Fluid-Structure Interaction Uncertainty over a Deformable Hypersonic Inflatable Aerodynamic Decelerator

Abstract #17

Andrew J. Brune* Dr. Serhat Hosder+ Karl T. Edquist#

*Aerospace Simulations Laboratory, Department of Mechanical and Aerospace Engineering, ajby96@mst.edu
+Aerospace Simulations Laboratory, Department of Mechanical and Aerospace Engineering, hosders@mst.edu
#NASA Langley Research Center, Atmospheric Flight and Entry Systems Branch, karl.t.edquist@nasa.gov

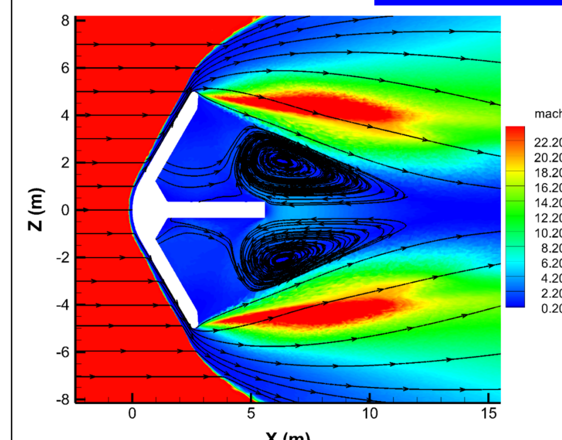
MOTIVATION

- Accurate uncertainty quantification (UQ) is important for the design of reliable and robust planetary entry vehicles.
- UQ can help improve the accuracy of physical models.
- Previous work by the authors performed UQ of the flowfield over a rigid Hypersonic Inflatable Aerodynamic Decelerator (HIAD) in preparation for the fluid-structure UQ presented here.

OBJECTIVES

- Apply an efficient and accurate UQ approach to the analysis of high-fidelity fluid-structure interaction (FSI) modeling over a deformable HIAD
- Quantify the uncertainty in the HIAD deflection, aerodynamic heating, wall pressure, and shear stress
- Identify significant uncertain parameters that contribute to the output uncertainty

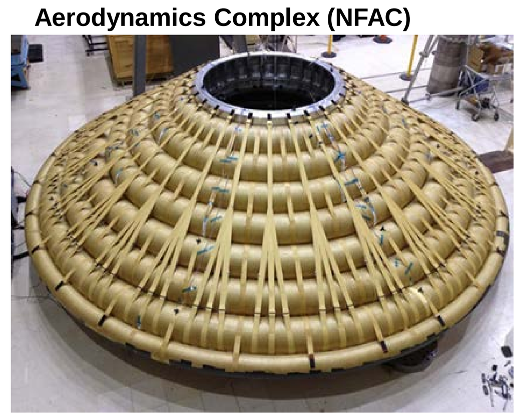
HIAD ANALYSIS AND DESIGN



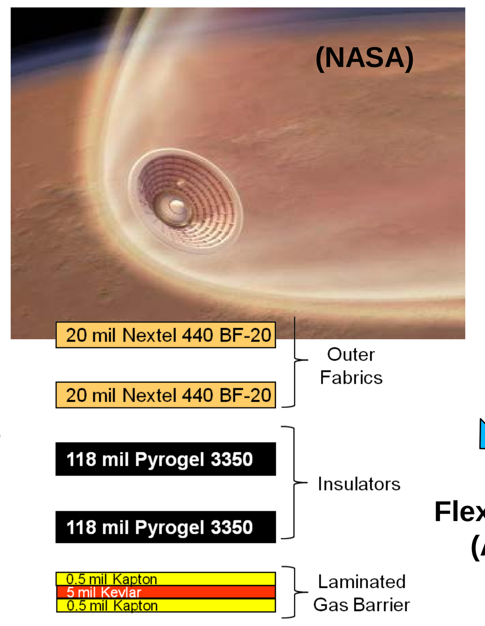
Hypersonic flow modeling
Year 2014

Fluid-structure interaction
Year 2015 (current study)

6m test article at National Full-Scale Aerodynamics Complex (NFAC)



Structural modeling (NASA)

