APPLICATION OF OPTIMIZATION SOFTWARE TO AID THE DESIGN OF AN AIRBAG DECELERATOR SYSTEM

Benjamin A. Tutt and John M. Sanders
Irvin Aerospace Inc. Santa Ana, California

Sonalee Myneni
Altair Engineering Inc. Irvine, California

Abstract

This paper documents the development of an airbag decelerator system for the National Aerospace Laboratory of Japan (NAL) devised Jet Powered Supersonic Experimental Airplane (NEXST-2). An optimization tool, Altair HyperStudy, has been employed to optimize the design of the airbag system. The results presented highlight the benefit of using such software for a complex system containing many variables.

Introduction

The NEXST-2 forms the jet-powered half of the Japanese experimental supersonic transport project. This project, supported by the Japanese Heavy Industry: Mitsubishi, Kawasaki, Fuji and AI Ishikawajima Aerospace began in 1997 with the aim to establish leading-edge technologies required by a next-generation supersonic transport – a 300 seat aircraft that cruises at more than twice the speed of sound, see Figure 1.

Figure 1

The first test launch of the NEXST-1, the non-powered half of the supersonic transport project, failed in a very public and spectacular fashion last summer in the Australian desert. The 1:10 scale model was attached to a purpose built rocket that was designed to thrust it to a height of 12.5 miles and a speed of 1,522 mph. After the 14 minute test flight, the two ton, unmanned aircraft was expected to release its Irvin Aerospace developed parachutes and undergo a controlled descent. Unfortunately, only seconds after launch the aircraft lost control and began an erratic spiral towards the Earth.

The purpose of the NEXST-1 was, and still is, to assess the aerodynamic performance of the vehicle and gather data to validate the many hours of wind tunnel and computer simulation work.

The purpose of the NEXST-2, due to fly in 2006, is to demonstrate the integration of a composite structure, propulsion system, stable air-intakes and sonic boom reduction techniques.

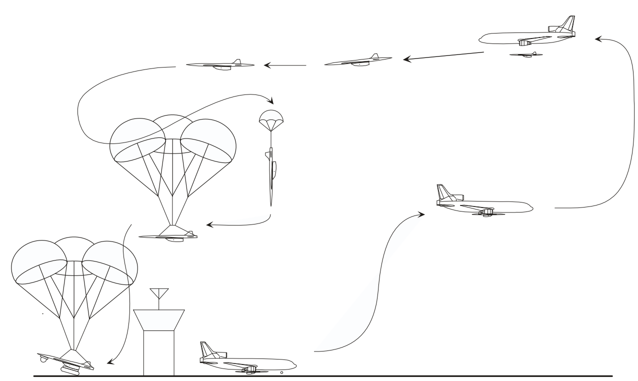

Figure 2

The 2750kg unmanned test vehicle will be launched from a large carrier aircraft at a pre-defined altitude. Upon completion of its flight test the tailcone of the aircraft will be ejected, releasing a drogue chute and subsequent cluster of three main canopies. The vehicle will then undertake a reorientation sequence and stabilize in a horizontal position under the cluster. At a specific height above the landing zone, compartment covers will be explosively opened and the airbags will begin inflation. Figure 2 summarizes this flight plan.

System Requirements

Under parachute, the NEXST-2 will be descending at a rate of 6.5 m/s. The nature of the system and the prevailing environmental conditions dictate that it could be landing with a yaw angle of anywhere between 0 and 360 degrees with a lateral velocity of up to 6 m/s. This effectively means that the impact attenuation system is required to be a multi-directional decelerator.

The allowable impact deceleration for this system is 6 g (58.8 m/s^2). The vehicle is also required to maintain ground clearance for a number of hours after the initial impact.

Decelerator Downsizing

Airbags continue to increase their popularity for the impact attenuation of air vehicles such as the NEXST-2. The aerodynamic test nature of the flight, dictates that any recovery system be stowed internal to the airframe. Air bags require little stowage volume relative to a crushable alternative. They also lend themselves to internal stowage as deployment can be driven by the inflation process.

