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Preliminary Structural Sensitivity Study of Hypersonic Inflatable Aerodynamic Decelerator Using Probabilistic Methods

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Abstract

Acceptance of new spacecraft structural architectures and concepts requires validated design methods to minimize the expense involved with technology validation via flight-testing. This paper explores the implementation of probabilistic methods in the sensitivity analysis of the structural response of a Hypersonic Inflatable Aerodynamic Decelerator (HIAD). HIAD architectures are attractive for spacecraft deceleration because they are lightweight, store compactly, and utilize the atmosphere to decelerate a spacecraft during re-entry. However, designers are hesitant to include these inflatable approaches for large payloads or spacecraft because of the lack of flight validation. In the example presented here, the structural parameters of an existing HIAD model have been varied to illustrate the design approach utilizing uncertainty-based methods. Surrogate models have been used to reduce computational expense several orders of magnitude. The suitability of the design is based on assessing variation in the resulting cone angle. The acceptable cone angle variation would rely on the aerodynamic requirements.

Introduction

High reliability entry, descent, and landing systems have been in demand for all classes of space applications. Specific applications include, ISS return mass, sample return, Mars exploration vehicles, and human-rated exploration vehicles. Architectures that incorporate Hypersonic Inflatable Aerodynamic Decelerators (HIADs) show promise for many of these applications, as discussed in Refs. [1-3]. Also various Inflatable Aerodynamic Decelerators (IADs) were proposed, studied, and reported in Refs. [4-6]. More recently, a series of small-scale test flights has demonstrated a basic functionality of a stacked torus configuration at the 3-m diameter scale, see Refs. [7 and 8]. HIAD diameters up to 81-m have been proposed, Ref. [1]. Traditionally, for such designs to gain acceptability, they need to be verified and validated through full-scale testing. Unfortunately, ground test demonstration of the structural reliability to aerodynamic loading is difficult due to limited test facility size and gravity effects. Therefore, such concepts will require certification through test-validated analysis. Fortunately, significant advances have occurred in the numerical simulation of the response of complex structural systems. For example, simulations can incorporate structural aspects such as geometrically accurate models and advanced material models to include nonlinear stress-strain behaviors, woven fabrics, and airbag inflation. This was demonstrated for the Orion Landing System – Advanced Development Project, where the space landing system effectively incorporated modeling of airbags (soft goods) in the early design process, see Refs. [9 and 10].

The HIAD structural analysis problem presents several design challenges. 1) Formal design approaches do not exist to address the various HIAD concepts. 2) HIAD structures exhibit complex structural responses to include soft goods and multiple load paths. 3) Designs of such systems require computationally efficient and robust modeling tools. Detailed computational tools to analyze the structural response of such systems are becoming sufficiently mature to accurately model the response of these complex structures. Computationally efficient models are also critical to enable completion of numerous simulations, where numerous executions of nonlinear, transient dynamics simulations are needed to verify the design. This study concentrates on extending preliminary modeling work by incorporating probabilistic methods in the design process. Concurrent with this analysis effort, experiments were conducted to acquire structural response data for 3-m and 6-m HIAD stacked-torus configurations to support model assessment of simulation adequacy. Refs. [11 and 12] contain additional information about this HIAD application.

Probabilistic analysis (PA) methods are often used to study parameter variability during the design process for the purposes of assessing reliability and robustness. In these cases parameter variations and their representation are selected based on expected parameter excursions from the as-built system. However, in this study PA tools are used to conduct parametric studies where the uncertainty model description represents a design space, as opposed to the uncertainty space. It is easy to lose sight of the fact that for many complex structures relying on inflated elements, that brute force approaches are often impractical. In addition more sophisticated methods may be required to optimally use the results from a relatively small number of simulations. For example, thousands of simulations using a Monte Carlo approach are typically not feasible. As the number of parameters, number of responses, and runtimes increase, a more streamlined and systematic approach may be required. One option is to incorporate surrogate models in the implementation of probabilistic methods to improve the computational efficiency. Refs. [13 and 14] provide examples for aeronautical applications, which focus on model adequacy. Ref. [15] provides an example for implementation in the spacecraft design process.

This paper begins with a brief overview of the finite element model (FEM) and the probabilistic analysis approach, followed by a discussion of the results. Within the discussion of the results, parameter sensitivity and variation in cone angle results are provided. Finally, concluding remarks provide general comments about the approach and findings.

