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On the Application of a Response Surface Technique to Analyze Roll-Over Stability of Capsules With Airbags Using LS-Dyna

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Abstract

As NASA moves towards developing technologies needed to implement its new Exploration program, studies conducted for Apollo in the 1960's to understand the roll-over stability of capsules landing are being revisited. Although rigid body kinematics analyses of the roll-over behavior of capsules on impact provided critical insight to the Apollo problem, extensive ground test programs were also used. For the new Orion spacecraft being developed to implement today's Exploration program, new air-bag designs have improved sufficiently for NASA to consider their use to mitigate landing loads to ensure crew safety and to enable re-usability of the capsule. Simple kinematics models provide only limited understanding of the behavior of these air bag systems, and more sophisticated tools must be used. In particular, NASA and its contractors are using the LS-Dyna nonlinear simulation code for impact response predictions of the full Orion vehicle with air bags by leveraging the extensive air bag prediction work previously done by the automotive industry. However, even in today's computational environment, these analyses are still high-dimensional, time consuming, and computationally intensive. To alleviate the computational burden, this paper presents an approach that uses deterministic sampling techniques and an adaptive response surface method to not only use existing LS-Dyna solutions but also to interpolate from LS-Dyna solutions to predict the stability boundaries for a capsule on airbags. Although details of the capsule design with airbags are not provided because of their proprietary nature, results for the stability boundary in terms of impact velocities, capsule attitude, impact plane orientation, and impact surface friction are all discussed.

Introduction

During the development of the Apollo capsule, a comprehensive test program was undertaken to study the stability issues associated with landing on soil and water. Because of the limited computational capabilities, engineers made extensive use of experimental data to complement simple analyses to understand the behavior of such systems under a variety of different conditions. *McCullough and Lands* [1] provided an outstanding report on Apollo Command Module (CM) land impact tests. Work by *Chenoweth* [2] provided a more analytical approach to the problem including the derivation of fundamental expressions relating vehicle rigid body dynamics and stability. Other authors like *Howes and Whitnah* [3-4] discussed the rigid body kinematics of the capsule prior to impact and provided limited information on predicted body loads based on this analysis for both land and water impacts. Although this work is fundamental to the understanding of the behavior of such systems on impact, the increasing complexity of the newer energy attenuation system designs along with the availability of sophisticated non-linear simulations codes have prompted program managers to increase their reliance on high fidelity computer simulations to make critical decisions. However, even today, program managers are often asked to make decisions about off-nominal conditions when they have access to only a limited number of high fidelity solutions. This paper presents an approach for addressing precisely this challenge.

The increased complexity of models and the increased capability of computer systems have dramatically changed the fidelity of models being developed. As these complex models are developed, it is important to not only understand the "single-parameter-set" behavior of the baseline system studied but also to understand changes in the model behavior as "multiple-parameter-sets" studies are conducted. Ideally, if one could develop a functional relationship between the parameters and a response quantity of interest, this functional relationship could be used to conduct studies of the off-nominal conditions. A technique that provides such a functional relationship is known as a response surface technique. *Myers* [5] in his book provided a review of some of the most commonly used techniques to create response surfaces (RS) surrogate models. Instead, the work discussed here uses an adaptive Moving Least Squares (MLS) response surface technique developed by *Krishnamurthy* [6] that has been used successfully for dynamic problems. This technique, in contrast to the more conventional RS approaches, uses a formulation where the response surface parameters are functions of the input parameters (i.e. at each evaluation point new RS parameters are computed), thus making it adaptive; consequently, this method tends to perform well even in problems where conventional RS approaches fail.

Results reported here are part of an internal stability study of capsules landing with airbags. Although the proprietary nature of the model prohibits a detail discussion of the formulation, information regarding the process to create the data, sample the parameter space, determine the accuracy of response surface predictions, and finally, develop stability boundary predictions are all presented.

General Description of the LS-Dyna Model

A finite element model of the CEV capsule with airbags was developed using LS-Dyna [7]. LS-Dyna is a commercial, nonlinear, transient dynamic, finite element code derived from the public domain code DYNA3D, which was developed at Lawrence Livermore National Laboratories in the 1970's. The model consisted of mainly shell elements, 16,721 shell elements and 16,774 nodes, with rigid material properties for the capsule and elastic properties for the airbags. Inertial properties for the capsule are defined rather than calculated from the finite element mesh using the key word *PART_INERTIA. The airbags are modeled as control volumes and pressurized before impact. A Wang-Nefske model is used for modeling the thermodynamic relationships of the inflation gas and for defining the gas flow through the vents. A fixed rigid-wall was used to represent the impact surface to simplify the model and to reduce computational time. Finally, gravity load and initial velocities are also easily defined for all nodes using *BODY_LOAD and *INITIAL_VELOCITY, respectively.

