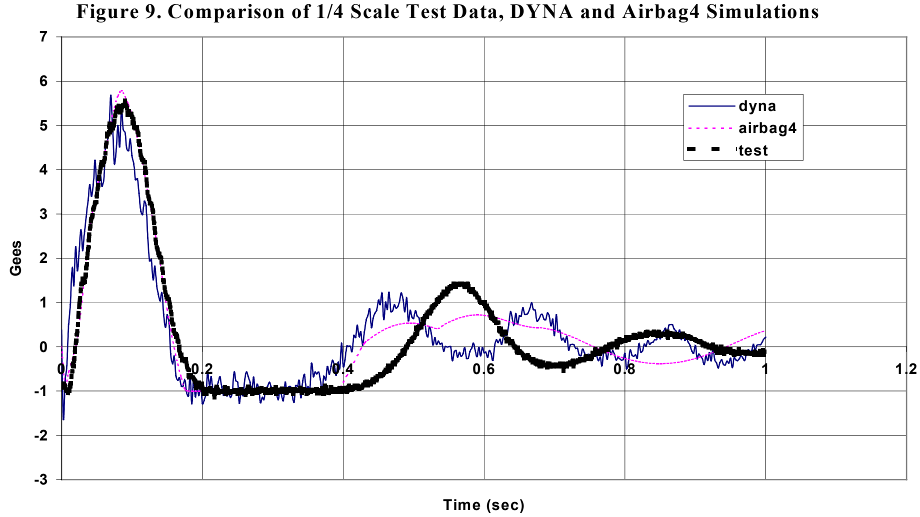


Figure 9 plots the DYNA calculated rigid body acceleration at the vehicle's center of gravity. And compares it to the response of the ¼ scale LAP vehicle taken from the center station vertical accelerometer. Figure 9 shows a peak acceleration of 5.6 g's occurring at a time of .07 seconds for the DYNA unfiltered data. The experimental results indicate a peak acceleration of 5.58 g's occurring at .076 seconds. The comparison to DYNA is within .006 seconds for the time at which the peak acceleration occurs and the magnitude is within .4%. Further comparison of the results show that the initial impact on the primary bag took place over a period of .19 to .20 seconds, for both analysis and test. To evaluate the 2nd impact on the bottoming bag, the DYNA data showed a 1.2 g peak on the non-vented bag at around .48 seconds after impact. This compared to a measured 1.4 g's at .56 seconds.

The velocity comparison is shown on figure 10, next page, DYNA calculated a maximum rebound velocity of 3 fps compared to 3.7 fps for the measured velocity and predicts the same rigid body oscillation as the vehicle settles out on its bottoming bags. Comparison of the bag pressures, figure 11, also on the next page, shows a DYNA value of 19.45 peak absolute pressure compared to about 19.8 psia for the test data and with the peaks occurring at .06 and .08 seconds for both the DYNA and experimental data. The pressure comparison was done for just one of the outer airbags, similar comparisons were found in general for all other airbags. Evaluation of the test data, DYNA simulation results, as well as the Airbag4 results, all showed a very close correlation. Based on these results, it seems reasonable that LS-DYNA can be used as an engineering tool to help in the design and analysis of airbag landing impact attenuation systems and has allowed for further development of the so called "design" models.