Another significant recovery system design driver is the large engine nacelles that hang a considerable distance below the fuselage, see Figure 3. Both the high percentage of the compression stroke used for shock absorption and the total energy absorption capability of an airbag system aid the protection of these large nacelles.

Figure 3

The use of a permanently inflated anti-bottoming airbag will enable the vehicle to remain off the ground and provide protection against a rocky terrain until ground support arrives.

Simulation Software

Irvin Aerospace has applied the Finite Element Analysis (FEA) tool LS-DYNA to many airbag and fabric structure problems, developing a high level of confidence in the ability of this tool to accurately predict the performance of airbags during impact. These applications include the HOPE-X High Speed Flight Demonstrator (HSFD)[1] a similar airbag decelerator program completed for Fuji Heavy Industries.

Further information regarding Irvin's application of this tool and correlation with test data is presented in References 2 through 6.

The LS-DYNA tool has several unique features, which make it well suited for modeling this class of airbag system, these include:

- An airbag control volume algorithm that handles the thermodynamic calculations related to airbag deformation and gas venting, and applies the resulting airbag pressures back onto the airbag structure.
- Active control of the airbag venting.
- Incorporation of airbag vent blockage modeling.
- Rigid body material definitions, which simplify vehicle structure and significantly reduce the computational overheads associated with the modeling process.
- Fabric material definition, which enables fabric behavior to be accurately modeled.

The greatest advantage that LS-DYNA holds over most other FEA tools is its ability to accurately predict and handle the large deformations associated with a fabric structure, particularly one that vents.

Historically, airbag design has relied heavily upon expensive and extensive testing to develop a sufficient system. Recently, with simulation advances and the exponential increase in the price of conducting tests, the popularity of computer modeling has increased in the recovery system industry.

Optimization software has evolved significantly over the past 5 years and is regularly used in many other industries. It is currently at a stage where it can play a valuable part in automating the search for an optimum airbag decelerator design.

Closed-loop optimization software is currently restricted to the field of linear statics problem solving. The optimization technique that Altair has chosen to develop for systems involving behaviors of a non-linear type is to create an add-on to existing non-linear solvers. This add-on links a response surface or finite difference sensitivity analysis optimization method to the inputs and outputs of the associated solver[8].

Usually intuition and past experience leads the iterative process of finding the best design. Although in past experiences these characteristics have also been known to, at times, blinker the development process. In some cases, particularly when a problem involves many variables the determination of design modifications based upon analysis results can become complicated. In these cases system optimization based upon computational methods can be a useful tool to support the design process

Airbag Configuration Development

Figures 4 through 6 illustrate several of the airbag configuration concepts analyzed during the early stages of this program.

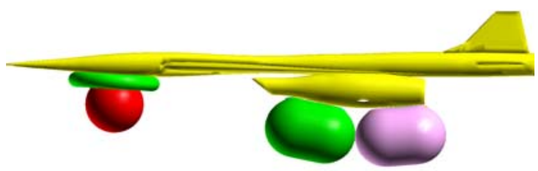

Figure 4

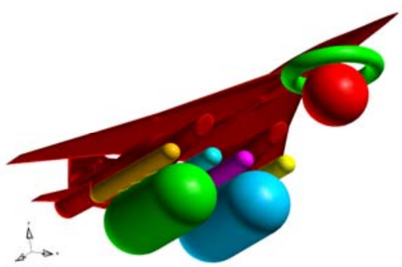

Figure 5

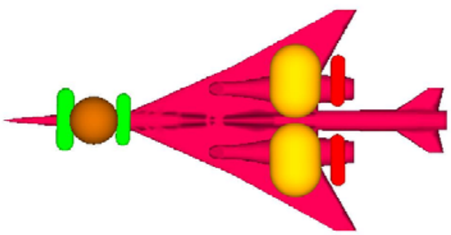

Figure 6

Optimization

The optimization process can be described as a mathematical relationship consisting of objectives, responses and constraints.