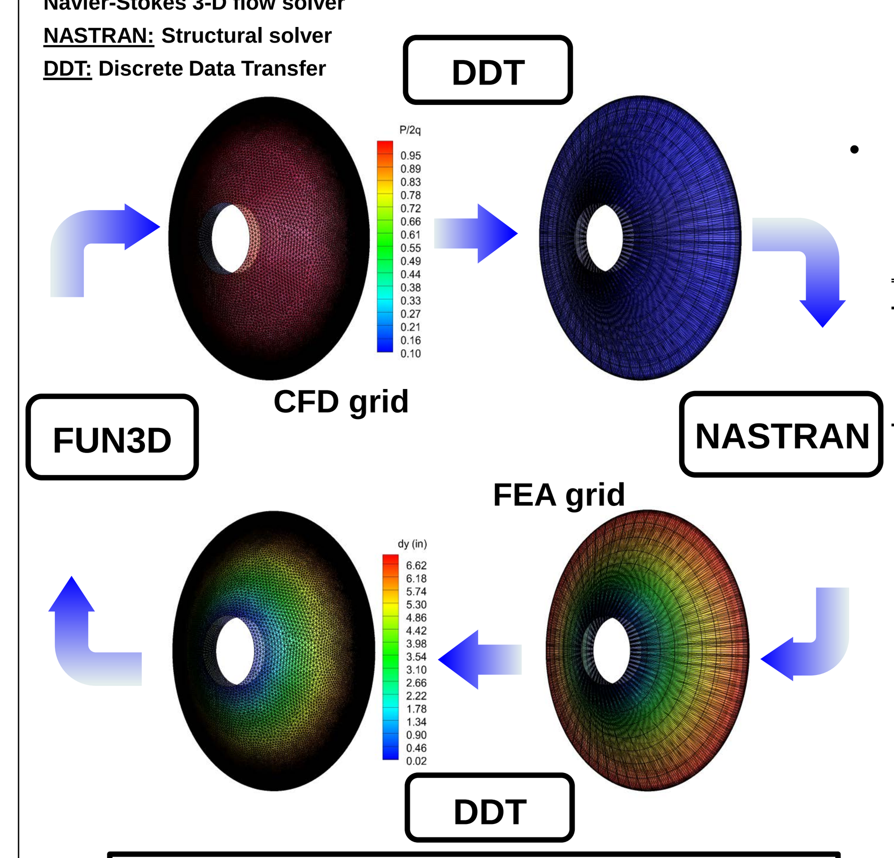


Material Thermal Response
Year 2016 (future work)

Material Thermal Response
Year 2016 (future work)

Flexible TPS modeling
(AIAA 2001-2510)

FLUID-STRUCTURE INTERACTION



Loosely-coupled iterative process

- FSI modeling subject to uncertainties
  - Operating (freestream) conditions
  - Flowfield parameters
  - Structural modeling parameters
- High-fidelity FSI modeling can be computationally expensive
  - Monte Carlo infeasible
  - Need an efficient but accurate UQ approach

Parameter	Description	Classification	Uncertainty	Ref.
NSTRF Y1 Wall Pressure/Shear Stress Contributions				
V_{inf}	Freestream Velocity (m/s)	Normal	0.5% CoV	Brune et al.
ρ_{inf}	Freestream Density (m/s)	Uniform	±30%	
A	CO_2-CO_2 Binary Collision Integral	Epistemic	±30%	
Structural Boundary Condition				
P_0	Inflation Pressure	Normal	2% CoV	HIAD Inflatable Structures test data archive
Elastic Modulus (Tensile Stiffness)				
E_C	Technora Cords	Epistemic	[-50%, +20%]	
E_{3K}	3-K Kevlar Straps	Epistemic	±20%	
E_{4K}	4-K Kevlar Straps	Epistemic	±20%	
E_L	Torus Orthotropic Laminate (Longitudinal)	Epistemic	±25%	
E_T	Torus Orthotropic Laminate (Transverse)	Epistemic	±20%	
Poisson Ratio				
υ_c	Technora Cords	Epistemic	±20%	
υ_{3K}	3-K Kevlar Straps	Epistemic	±20%	
υ_{4K}	4-K Kevlar Straps	Epistemic	±20%	
υ_{LT}	Torus Orthotropic Laminate (uniaxial)	Epistemic	±15%	
Shear Modulus (Torsional Stiffness)				
G_{LT}	Torus Orthotropic Laminate (In-plane)	Epistemic	±25%	
G_{LN}	Torus Orthotropic Laminate (Transverse)	Epistemic	±25%	
G_{TN}	Torus Orthotropic Laminate (Transverse)	Epistemic	±25%	

POLYNOMIAL CHAOS EXPANSIONS (PCE) WITH SPARSE APPROXIMATION

- PCE is a surrogate modeling technique based on a spectral representation of the uncertainty. A random function is decomposed into separable deterministic and stochastic components.