Figure 10. Velocity Comparison of 1/4 Scale Test Data, DYNA and Airbag4

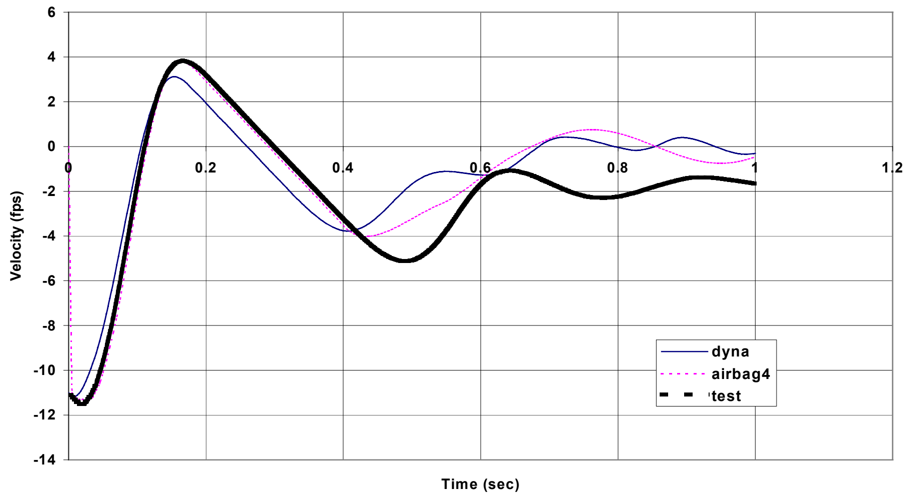
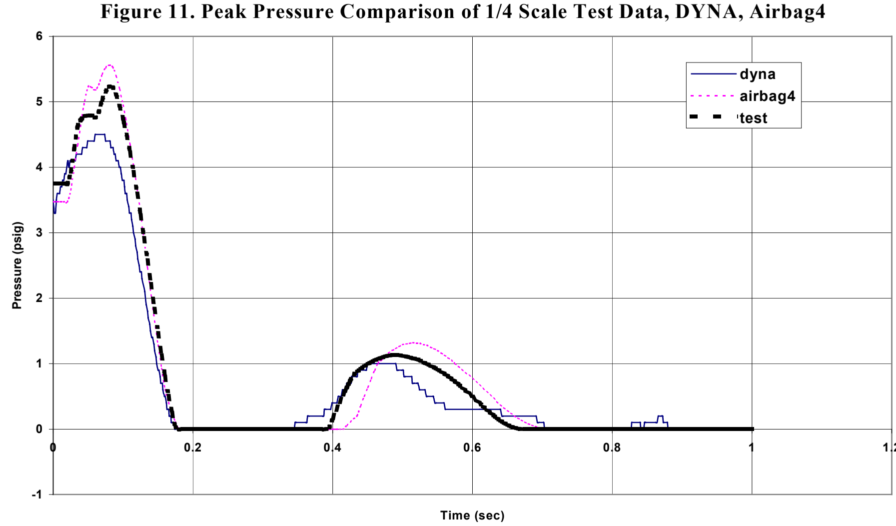


Figure 11. Peak Pressure Comparison of 1/4 Scale Test Data, DYNA, Airbag4



Development of the LAP and OV Design Models

The LAP and OV models are called "design" models because of their higher fidelity and intended usage. An earlier "theoretical" model of the LAP consisted of 10,900 elements and was used to get a basic running model. The design model is made of 42,372 elements and was constructed with the purpose of simulating the LAP airbags with as much accuracy as possible.

In comparison to the theoretical model, a number of significant improvements in the modeling approach were made to help achieve a more realistic model. The earlier shell model that incorrectly assumed material bending was replaced with a fabric element. This element is a membrane element that carries only in plane forces; in addition the no compressive stress option was also successfully implemented. The isotropic stress-strain law for the material itself was not changed and its modulus remained 1,000,000 psi as before. The material thickness was again assumed to be 0.01 inches in the bag and 0.05 inches in the flaps.

The most significant change in the design model is in the modeling of the bag attachment to the vehicle. Here the airbag compartment walls were included and flaps attached to the walls at their hinge locations were used to connect the bags to the vehicle. Because of the expected large loads introduced into the flap and bags at these attachment points, a lot of work was put into this portion of the modeling effort in order to get a model that would correctly predict this effect as best as possible. The main goal of this design model is to get very accurate predictions of bag and flap stresses. For that reason, a fine as mesh as was economically possible was used both in the bag acreage and at the flap to bag attachment points.

The modeling approach used to simulate the inner bag and its interface with the outer bag was updated and improved as well. A much more rigorous modeling effort was made in more accurately simulating how the surfaces of the vehicle, outer bag, inner bag, flaps, and compartment walls all interfaced with one another. Also the airbag control volume definition approach was modified in a way that resulted in a significant reduction in total elements used for the same level of accuracy achieved. Previously, the inner bags were modeled using two layers of coincident elements at half their thickness. This was done so that the primary, non-vented bag could be made from one material with consistent node connectivity resulting in uniform outward normals. A similar approach was applied to the non-vented bag. In the design model the double layering of elements for the inner bag was reduced to one layer only, at its 0.01 thickness. This approach was made possible by using a multi-material airbag control volume definition. The vented airbag is made from two parts. Part one is the outer wall and part two is the inner wall. The non-vented bag is also made of two parts, with part one being the same inner wall as defined in the vented bag. And part two is the interface material that transfers the flap loads into both the inner and outer airbag. This approach saved the number of elements used to define the inner airbag times six airbags.