Estimation of Initial Conditions for LS-Dyna Model

To study stability of a capsule on impact, one must be able to vary the initial conditions; i.e., velocities, capsule orientation, and impact surface orientation. Until recently, LS-Dyna required model regeneration every time the orientation of the capsule or impact surface was changed. The *DEFINE_TRANSFORMATION option allows users to re-position the capsule by changing the location and orientation of the center-of-gravity. Similarly, the impact plane location and orientation, initial velocities, and even surface conditions like friction are easily changed.

Although initial conditions can be easily prescribed in LS-Dyna, the impact conditions control the behavior after impact for stability analysis. Often times these two are the same if the initial conditions in LS-Dyna are set just prior to impact. However, for a capsule with airbags, time for airbag pressurization must also be allocated. Within LS-Dyna this can be handled two ways; by using the re-start feature in LS-Dyna or by prescribing initial conditions that result in the desired impact conditions. For this work, the second approach is used, and so the total simulation time includes pressurization time. To simplify recovering of initial conditions from impact conditions, trajectory estimates of 3-dimensional LS-Dyna models were restricted to 2-dimensions by zeroing out-of-plane components.

Consider, for example, the capsule shown in Fig. 1 with the center of gravity (CG) located at a location yet to be determined, at $x(t=0), z(t=0)$. Assume that the capsule motion starts with an initial velocity and pitch orientation angle θ, falls under a gravity load and impacts a ground plane defined by a point on the plane x_p, z_p and a unit normal $\vec{n} = n_x \vec{i} + n_z \vec{k}$. Also consider a capsule, shaped like circular sector of radius R_{cs}, with a moving reference attached to point A on the line of symmetry of the capsule. If the distance from point A to the CG is R_{cg} and an arbitrary distance between the CG and the ground is defined as D_c, the initial location of the CG can be set to;

$$\begin{aligned} z(t=0) &= R_{cg}\sin(\theta) - z_p \\ x(t=0) &= R_{cg}(1-\cos(\theta)) + x_p \qquad\qquad (1.1) \\ &\qquad - t_f(\dot{x}(t_f) + \frac{n_z}{n_x}\dot{z}(t_f)) - D_c \end{aligned}$$

This CG positioning allows for the capsule to clear the ground surface (if rotated) and for the airbags to inflate prior to impact. Also the parameter D_c is selected to ensure that the capsule system is not in contact with the impact plane before the simulation starts. To use Eq. (1.1) the user needs to input the horizontal and vertical impact velocities, time to impact (e.g. time needed for airbags to reach equilibrium after inflation), capsule pitch angle, and impact plane orientation while the formula estimates the proper location of the CG. The pitch angle is positive counterclockwise about a y-axis which is perpendicular to the schematic in Fig. 1. With this information, it is straightforward to automate and generate multiple LS-Dyna runs to investigate the capsule stability.