Model Description

Figure 1a shows the FEM representation of the inflatable decelerator. In this FEM, eight stacked and inflated tori are constrained by a network of woven straps with loads reacted at the Center Body. A uniform 0.75-psi pressure load is applied to the thin, flexible cover, see Figure 1b, which is fully constrained at the inner and outer rims. The pressure load is transferred to the HIAD structure through specification of contact surfaces within the FEM. Most of the applied pressure is reacted by the HIAD, with approximately 10 percent reacted at the cover constraints. This cover and loading configuration was modeled to replicate the planned static loading tests, Ref. [11].

The numerical simulations were executed in LS-Dyna^{TM}, a commercial, general-purpose, nonlinear, transient-dynamics, finite element code, Ref. [16]. The finite element model (FEM) contained 252,809 nodes, with 219,736 4-noded, fully-integrated, shell elements and 3752 2-noded seatbelt elements. The straps and tori were modeled with a shell element specially formulated for fabric materials undergoing large deformations. Torus-to-torus and strap-to-torus interactions were modeled using contact features. Each simulation required approximately four hours using four processors to compute the 0.2-second responses. Unlike many applications employing LS-Dyna, the end-state results and not the time varying responses were of primary interest. Additional simulations incorporating structural members with fabrics can be found in Refs. [17 and 18}.

For each torus, the nodal displacements along a radial line will be examined. Figure 2 contains a schematic of the inflated tori with the nodal locations identified. The loading is axisymmetric and the large number of straps make the structure nearly axisymmetric.

After examination of numerous circumferential locations, the response was deemed sufficiently axisymmetric for the application to examine one node per torus. The resultant displacements for these eight nodes are considered as critical response quantities for the overall design process. The tori displacements provide a direct measurement of the deformed shape as a function of an applied aerodynamics load. Knowledge of the deformed shape is used to conduct predictions of the aerodynamic stability, heating loads, and control performance during re-entry. In this preliminary study, the nodal coordinates of Torus 1 and Torus 7 are used to approximate the global cone angle. Although not explicitly studied here, other design aspects, such as strap loads, could be evaluated with a similar process.

Sensitivity Analysis using Analysis of Variance

To study the global sensitivity of the critical response quantities due to parameter variations, five design parameters are assumed to be uncertain. The five design parameters used in this study are listed in Table 1 in terms of upper and lower bounds. Four of the parameters are related to material stiffness, namely - Tori fabric Young's modulus (E_{Tori}); 4K strap Young's modulus (E_{4K}); 3K strap Young's modulus (E_{3K}); and multiplier for the axial cord load curve ($M_{Axial\ cord}$). In addition, the torus fabric weave angle (α_{Tori}) was varied 10-degrees. Numerical values for each of the parameters identified in Table 1 are assumed to be equally likely (i.e., to have uniform distribution) within the ranges specified in the table.

This study provides an example of incorporating probabilistic analysis for this type of application. Results reported here were focused on varying structural material parameters. The results and conclusions for a flight vehicle would vary as the design, design parameters, and parameter variances change. Prior to initiation of the probabilistic design process and to verify numerical stability, an extensive review of several simulation responses was performed. These responses include constraint forces, component energies, internal contact forces, tori pressures, displacements, strap loads, and visual inspection of deformed shapes.

Several approaches exist to conduct Analysis of Variance (ANOVA) for global parameter sensitivity estimates. In most cases, classical design of experiments (DOE) sampling of the parameter space is used where a parameter or set of parameters is held constant while other parameters are varied. This works well for most ANOVA applications. For computationally intensive problems, DOE sampling may not be appropriate when developing surrogate models is the ultimate goal. Although there are many techniques to create more adequate sampling of the parameter space, Halton-Leap deterministic sampling technique was chosen for this study, Ref. [19]. The Halton-Leap method creates multi-dimensional, uniformly distributed values between 0 and 1, which are then converted to engineering parameter values within the bounds specified in Table 1.

Numerous executions of nonlinear, dynamic simulations are not typically feasible because of time constraints. To alleviate this problem, a surrogate model in conjunction with the Sobol computation, Ref. [21], has been used to compute contributions of the five input parameters to the time-varying variance of the resultant displacement. For this problem, 80 LS-Dyna simulations were conducted and used to create a time-varying surrogate model using the Extended Radial Basis Function (ERBF) approach developed by Mullur and Messac, Ref. [20]. Global sensitivity measures were computed using the Sobol method, with the resultant displacement as the response of interest for the parameter sensitivities. Sobol's method is suitable for a nonlinear design space where a simple gradient computation at the parameter's mean may not be sufficient. A drawback of variance-based global sensitivity measures is the need for a large number of response samples (i.e, thousands) to compute the variance. Even for this application, while 10,000 responses using the surrogate model are possible to compute in less than 20 minutes, 10,000 FEM simulations could require orders of magnitude longer.