Objectives are typically global characteristics relating to the economy, mass or appearance of a system. Responses may include: stresses, displacements, accelerations or forces. Constraints are then applied to these responses. In general, the design problem can be summarized as follows:

Objective: $\psi_0(\mathbf{p}) \Rightarrow \min$ (1)

Constraints: $\psi_i(\mathbf{p}) \leq 0$ (2)

Design space: $\mathbf{p}^l \leq \mathbf{p} \leq \mathbf{p}^u$ (3)

Let $\psi_i(\mathbf{p})$ be the response of interest. The vector $\mathbf{p}$ contains the design variables. Then, a polynomial $\hat{\psi}_i(\mathbf{p})$, termed the response surface, of the degree q can be introduced such that:

$$\psi_i(\mathbf{p}) \approx \hat{\psi}_i(\mathbf{p}) \quad (4)$$

and,

$$\hat{\psi}_i(\mathbf{p}) = a_{i0} + \sum_{j=1}^{n} a_{ij} p_j + \sum_{j=1}^{n} \sum_{k=1}^{n} a_{ijk} p_j p_k + \ldots \quad (5)$$

where,

$i = 1, 2, \ldots, m+1$
$j, k = 1, 2, \ldots, n$

with the number of constraints m, the number of design variables n, and the polynomial coefficients a_{i0}, a_{ij}, a_{ijk}.

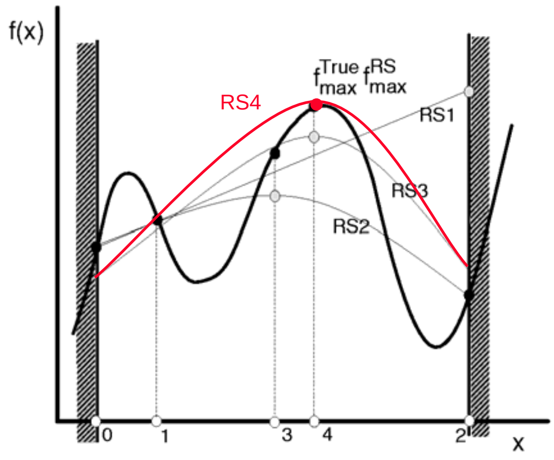

Figure 7

The polynomial coefficients are determined using a least squares fit of the response surface function on the non-linear analysis results. The optimization procedure uses the Sequential Response Surface method and is as follows[7]:

1. Analyze the initial design and n perturbed designs (1+n).
2. A least squares technique is used to determine the polynomial coefficients for the objective and each of the constraint functions.

- If the number of designs analyzed is 1+n, the linear coefficients are determined, resulting in a linear response surface RS1.
- As each of the next n designs are analyzed, the quadratic coefficients, are determined.
- If the number of designs analyzed are 1+n+(n+1)/(n/2), the designs are weighed to calculate coefficients to give the quadratic response surfaces (RS2, RS3, RS4, etc.), Figure 7.

3. Solve for the approximate optimum design using mathematical programming.
4. Analyze the approximate optimum design.
5. If the designs have converged then stop.
6. If the designs have not converged, go to step 2.

This process is described in a simplified form in Figure 8.

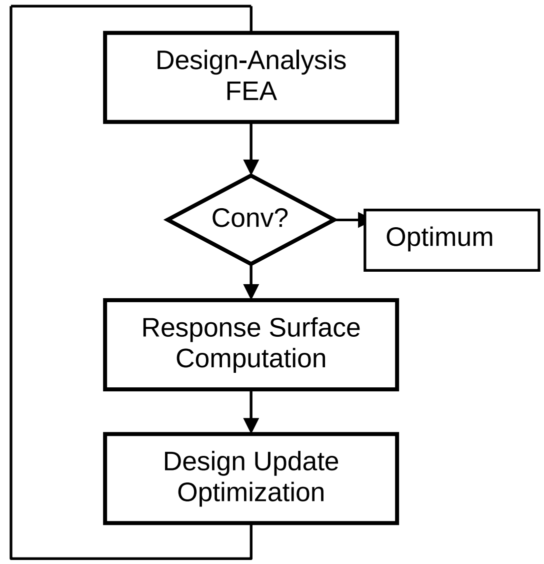

Figure 8

During the early stages of this program an interim airbag configuration and associated vehicle properties where used as a test study for StudyWizard, Altair's predecessor to HyperStudy.