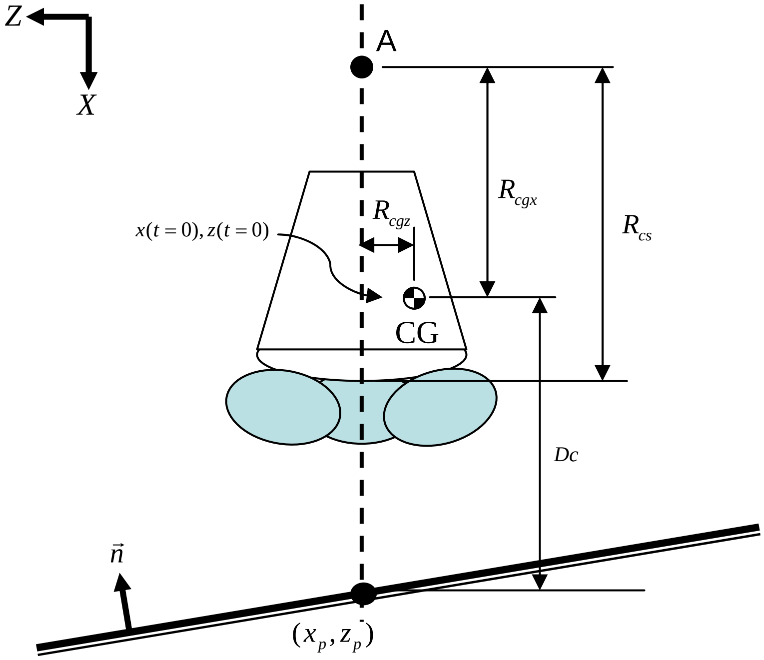

Fig. 1 Capsule location definition

Although Eq. (1.1) is relatively simple, for capsules with complex impact surfaces, it is difficult to estimate the exact impact point. Nonetheless, this was not necessary in this study. Instead, the true impact conditions were extracted from the LS-Dyna simulations.

Computational Framework

To conduct a study like this one that requires many permutations of the model initial conditions, it is preferable to automate the generation of LS-Dyna solutions and parameter values. Furthermore, it is important to develop a computational framework for automation that allows the engineers developing the models to use their preferred tools. Because the impact dynamics community uses LS-Dyna routinely, it is convenient to manipulate the LS-Dyna input file structure directly. Figure 2 shows a data flow diagram implemented using MATLAB [8] Script files. These script files modify the LS-Dyna input file automatically to update parameter values using a priori knowledge of the parameter variations, execute LS-Dyna, and read LS-Dyna output files. By storing all results within the MATLAB environment, all the MATLAB toolboxes are available for use.

In order to make this approach viable for computationally intensive LS-Dyna models, it is proposed (as depicted in the center of figure 2), that input-output mapping of the parameter values to LS-Dyna response outputs be captured using an adaptive response surface technique. For this task two critical elements are required; 1) an efficient response surface technique, and 2) an efficient multi-dimensional sampling technique. Comments on the selection of both approaches are provided next.

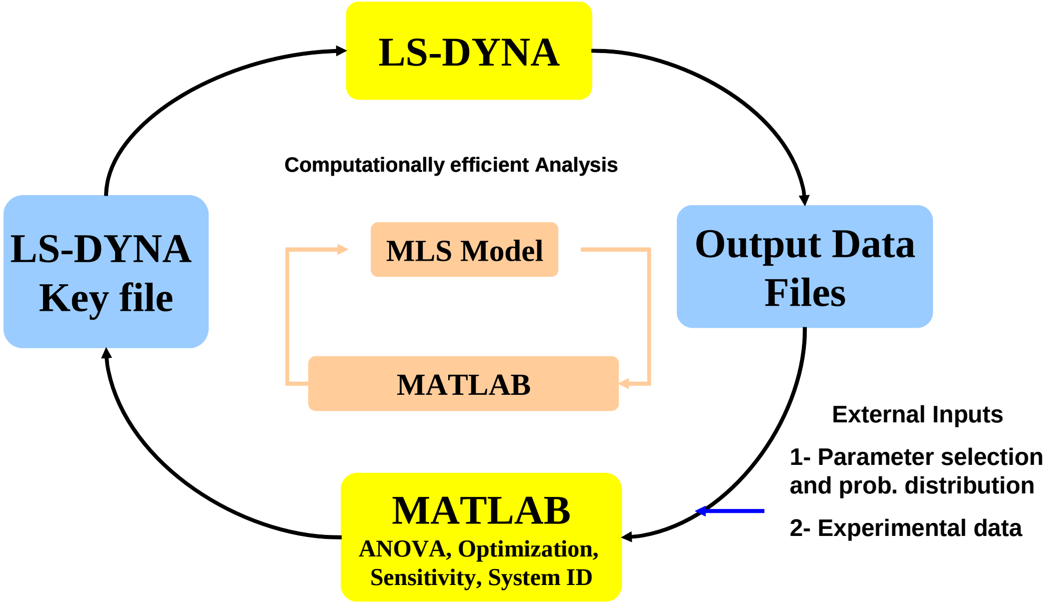

Fig. 2 Computational framework using LS-DYNA and MATLAB

Moving Least Squares (MLS) Response Surface Formulation

A response surface model is a mathematical representation of input variables (variables that the user controls) and output variables (dependent variables). Many papers have been published on response surface techniques but the approach selected for this application is from *Krishnamurthy* [2002], because it has been successfully used for dynamic problems. In this formulation the input/output relationship is given in parametric form as