Results

The 80-simulation set containing displacement time histories was used to generate the surrogate models (i.e., ERBF response surfaces). A unique response surface is generated at each time step. For the resultants presented in this document, 2001 response surfaces were generated for each torus displacement response location. Although the end-state results are of primary interest, the change in sensitivities over time provides insights into the model behavior and stability during loading.

When working with surrogate models, users should always be concerned about their adequacy. Surrogate model adequacy was assessed by the removal of the *ith* LS-Dyna solution from the solution set and the comparison of it to the surrogate prediction. In other words, the surrogate model did not contain the *ith* solution being evaluated. This approach was implemented because nonlinear FEM simulations are often computationally expensive. The removal process, depicted in Figure 3, can be performed with all 80 LS-Dyna solutions. The comparison of end-state resultant displacement for the ERBF surrogate and the LS-Dyna simulation for Torus 1 and Torus 7 are provided in Figures 4 and 5, respectively. The greater discrepancy between ERBF and LS-Dyna for Torus 7 when compared to that for Torus 1 is likely attributed to the greater distance from the Center Body. The farther the torus is from the Center Body the greater the number of structural elements that become involved in the response. Perfect agreement is not anticipated when approximating the detailed multi-hour simulation of the complete structure response with a surrogate response requiring less than a second to compute. The level of agreement, as evidenced by a correlation coefficient greater than 0.9, is considered sufficient to proceed with assessing parameter importance. If this level of agreement were deemed insufficient, new simulation results can be incorporated to improve the surrogate's accuracy. Also, subsequently the surrogate model results can be used to compute the cone angle.

Sensitivity Results

Figures 6 and 7 show the time-dependent results of the Sobol variance computations for Torus 1 and Torus 7, respectively. The bars at each time slice provide an indication of the contribution of the parameter to the total variance. For example, in Figure 6, at the final time (0.2 s) nearly all of the variance of the resultant displacement for Torus 1 can be attributed to variation in E_{4K} (indicated in mustard). For Torus 7, the variability is primarily split between the three Young's modulus parameters. These results show that the parameter sensitivities of the displacements vary by torus. Drastic variations over time could results from insufficient number of FEM simulations or FEM numerical instabilities. Thus the smooth variations over time and nearly constant distributions after 0.1 s provide additional encouragement about quality of the sensitivity results. It was anticipated that one of the parameters could have been eliminated. These results indicate that variations in the Axial Strap Multiplier and the Torus Braid Angle do not significantly contribute the variability of the tori resultant displacements. Thus these parameters could be held constant or eliminated as uncertain variables.

In general, methods such as that proposed by Sobol, should be used to determine parameter importance for problems exhibiting significant non-linear behavior. However, for this problem, the correlation coefficient of the displacements for each torus as a function of uncertain parameter are also computed and provided in Figure 8. The results in Figure 8 show a shift in importance of the Young's modulus parameters when progressing from inner to outer tori. More importantly, the parameter sensitivity of the displacements varies by torus. Thus the displacements of multiply tori must be incorporated when considering parameter importance on the deformed global structural shape.

The variance computations provide insight into parameter importance. However, care must be exercised when one uses variance information in the design process since the variance is implicitly dependent on the range of the input parameters. Thus, if the parameter maxima and minima in Table 1 were changed, then the corresponding parameter contribution to the variance will also change.

Cone Angle Variation Results

The end-state cone angle of the collective HIAD tori structure is derived from end-state coordinates of Torus 1 and Torus 7. The cone angle approximations using Torus 1 and Torus 7 results are shown in Figure 9. Statistics for 10,000 ERBF approximations are also provided. The re-entry heating, stability, and decelerations are strongly dependent on this cone angle. For example, a notional aeroheating requirement could limit the cone angle to vary no more than 0.5-degrees from the nominal. In that case, the design space is too broad with regard to the material properties. If, on the other hand, the aeroheating could accept 3-degree variations from the nominal, then the current design space is sufficient.