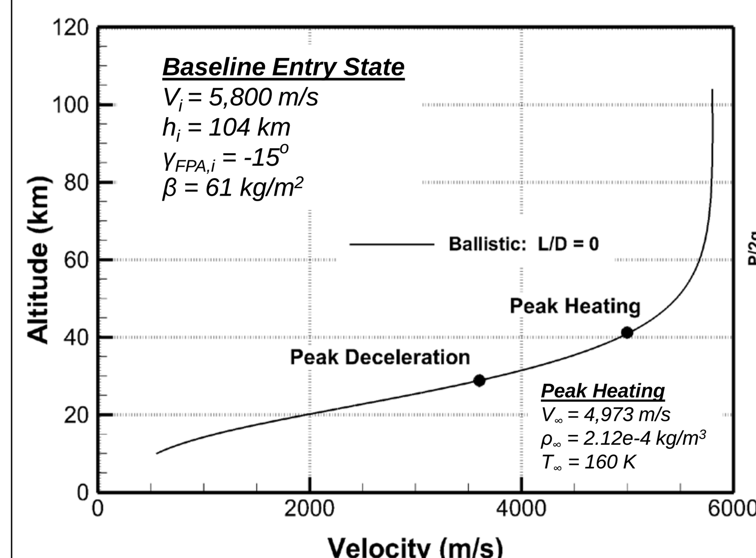
$$\alpha^*(\vec{x},\vec{\xi}) = \sum_{i=0}^{P} \alpha_i(\vec{x})\Psi_i(\vec{\xi}) \qquad N_t = P+1 = \frac{(n+p)!}{n!\,p!}$$

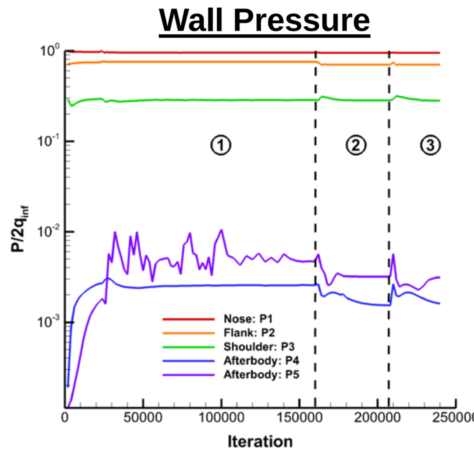
- For a PCE of order p comprised of n uncertain parameters, N_t deterministic model evaluations are required.
- An approach to improve efficiency is to seek an approximate solution to the underdetermined linear system via L_1-minimization, commonly referred to as Basis Pursuit Denoising, to obtain the PCE coefficients.

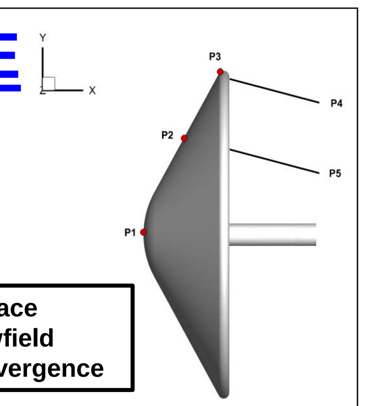
$$\min \|\alpha\|_1 \quad \text{subject to} \quad \|\Psi\alpha - \alpha^*\|_2 \le \delta$$

- Convergence of the coefficients can be measured with increasing sample size for improved efficiency.