$$
\begin{aligned}
\widehat{U} &= p^T A^{-1} B U \\
A &\equiv \sum_{i=1}^{N} w_i(v)\, p(v_i)\, p_i^T(v_i) \\
B &\equiv \sum_{i=1}^{N} w_i(v)\, p(v_i) \\
P^T &\equiv \begin{bmatrix} p(v_1) & p(v_2) & \cdots & p(v_N) \end{bmatrix}
\end{aligned}
\tag{1.2}
$$

where $\widehat{U} \in \mathbb{R}^{1\times qN}$ is a vector of predictions, $U \in \mathbb{R}^{1\times qN}$ is a vector of responses (often obtained from high fidelity analyses and stacked row-wise), v_i is the i^{th} parameter vector from a sample population whereas v is a variable representing the parameters, N is the population size, $w_i(v)$ is a user-defined function that weights the proximity of other parameter vectors on the response surface, q is the number of outputs (sensors), and $p(v)$ is a set of basis functions. *Krishnamurthy* [2002] provided several weighting functions to handle problems with different continuity requirements given as a function of the proximity radius, where the radius was defined as $\rho = \left\| v_i - v \right\|_2 / l$ and l is a user defined distance. In our implementation of MLS, the proximity radius is computed directly from data using a quadratic search to minimize the error between the data and the response surface prediction. Also, the $\operatorname{sinc}(\rho) = \sin(\rho)/\rho$ function is used instead of having a catalog of weighting functions for problems with different continuity requirements. To report the quality of the MLS model the normalized error is computed as $e = \max\left| y - y_t \right| / \left\| y - y_t \right\|_2$, where y is the predicted response and y_t is the exact value. This error is computed over all the outputs and the maximum value is reported for the cases discussed later in the paper.

Selection of Input Parameters

To begin the process of creating a response surface model from LS-Dyna runs, the first step after a model has been created is to decide what parameters need to vary and by how much, i.e. upper and lower bounds. In our problem, the parameters selected are the vertical and horizontal velocity, the capsule pitch angle, the impact plane angle, and the impact surface friction coefficient. With five input parameters the minimum number of

LS-Dyna runs required to create a response surface of order 2 is 21, order 3 is 56 and order 4 is 126. Of course for improved accuracy a much larger number is required.

Because for this problem it is best to prescribe impact conditions, Equation (1.1) is used along with the desired vertical impact velocities to obtain a set of initial conditions for used in the LS-Dyna runs. Also, airbag pressurization time is set to 0.26 seconds. A parameter definition list is shown in Table 1 with the nominal, upper, and lower bounds for the parameters values defined.

Table 1. Parameter definition for stability analysis

Parameter Description	**Lower Bound**	**Upper Bound**	**Nominal**
X-Velocity (in/s)	151.9	273.8	211.9
Z-Velocity (in/s)	-600.0	-360.2	-480.0
Pitch Angle (deg)	-4.9	5.0	0.0
Ground Angle (deg)	-5.0	4.9	0.0
CG-X-Position (in)	-27.9	18.4	2.9
CG-Z-Position (in)	6.0	17.1	6.0
Friction Coeff.	0.60	0.99	0.60

Note that in Table 1 the computed CG location is given in lieu of the desired impact vertical velocity; that are input into Eq. (1.1) to get the initial vertical velocity and capsule CG location. From the users' perspective, the information in Table 1 is what is required to run LS-Dyna. Admittedly, this is a subtle distinction but very important to get the correct results.

Deterministic Sampling of the Input Parameters

A critical step when creating response surface models is in the sampling of the parameter domain. That is, having selected a set of parameters as our inputs to the response surface algorithm, sampling of parameters values over their prescribed domain is critical. For this purpose a modified Halton (Halton-leaped) deterministic sampling approach described in Ref. [9] and studied extensively in Ref. [10] has been selected. The selection is based not only on the improved convergence of statistical parameters that this approach provides (over strictly random sampling) but also in that it allows setting of the problem sequentially. In the past when random sequences were used to prescribe a population for the input parameters, the total population size needed to be known at the onset or risk having repeated or correlated parameter values if more solutions were later required. With Halton-leaped, this is no longer a problem and in fact it is best to set up the problem sequentially.