Concluding Remarks

Acceptance of new spacecraft structures architectures and concepts requires validated design methods to minimize the expense involved with technology validation flight-testing. This paper discusses a global sensitivity approach for evaluation of the structural response of a Hypersonic Inflatable Aerodynamic Decelerator (HIAD). The simulation of the response of a HIAD structure with static external pressure loading was automated with a combination of Matlab scripts and LS-Dyna simulations. A surrogate model was generated to provide displacement responses, and a correlation coefficient metric was established to evaluate the surrogate adequacy. The global sensitivity of the resultant displacement results shows that parameter sensitivity is dependent on torus location. However, the displacement variations were most affected by the Young's modulus of the straps and the tori. For this application, the axial strap multiplier and tori fabric angle could be held constant. Finally, the end-state cone angle was derived from two tori coordinates. The cone angle variation was compared to a notional cone angle requirement. Ultimately, an acceptable range in cone angles would be specified by project.

Acknowledgements

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Table 1. Parameter uncertainty model.

Parameter	**Minimum**	**Maximum**
$M_{\text{Axial cord}}$	0.1	1.0
α_{Tori}	60°	70°
E_{Tori}	$1\text{x}10^5$ psi	$1\text{x}10^6$ psi
E_{3K}	$4\text{x}10^5$ psi	$4\text{x}10^6$ psi
E_{4K}	$2\text{x}10^5$ psi	$2\text{x}10^6$ psi

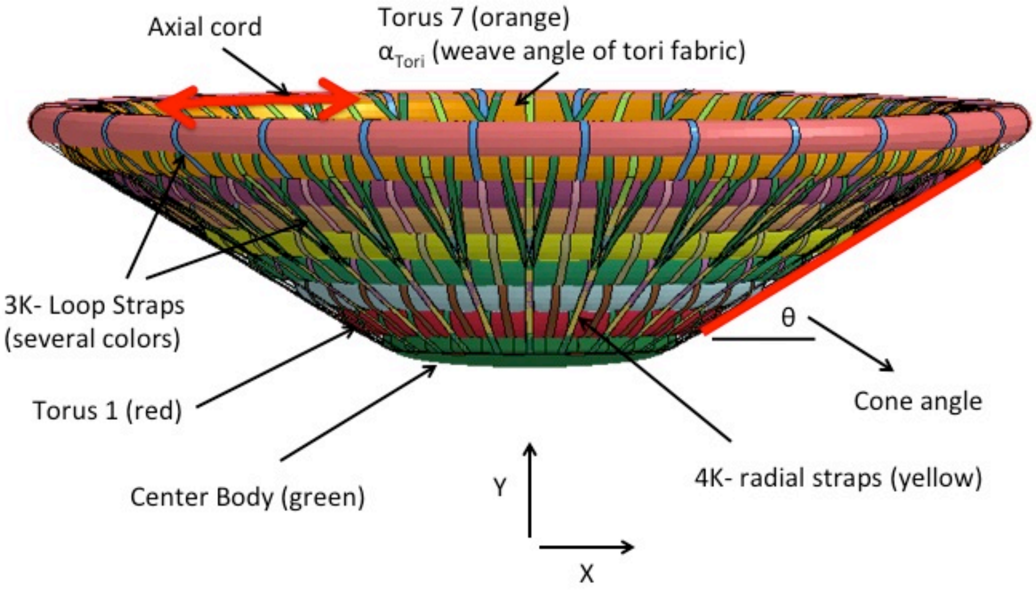


Figure 1a. Finite element model without cover.