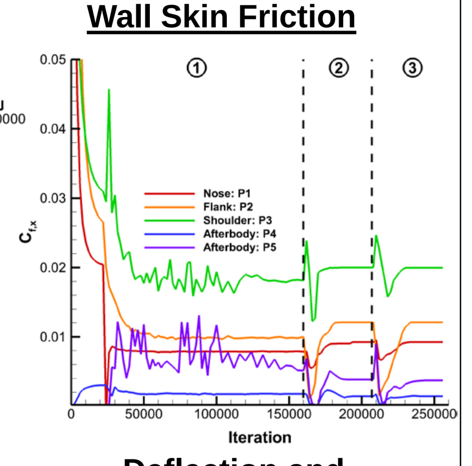
BASELINE REFERENCE CASE

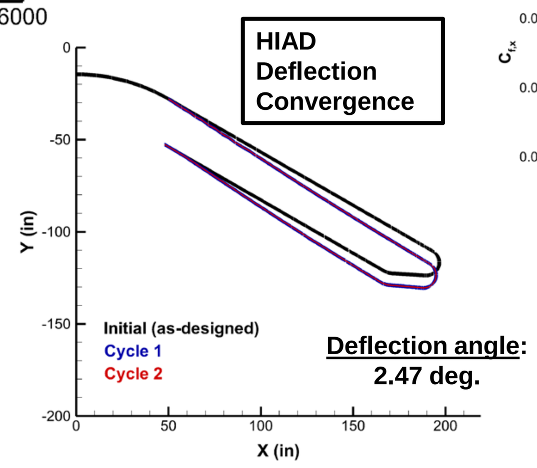






Surface Flowfield Convergence

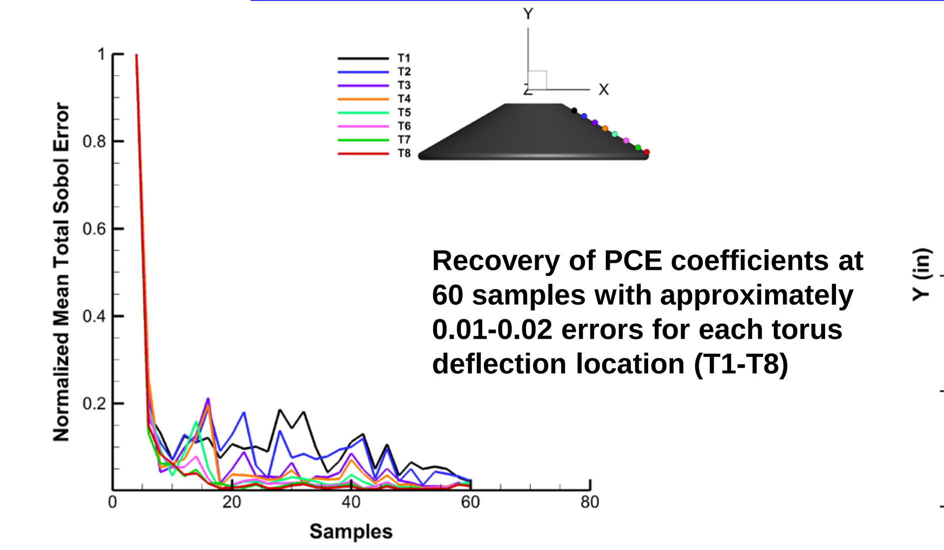


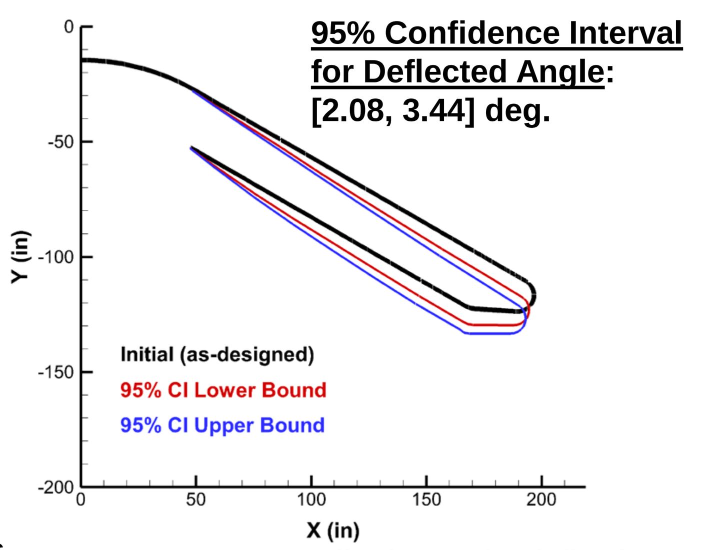


- Consider ballistic entry to Mars with a HIAD entry architecture
- Consider peak heating trajectory location for UQ
- Consider a 10m deformable HIAD, scaled from 6m NFAC test article