Assessment of MLS Method

There are many aspects of the formulation that need further investigation; namely the RS order, solution accuracy, solution bandwidth, population size, parameter bound selection, analysis of variance, and many others. Nonetheless, results documented here are intended to provide initial insights on the potential benefits of this approach and to provide an estimate of the stability boundary for a capsule fitted with airbags. Without this formulation the alternative was to conduct hundreds of LS-Dyna runs to compute enough solutions to properly describe the stability boundary. This of course is time consuming to do with LS-Dyna models whose execution time is 2.5 hours per solution. For this effort, results from 91 LS-Dyna runs were collected over four days by distributing the LS-Dyna cases to run on three separate computers.

To ascertain the validity of MLS estimates computed from the 91 LS-Dyna cases, it is instructive to compare them to LS-Dyna solutions. One way to do this is to show how MLS solutions transition between two known LS-Dyna solutions. For this, define a parameter transition vector v using the j^{th} parameter vector v_j, the n^{th} parameter vector v_n, and the scalar variation $v = \lambda v_j + (1-\lambda) v_n$ where λ is a scalar ranging from 0 to 1. Since LS-Dyna solutions for the j^{th} and n^{th} parameter vector exist, the new parameter v is now used in the MLS algorithm to estimate in-between solutions. Figure 3 shows the in-between MLS and the two LS-Dyna solutions for pitch rotation as a function of time and λ, where v_j and v_n are two arbitrarily chosen parameter vectors for an MLS surface of order 2. For stability assessments, if the pitch angle is less that 1.57 rad. (90 degrees), as is the case for $\lambda = 0$, the capsule is stable after impact whereas for cases where the pitch angle is greater than 1.57 rad., as is the case for $\lambda = 1$, the capsule rolls-over. Note that MLS interpolation provides solutions from one stable LS-Dyna solution $\lambda = 0$ (in blue) to one unstable LS-Dyna solution $\lambda = 1$ (in blue). It is worth noting that for cases where the order of the MLS surface is 3, results showed a few instances where the capsule turned in the opposite direction even though the solution set did not contain any cases where the capsule flipped back. Finally, negative signs in the angles and velocities correspond to motion in the direction of travel.

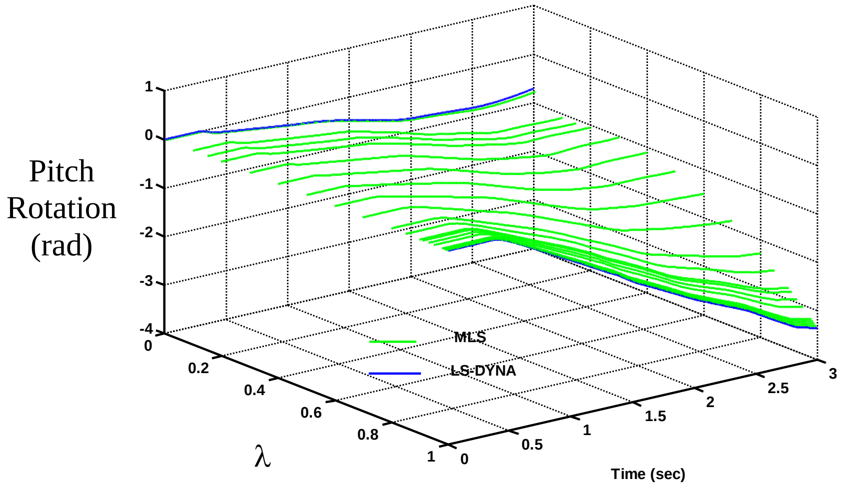

Fig. 3 Response surface interpolation between LS-DYNA solutions

A second metric used to evaluate the prediction accuracy is the normalized error between MLS and LS-Dyna defined earlier as $e = \max|y - y_t| / \|y - y_t\|_2$. Figure 4 shows the normalized error times 100 for outputs 1-6 corresponding to V_x, V_y, V_z, θ_x, θ_y, and θ_z. This error is computed for all 91 LS-Dyna solutions and only the worst case for each output is plotted; the largest error computed for any output across all cases was less that 10% overall.