Figure 12 shows the fine overall meshing of the LAP airbags and 1st Stage, this view is taken from the LS-DYNA computer simulation at .10 seconds after impact and shows the deforming shape of the outer airbags during blowdown. Note the bands of finer elements that are the result of the flap geometry and how it propagates through the mesh. Figure 13, next page, shows a typical inner and outer airbag cross-section, an airbag compartment and the attachment flaps In figure 14 one sees the mesh definition of the smaller inner airbag and the flaps that are used to attach both the inner and outer airbags. The outer airbag has been removed for clarity.

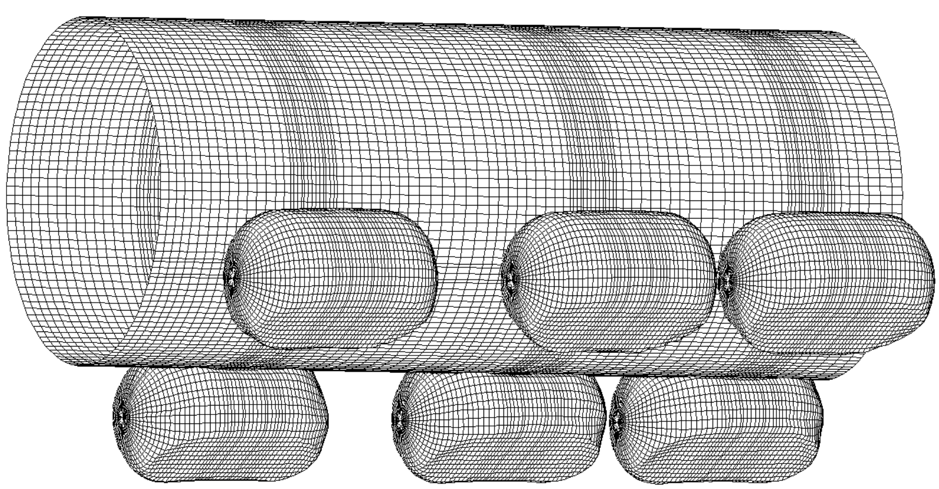


Figure 12. High Fidelity LAP Design Finite Element Model

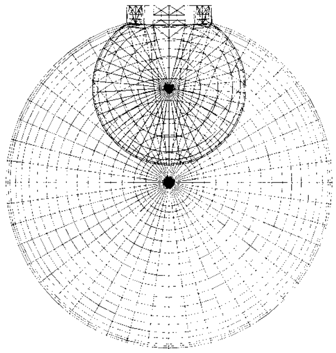


Figure 13. Outer Bag and Attachments

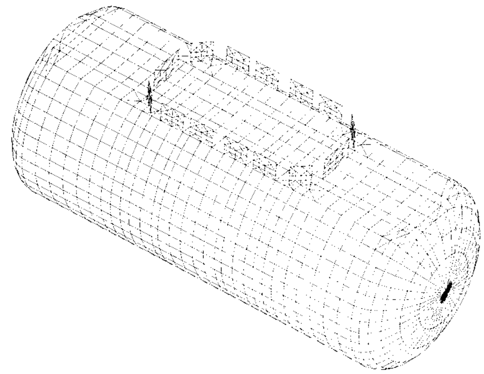


Figure 14. Inner Bag and Flaps

The OV "design" finite element model contains 55,377 elements; figure 15 is again taken from the LS-DYNA impact simulation showing the airbags being compressed between the ground plane and the sides of the vehicle. This model provides a discritization level of accuracy that is approaching practical limitations in terms of economical solution times. The runs were initially made on Pentium Pro 200 MHz machines; later runs were made using the 400 MHz machines, which reduced the solution time in half. It would be safe to say that any further decrease in element size, to get better stress results, would just be too prohibitively expensive.