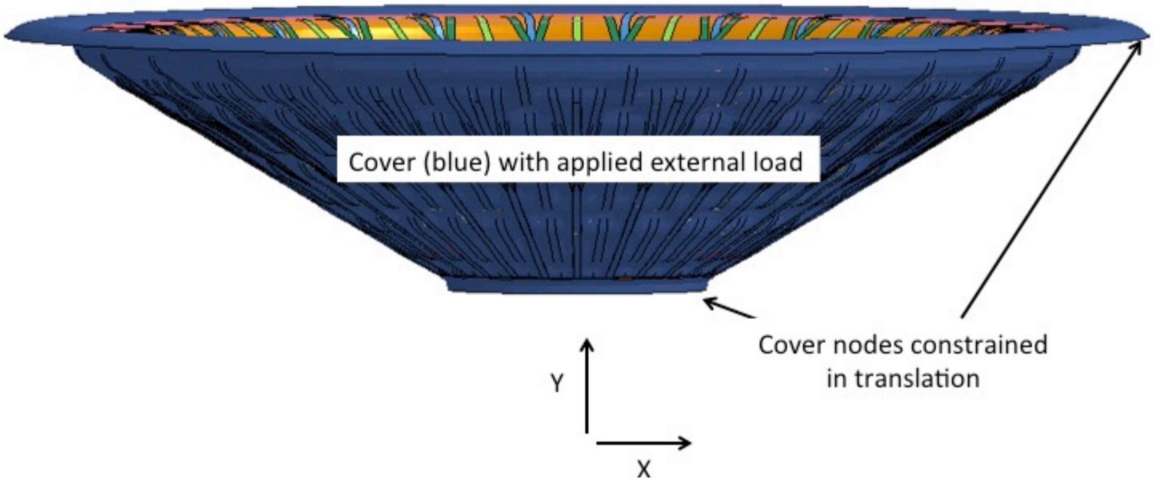


Figure 1b. Finite element model with cover.

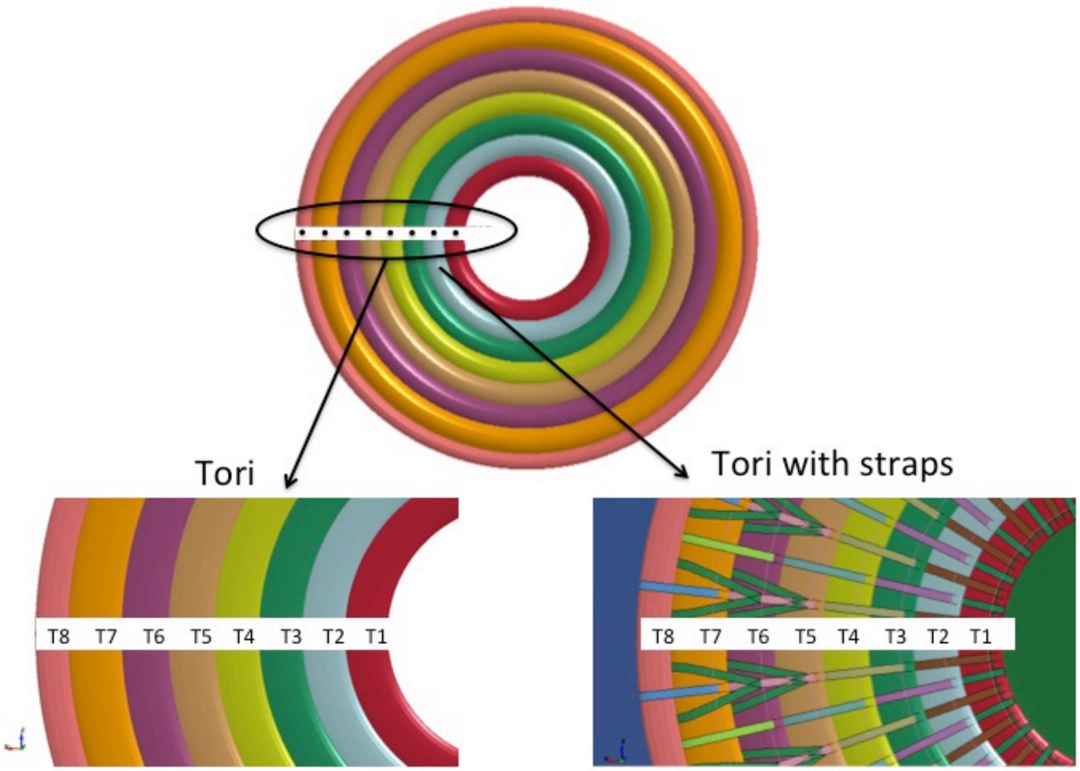


Figure 2. Location of displacement responses on tori.