The aim of the study was to reduce the roll angle of the vehicle when subjected to a broadside landing.

The design variables chosen for this study were the airbag vent area and the venting trigger. The signal for venting the airbags is the vertical acceleration experienced at the vehicle's CG.

The results of this initial test study, presented in Figures 9-11, produced an enhanced airbag configuration and highlighted the potential of the tool to significantly improve the impact attenuation performance of the airbag system.

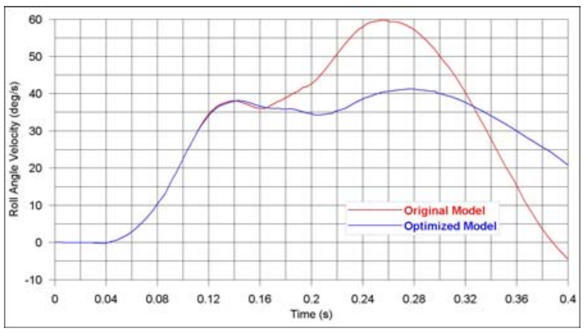

Figure 9

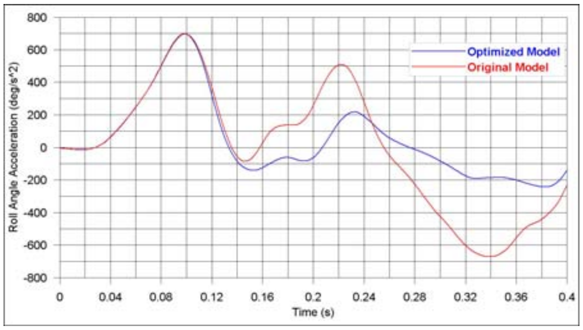

Figure 10

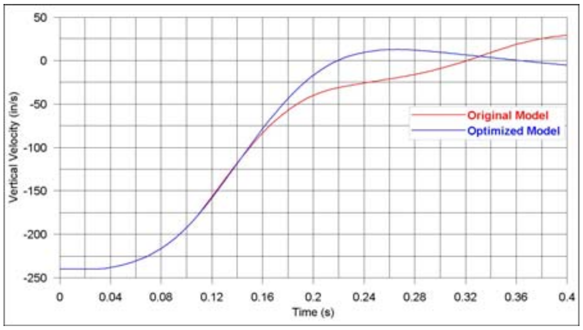

Figure 11

The optimization process identified that a 15% reduction in the vertical acceleration required to initiate venting of the airbags and a 28% reduction in the vent area, produced an increase in vehicle wing clearance of 10in, illustrated in Figure 12. Clearly, this was a significant achievement.

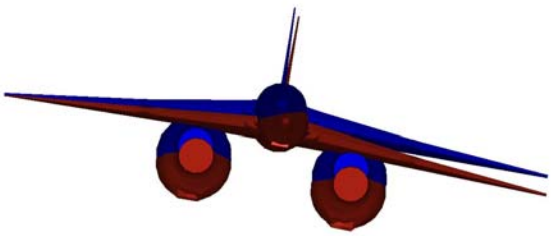

Figure 12

As the program matured and the geometry and mass properties of the test vehicle became stable the opportunity for further optimization appeared.

The optimization that best suited the program as a whole, was to identify optimum airbag characteristics for both a forward and broadside landing scenario. HyperStudy has the ability to produce a single optimized design for a number of landing scenarios, this capability will be utilized at a later date.

Table 1 details the physical parameters, design variables, which could be changed within the airbag system. The objective of the optimization was set to reduce the vertical acceleration of the test aircraft.