Deflection and surface flowfield converged at the end of two FSI cycles

HIAD DEFLECTION UNCERTAINTY



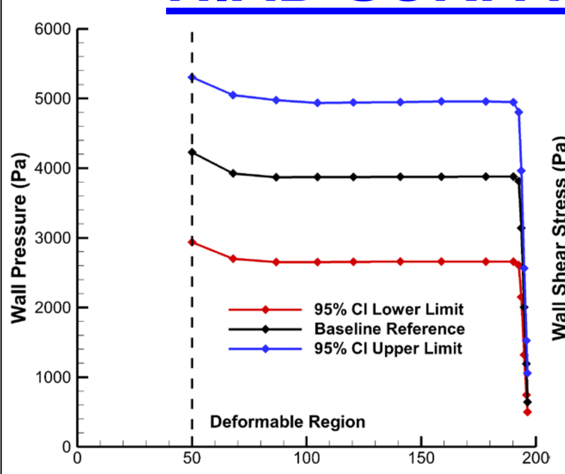


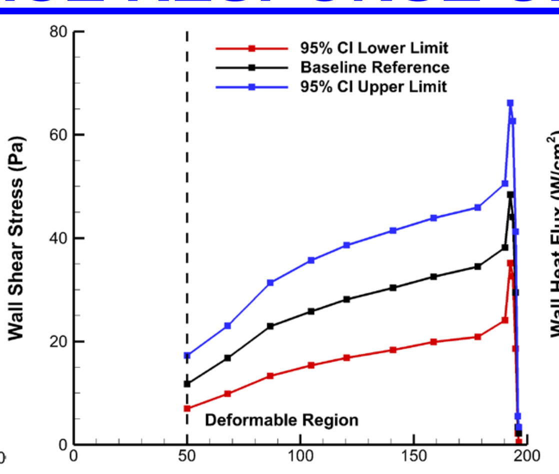
Contributions to Deflection Uncertainty at Selected Locations
(T1-T8 denote torus in order from rigid nose cap to shoulder)

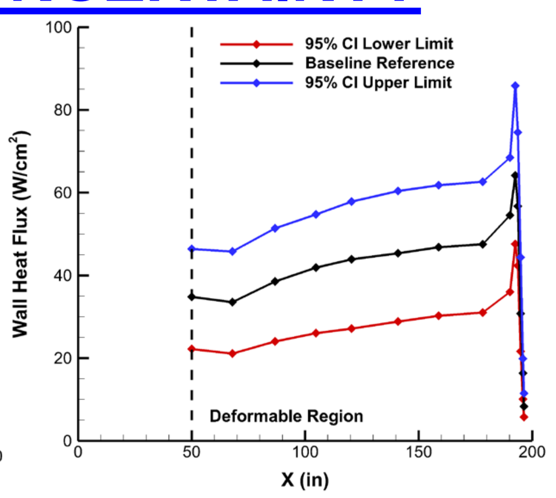
Uncertain Parameter	T1	T2	T3	T4	T5	T6	T7	T8
E_C	23.6%	32.9%	66.6%	73.9%	82.5%	85.1%	86.7%	87.2%
E_T	20.2%	16.8%	8.3%	5.9%	2.6%	2.4%	1.3%	1.1%
P_0	14.0%	11.9%	2.5%	1.6%	1.1%	1.0%		
E_L	11.8%	8.6%	2.3%	1.8%				
υ_{LT}	11.8%	11.1%	7.0%	5.3%	3.3%	2.3%	1.6%	1.4%
E_{4K}	9.3%	7.9%	5.0%	4.2%	4.3%	4.0%	4.3%	4.6%
ρ_{inf}	3.4%	2.7%	1.0%					
υ_{4K}	3.3%	2.4%	2.1%	2.0%	1.4%	1.1%	1.0%	1.0%

- 90% contribution to the deflection uncertainty outlined in red
- Main contributors to the deflection uncertainty are the tensile stiffnesses (E):
  - Technora cords
  - Torus
  - 4-K radial straps
- Torus, 4-K straps, and inflation pressure (P_0) become more important towards T1