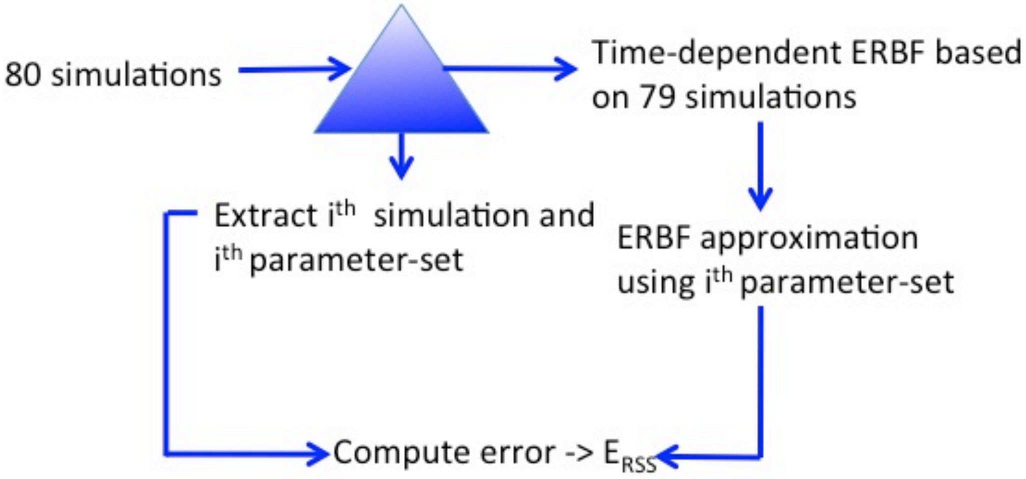


Figure 3. Schematic of simulation removal process

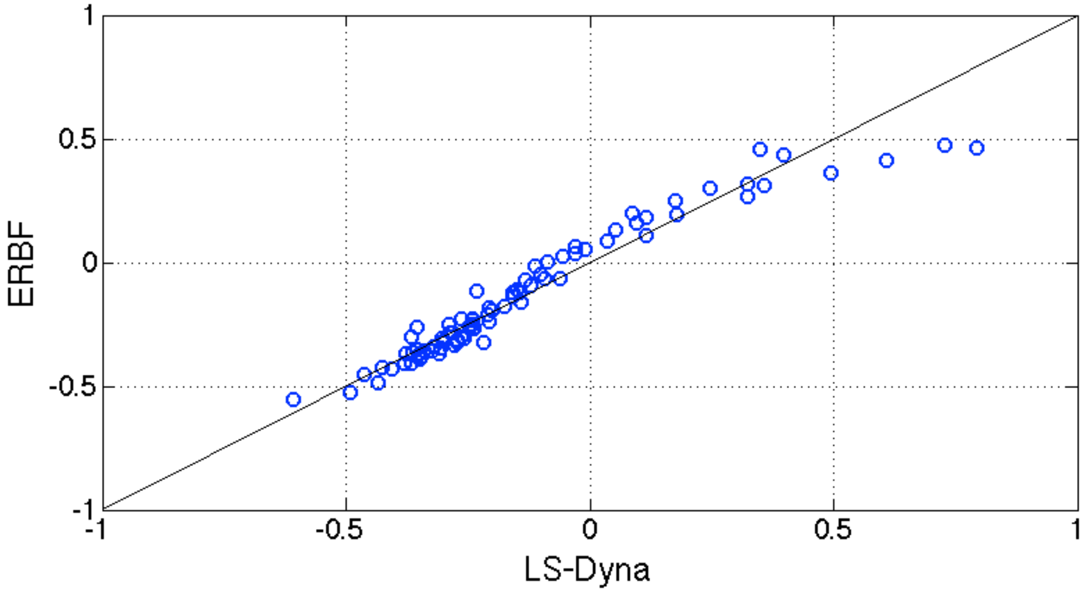


Figure 4. Comparison of LS-Dyna and ERBF end-time displacements for Torus 1 (Correlation coefficient=0.97).