Design Variable	**Airbag Parameter**	**Nominal value**	**Min.**	**Max**
1	nosebag vent area	25 in^2	20	40
2	nosebag pressure	5 psi	3	6
3	accl. trigger	1158 in/s^2	772	1544
4	rearbag vent area	35 in^2	20	40
5	rearbag pressure	5 psi	3	6

Table 1

A number of responses have been used to classify the problem.

Response 1 tracks the maximum value of vector v_2, the vertical velocity of the vehicle, over a time period referenced by time index values.

r_1 = max(v_2[subrange(v_1,27353,62706)])

Response 2 refers to the maximum value of the vertical acceleration of the vehicle.

r_2 = max(v_3)

Response 3 tracks the maximum pitch angle of the vehicle throughout the time subrange given by a separate pair of time index values.

r_3 = max(v_4[subrange(v_1,37454,62706)])

Responses 4 and 5 follow the minimum values of responses 1 and 3, respectively.

r_4 = min(v_2[subrange(v_1,27353,62706)])

r_5 = min(v_4[subrange(v_1,37454,62706)])

The constraints, detailed in Table 2 were applied to the five responses to control the maximum vertical acceleration, to ensure minimal bouncing upon impact and to limit the pitch rotation of the aircraft to avoid nose contact during landing.

Response	Constraint
1 Max. Vertical Vel	< 30 in/s
2 Max Vertical Accl.	< 6 g
3 Max Pitch Angle	< -2 deg
4 Min Vertical Vel.	> -30 in/s
5 Min Pitch Angle	> -8 deg

Table 2

The optimization process conducted for this forward landing scenario converged after 15 iterations. The design is compared with the nominal run in Figures 12 to 14.

Figures 12 and 13 compare the vertical velocity and pitch angle, respectively- of the two simulations. The figures depict an optimized design whose airbag characteristics reduce the tendency of the vehicle to bounce and provide an enhanced corrective motion to the nose of the vehicle.

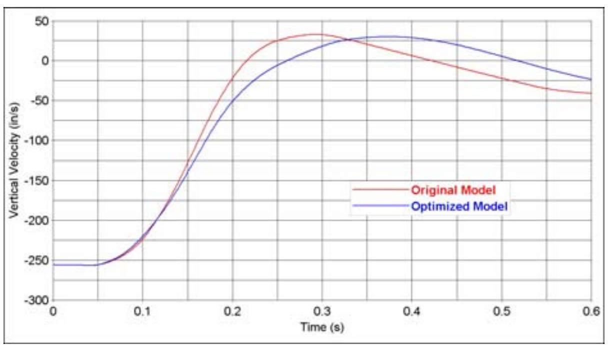

Figure 12

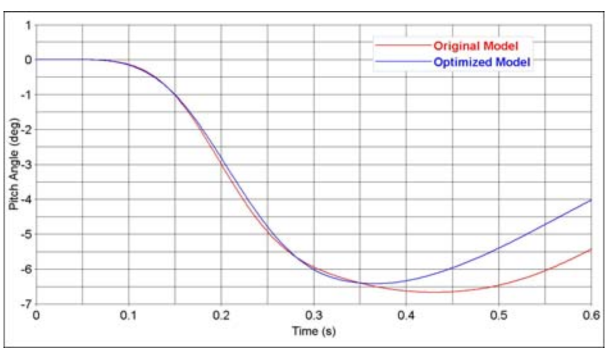

Figure 13

Of most significance is the reduction in the vertical acceleration experienced at the CG of the aircraft. The vertical acceleration of the vehicle reduced from 6.2g to 5g. This reduction is highly beneficial as it suggests that the size of the stroke airbags could be reduced, with obvious repercussions to the mass and stowage volume of those bags. Figure 14 illustrates this reduction.