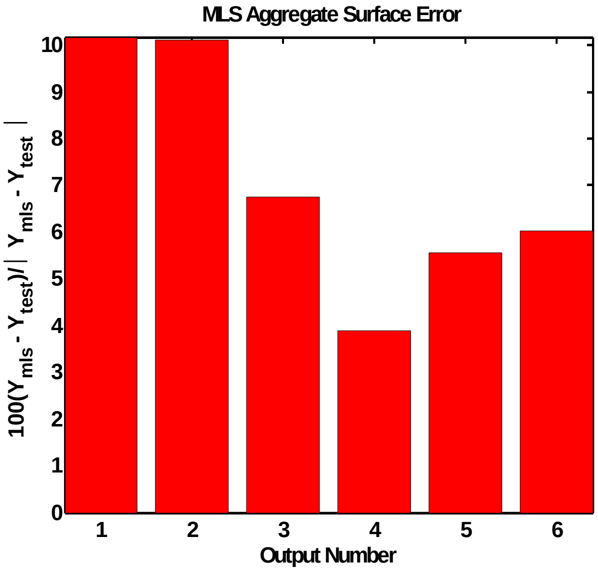

Fig. 4 Worst case error between LS-DYNA and MLS

Discussion of Stability Results

At this point the MLS model can be used to predict the capsule responses under various impact conditions for a range of horizontal velocities and impact surface friction values. To study stability, the response quantity of interest is the CG pitch angle after impact. If the maximum roll-over angle exceeds 90 degrees, it is likely that the capsule rolled-over. Figure 5 shows a contour plot with lines of equal maximum roll-over angle as a function of horizontal speed and friction while holding the vertical velocity at 312 in/sec and the initial pitch angle at 0. As an example, the plots shows the capsule is unstable for a friction of 0.65 and horizontal velocities greater than 490 in/sec. Similarly, for horizontal velocities greater than 460 in/sec and a friction value of 0.9 the capsule is unstable. As expected, as friction increases the range of horizontal velocities where the capsule is stable decreases.

Figure 6 shows the stability contour for the initial pitch angle and horizontal velocity for cases with the friction level held at $\mu = 0.6$ and a vertical impact velocity of V_x=312 in/sec. In contrast to results in Figure 5, this stability contour shows a “bucket” of solutions where the maximum roll-over angle is less than 90 degrees.

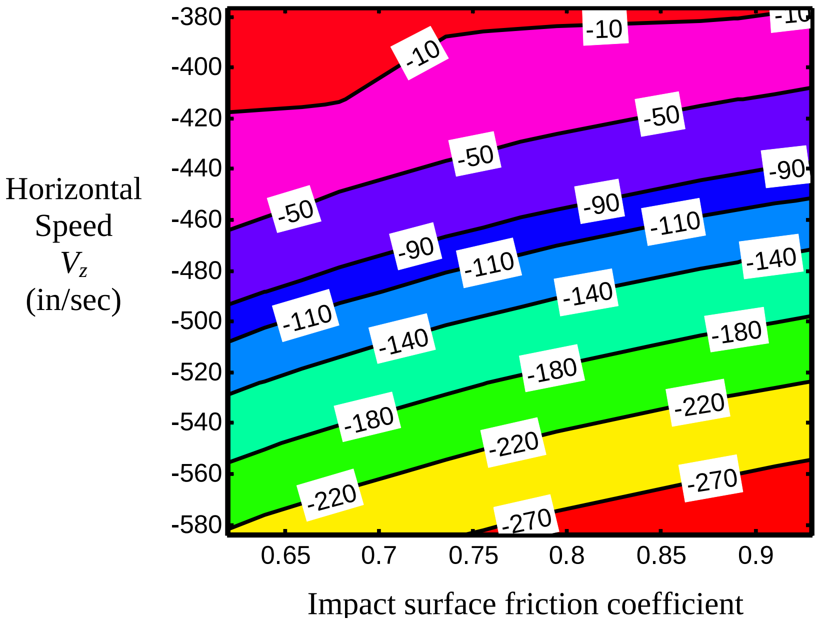

Fig. 5 Stability contour; 0 deg initial pitch angle and V_x=312 in/sec

One last case of interest is for impacts where the capsule has an initial pitch angle on impact. To illustrate this case a 4.5 degrees heel-in condition (i.e., impact point located at the rear of the capsule) is arbitrarily selected. Figure 7 shows the stability contour for friction values and horizontal velocities while the vertical impact velocity is 312 in/sec. When compared to results shown in figure 5, notice that the stability boundary moved up slightly indicating a reduction in the stable region area.