HIAD SURFACE RESPONSE UNCERTAINTY







Contributions to Wall Heat Flux Uncertainty

Uncertain Parameter	Flank 1 (T1)	Flank 2 (T5)	Shoulder (T12)
ρ_{inf}	92.7%	93.6%	91.4%
δ	4.5%	4.7%	4.9%
CO_2-CO_2	1.6%	1.1%	2.4%
V_{inf}	1.1%	0.6%	1.3%

Contributions to Wall Pressure Uncertainty

Uncertain Parameter	Flank 1 (T1)	Flank 2 (T5)	Flank 3 (T7)	Flank 4 (T9)	Shoulder (T12)
ρ_{inf}	87.7%	87.9%	87.6%	88.0%	7.1%
δ	10.7%	10.8%	10.8%	10.6%	92.9%
V_{inf}	1.6%	1.3%	1.6%	1.4%	0.2%

Contributions to Wall Shear Stress Uncertainty

Uncertain Parameter	Flank 1 (T1)	Flank 2 (T5)	Shoulder (T12)
ρ_{inf}	62.4%	61.9%	61.6%
CO_2-CO_2	34.3%	33.9%	36.1%
δ	2.4%	2.6%	1.2%
V_{inf}	0.9%	1.6%	1.1%

- Freestream density is the main contributor to wall heat flux, shear, and pressure uncertainties
- CO_2-CO_2 collision interaction important in the wall heat flux and shear uncertainties – affects transport properties
- HIAD deformation is particularly significant in the wall pressure uncertainty – due to structural uncertainties

CONCLUSIONS

- An efficient uncertainty quantification approach was applied to the analysis of fluid-structure interaction over a deformable HIAD aeroshell geometry
- Approximately half of the 16 uncertain flowfield and structural modeling parameters contribute to the uncertainty in the deflection, aerodynamic heating, wall shear stress, and wall pressure
  - Deflection: tensile stiffnesses of cords, straps, and torus structure; inflation pressure
  - HIAD surface conditions: freestream density, shape deformation (deflection), and CO_2-CO_2 binary collision interaction
- Future work includes coupled fluid-TPS response analyses of HIADs for Mars entry, which utilizes the results obtained from flowfield uncertainty analysis

REFERENCES

- Dwyer-Cianciolo, A. M. et al. "Entry, Descent, and Landing Systems Analysis Study: Phase 2 Report on Exploration Feed-Forward Systems," Tech. rep., NASA/TM-217055, Feb. 2011.
- Swanson, G. et al., "Structural Strap Tension Measurements of a 6-meter Hypersonic Inflatable Aerodynamic Decelerator under Static and Dynamic Loading, AIAA 2013-1287," March 2013.
- Samareh, J. A., "Discrete Data Transfer Technique for Fluid-Structure Interaction, AIAA 2007-4309," June 2007.

RELEVANT PUBLICATIONS

- West IV, T. K. and Hosder, S., "Uncertainty Quantification of Hypersonic Reentry Flows using Sparse Sampling and Stochastic Expansions," *Journal of Spacecraft and Rockets*, Vol. 52, No. 1, 2015, pp. 120-133.
- Brune, A. J., West IV, T. K., Hosder, S. and Edquist, K. T., "Uncertainty Analysis of Mars Entry Flows over a Hypersonic Inflatable Aerodynamic Decelerator," *Journal of Spacecraft and Rockets*, Vol. 52, No. 3, 2015.
- Brune, A. J., Hosder, S., and Edquist, K. T., "Uncertainty Analysis of Fluid-Structure Interaction of a Deformable Hypersonic Inflatable Aerodynamic Decelerator," AIAA Paper to be presented at: *AIAA International Space Planes and Hypersonic Systems and Technologies Conference*, Glasgow, Scotland, July 2015.

ACKNOWLEDGEMENTS

- This work was supported by a NASA Space Technology Research Fellowship under training grant no. NNX13AL58H.
- The authors would like to thank the HIAD Structures working group at NASA Langley Research Center for providing necessary data to make this work possible, and Mike Lindell and Robert Biedron for providing guidance and technical support for the coupled fluid-structure modeling process.