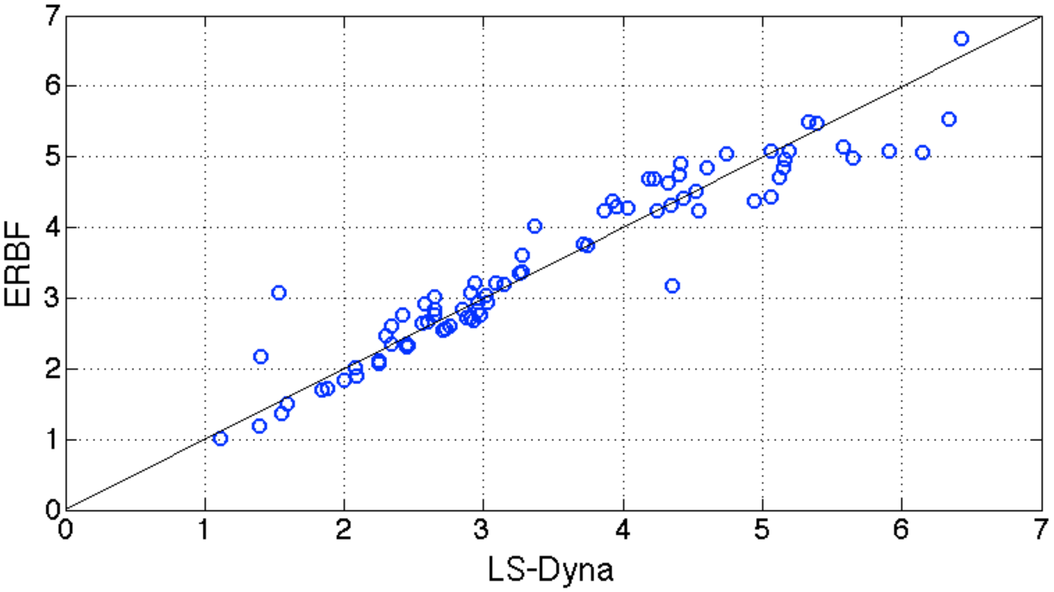


Figure 5. Comparison of LS-Dyna and ERBF end-time displacements for Torus 7 (Correlation coefficient=0.95).

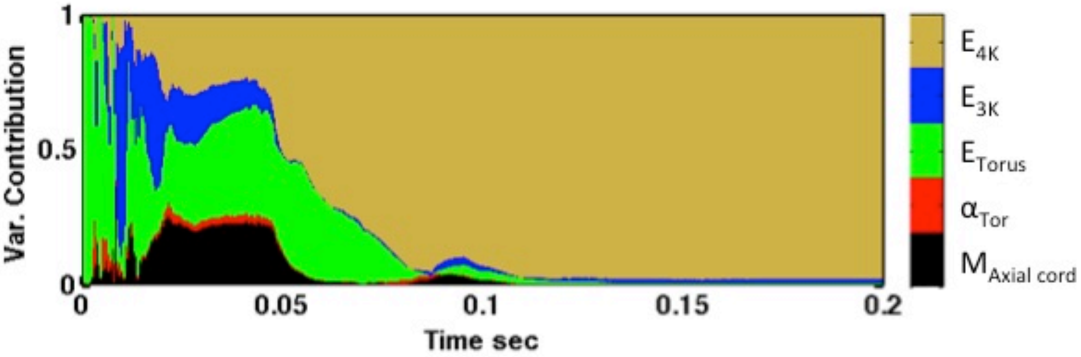


Figure 6. Time histories and variance for resultant displacement of Torus 1.

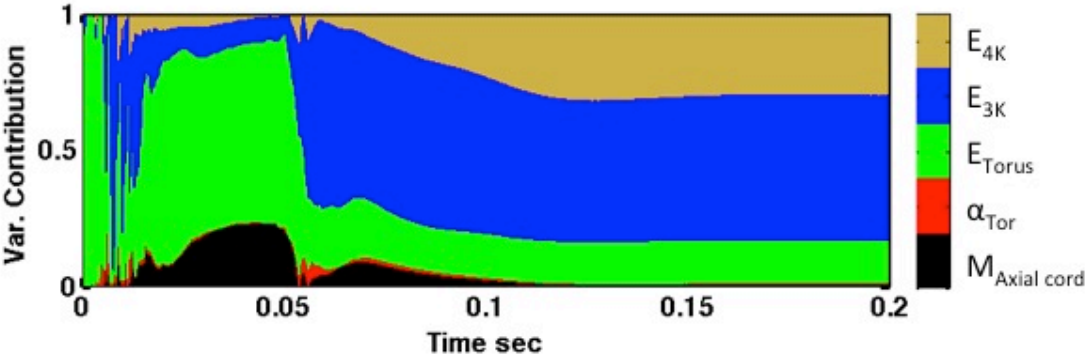


Figure 7. Time histories and variance for resultant displacement of Torus 7.