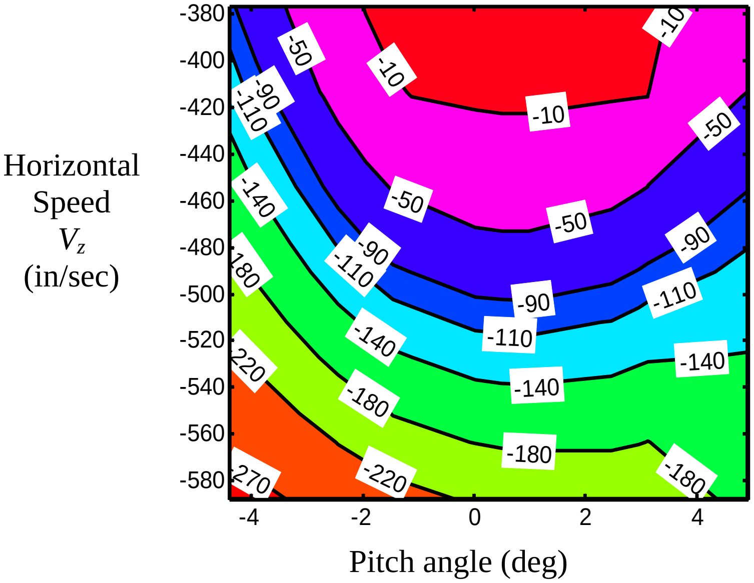

Fig. 6 Stability contour with friction coefficient and
μ=0.6 and V_x=312 in/sec

Concluding Remarks

An approach has been presented to use a finite set of solutions from LS-Dyna coupled with a response surface technique to predict the roll-over stability boundary of a capsule landing with airbags. Two aspects of this approach are relatively unique; the use of adaptive response surface techniques and the use of deterministic sampling on the input parameters. The Moving Least Squares (MLS) adaptive response surface technique is used to predict time responses outside the set computed using LS-Dyna. The Halton-leaped deterministic sampling approach is used to efficiently sample the parameter space and to parallelize the computations to take advantage of multiple computers. An added benefit of using Halton-leaped parameter sampling is that if additional LS-Dyna runs are needed to improve accuracy, the method easily creates new parameter samples without the risk of duplicating existing solutions. For this study, the MLS technique provides predictions better than 10% for most of the cases studied at a fraction of the computational cost of new LS-Dyna runs. Using the MLS surrogate model, predictions of the stability boundaries showing the interaction of parameters like horizontal and vertical velocity, pitch angles, and friction can all be studied independently of LS-Dyna after a core set of solutions is computed. In the case studied 90 degree rollover of the capsule is most likely to occur for horizontal velocities from 460 in/sec to 490 in/sec and friction coefficients from 0.6 to 1.

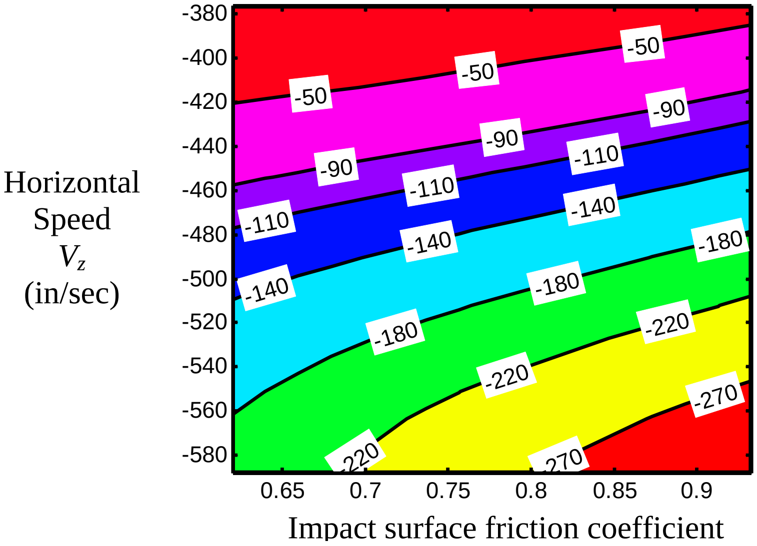

Fig. 7 Stability contour; 4.5 degrees initial pitch and V_x=312 in/sec

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14. ABSTRACT

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