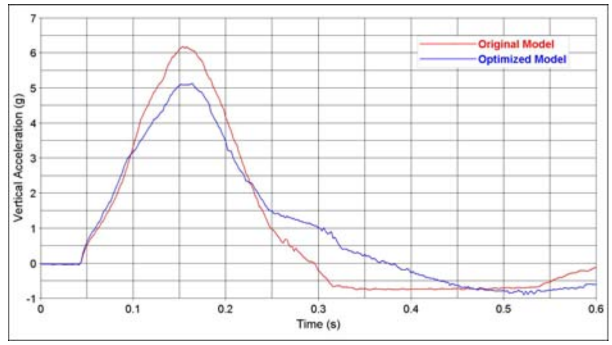

Figure 14

As discussed above a separate broadside optimization was also undertaken. For this optimization the design variables remained the same, the pitch angle responses were replaced by roll angle responses and the objective of minimizing the vertical acceleration was retained.

An optimum design was reached in 25 iterations, 60 hours of processor time on a Pentium II 900MHz. Figures 15 and 16 present the design variable values for the 25 iterations.

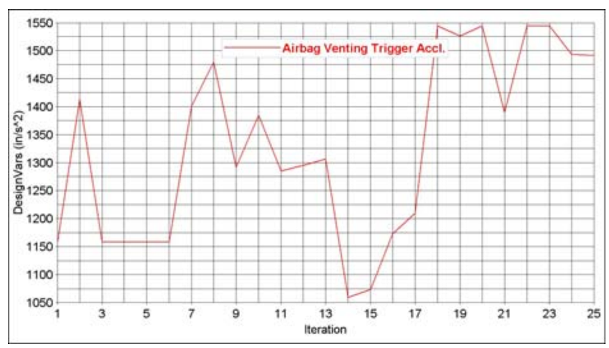

Figure 15

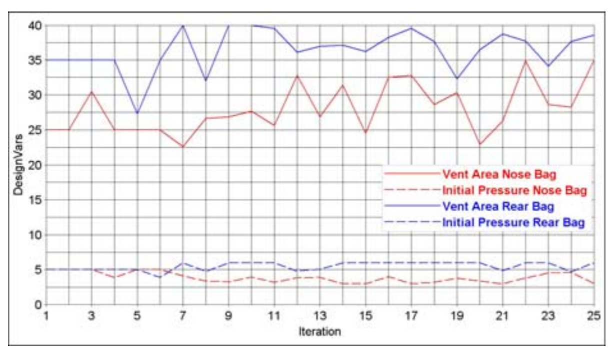

Figure 16

Figures 17 and 18 display the iteration history of the maximum acceleration and max/min vertical velocity of the test vehicle, respectively.

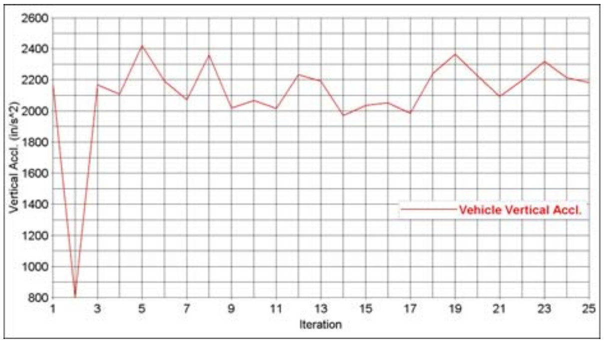

Figure 17

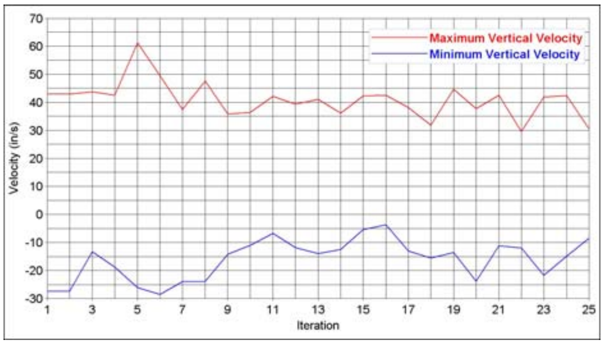

Figure 18

Figures 19 and 20 compare the optimized design with the nominal run.