The same basic modeling approach as used in the LAP model was applied to the OV model as well. The bags were made by first constructing the 60 inch diameter flat portion so that it would mate up to the flaps. Then both the outer bags and inner bags were meshed to interface with the initially flat portion of the bags.

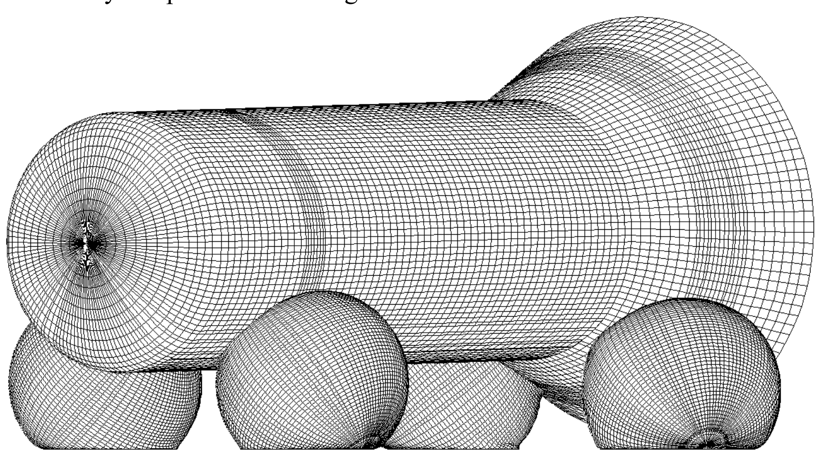
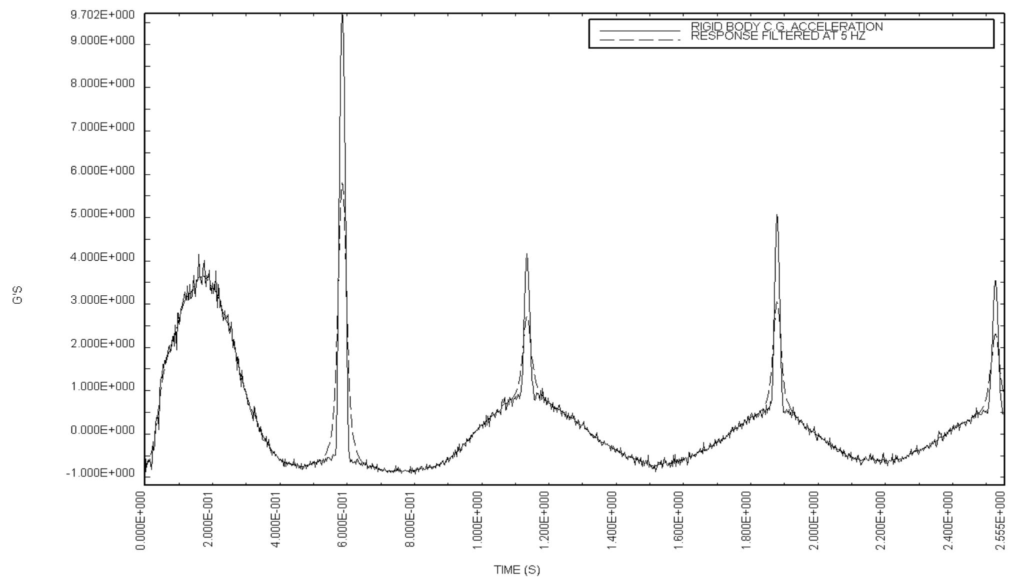


Figure 15. LS-DYNA Landing Simulation of the Kistler OV 2nd Stage

Figures 16 shows the vehicle impact acceleration for the first 2.55 seconds of the 1st stage LAP impact simulation. The raw acceleration curve has been filtered at 5 Hz and is shown as a dotted line in the figure. This was done to filter out the higher frequency content of the response and have a low frequency acceleration value to be used for vehicle design purposes. The design specification for the 1st stage is to limit the acceleration to 5 g's. The large outer airbags attenuate the 21 foot per second impact well below the requirement. The secondary impact on the inner "bumper" airbag is slightly higher and will require some adjustment of the various airbag design parameters. Subsequent rebounds as the vehicle settles out are attenuated by the "bumper" bags within the 5 g specification.