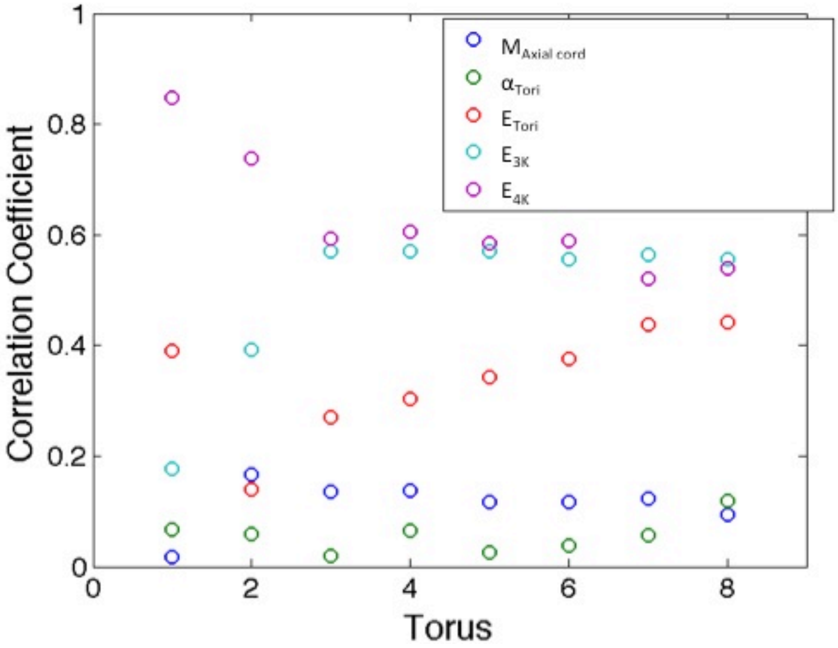
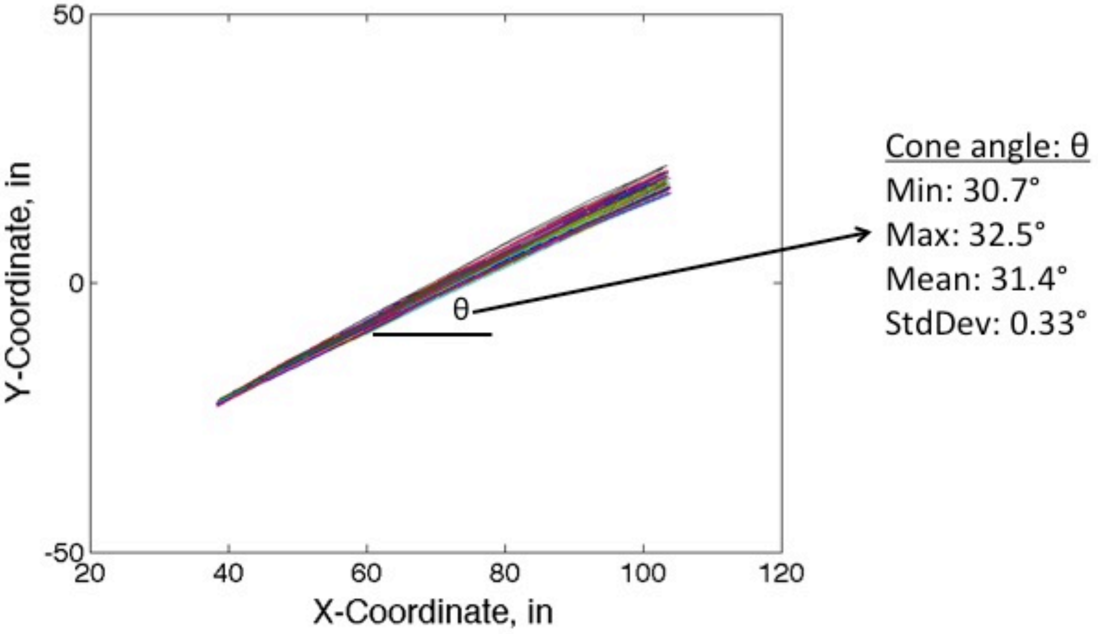


Figure 8. Correlation coefficients of tori end-time displacements as a function of design parameter.



Cone angle: θ
Min: 30.7°
Max: 32.5°
Mean: 31.4°
StdDev: 0.33°

Figure 9. Cone angles for the 10,000 ERBF realizations.

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14. ABSTRACT

Acceptance of new spacecraft structural architectures and concepts requires validated design methods to minimize the expense involved with technology validation via flight-testing. This paper explores the implementation of probabilistic methods in the sensitivity analysis of the structural response of a Hypersonic Inflatable Aerodynamic Decelerator (HIAD). HIAD architectures are attractive for spacecraft deceleration because they are lightweight, store compactly, and utilize the atmosphere to decelerate a spacecraft during re-entry. However, designers are hesitant to include these inflatable approaches for large payloads or spacecraft because of the lack of flight validation. In the example presented here, the structural parameters of an existing HIAD model have been varied to illustrate the design approach utilizing uncertainty-based methods. Surrogate models have been used to reduce computational expense several orders of magnitude. The suitability of the design is based on assessing variation in the resulting cone angle. The acceptable cone angle variation would rely on the aerodynamic requirements.

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