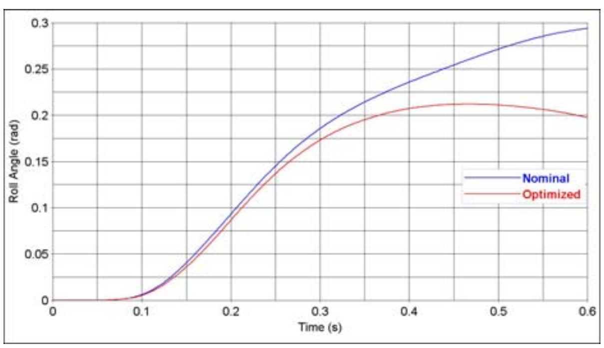

Figure 19

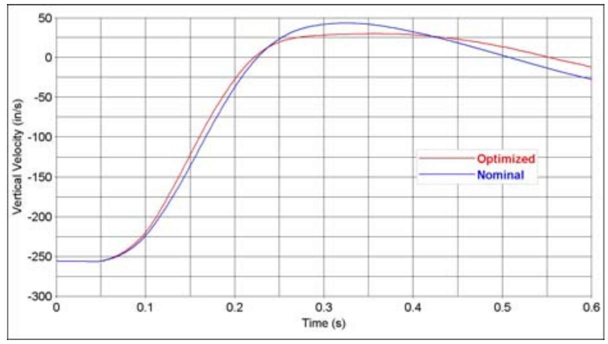

Figure 20

Conclusions

The results presented highlight the substantial benefits of an optimization process during the design phase of a system such as the impact attenuation of the NEXST-2 test aircraft.

For the program discussed in this paper, the Altair optimization software HyperStudy has identified a group of design variable values that have significantly improved the performance of the airbag system.

The advantages of optimization technology are not solely limited to producing an improved end result. An automated approach to the search for an optimum design reduced the effort and expense associated with comparing and altering designs, which can amount to significant cost savings when considering a complicated multi-variable problem.

References

1. GARDINIER, D. (Irvin Aerospace Inc.) YANAGIHARA, M., (NAL) KOBAYASHI, T., (NASDA) AMITO, A. (FHI). “Design and Testing of the HOPE-X HSFD II Landing System” AIAA Paper
2. McKINNEY, J. (Virtual Engineering) and TAYLOR, A. (Irvin Aerospace Inc.). “Use of LS-DYNA to Simulate the Airbag Landing Impact Attenuation of the Kistler K-1 Reusable Launch Vehicle”, LS-DYNA Users Conference.
3. TAYLOR, A., GARDINIER, D. and SABBERTON, A. “Design Optimization of the Beagle II Mars Lander Airbags through Explicit Finite Element Analysis”, LS-DYNA Users Conference.
4. TAYLOR, A “Design Optimization of the Beagle II Mars Lander Airbags through

Explicit Finite Element Analysis- An Update", LS-DYNA Users Conference.
5. TAYLOR, A "The Case for Explicit Finite Element Analysis of Fabric Systems, A Presentation of Real World Applications", AIAA Paper.
6. TAYLOR, A "The Case for Explicit Finite Element Analysis of Fabric Systems, A Comparison to Test Data", AIAA Paper.
7. SCHRAMM, U., THOMAS, H.L., "Crashworthiness Design using Structural Optimization", AIAA-98-4729, Proceedings of the 7th AIAA MDO Conference, St.Louis, MO, 1998.
8. SCHRAMM, U., THOMAS, H.L., and HAYES, K., "Parameter and Optimization Studies for Crashworthiness Design", AIAA-2000-4710, Proceedings of the 8th AIAA MDO Conference, Long Beach, CA, 2000.
9. SCHRAMM, U., "Multi-disciplinary Optimization for NVH and Crashworthiness", Proceedings of the First M.I.T. Conference on Fluid and Solid Mechanics, Boston, MA, 2001.
10. Altair HyperStudy V6.0, On-line Manual, (Altair Engineering Inc., Troy, MI, 2000).