Figures 16. LS-DYNA LAP Simulation Rigid Body Acceleration at C.G.

Figure 17 plots both the airbag pressures in the inner and outer airbags and at both the forward and aft ends of the vehicle. The inner airbags are initially pressurized at .50 psig less than the outer bags. On impact the outer bag contacts first and the pressure rapidly rises and starts to become larger than the inner bag. However, even though the inner bag is not being squeezed and compressed from the ground impact, its pressure rises due to the fact that it is inside the outer bag. Soon thereafter the outer bag reaches its pop pressure of 4.4 psig and vents down to atmospheric pressure whereby the kinetic energy of the impact is lost to the escaping gas. Because it is difficult to get the vehicle to a zero velocity, the inner bags that do not vent are used to absorb any residual velocity. Because the inner bags are non-vented there are a number of subsequent rebounds whereby the inner bag shows some rather large pressure pulses.

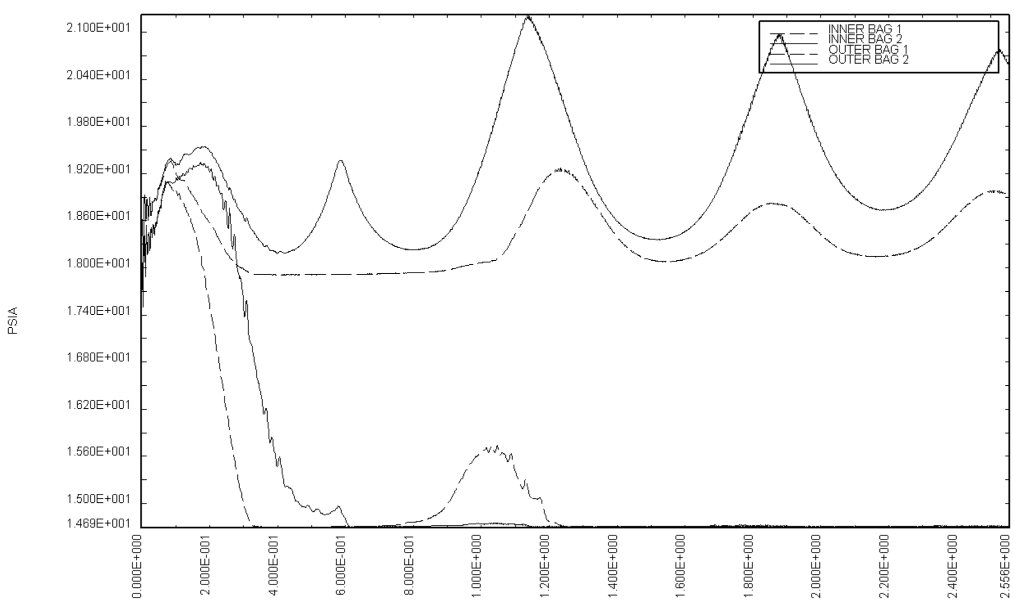


Figure 17. Typical LAP Inner and Outer Airbag Pressures

Conclusion

LS-DYNA has been used to support the development of the airbag landing impact attenuation system for the Kistler K1 launch vehicle. The first task was the construction of more simple so called theoretical models of both the 1st and 2nd stages. These models were used to perform impact simulations to validate the basic modeling approach. The next task involved construction of a ¼ scale LAP model at the same level of discritization as in the theoretical model but with the inclusion of a more realistic fabric material model. Comparison of the simulation results to the experimental test data was done over a number of test conditions and the results showed excellent correlation. The next phase resulted in the construction of two very highly detailed design models where all the complexities of how the bags are designed and attached to the vehicle was simulated. Although these models are time consuming to run, they provide a very detailed level of analysis that will be used by the airbag development contractor, Irvin Industries, to perform a number of task in an attempt to optimize the design of the vehicle and its airbags. Initial results of these models predict vehicle impact accelerations and individual bag pressures for both the inner and outer airbags. The model has also been validated against analytical equations to predict the correct membrane stresses in the cylindrical, elliptical and spherical portions of the inner and outer, LAP and OV, airbags. Further work will focus on using LS-DYNA to simulate the landing of the vehicle under un-testable design conditions and evaluate the performance of the airbags with the goal of improving the design to the fullest extent possible.