HIAD Advancements and Extension of Mission Applications

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Abstract: The Hypersonic Inflatable Aerodynamic Decelerator (HIAD) technology has made significant advancements over the last decade with flight test demonstrations and ground development campaigns. The first generation (Gen-1) design and materials were flight tested with the successful third Inflatable Reentry Vehicle Experiment flight test of a 3-m HIAD (IRVE-3). Ground development efforts incorporated materials with higher thermal capabilities for the inflatable structure (IS) and flexible thermal protection system (F-TPS) as a second generation (Gen-2) system. Current efforts and plans are focused on extending capabilities to improve overall system performance and reduce areal weight, as well as expand mission applicability. F-TPS materials that offer greater thermal resistance, and ability to be packed to greater density, for a given thickness are being tested to demonstrated thermal performance benefits and manufacturability at flight-relevant scale. IS materials and construction methods are being investigated to reduce mass, increase load capacities, and improve durability for packing. Previous HIAD systems focused on symmetric geometries using stacked torus construction. Flight simulations and trajectory analysis show that symmetrical HIADs may provide L/D up to 0.25 via movable center of gravity (CG) offsets. HIAD capabilities can be greatly expanded to suit a broader range of mission applications with asymmetric shapes and/or modulating L/D. Various HIAD concepts are being developed to provide greater control to improve landing accuracy and reduce dependency upon propulsion systems during descent and landing. Concepts being studied include a canted stack torus design, control surfaces, and morphing configurations that allow the shape to be actively manipulated for flight control. This paper provides a summary of recent HIAD development activities, and plans for future HIAD developments including advanced materials, improved construction techniques, and alternate geometry concepts that will greatly expand HIAD mission applications.

1. Introduction

Hypersonic Inflatable Aerodynamic Decelerators (HIADs) provides considerable system mass and volume savings over rigid aeroshell technology while enabling larger payload delivery and greater landing access capabilities. Over the past decade, the performance capabilities of HIADs have been demonstrated with sounding rocket flight demonstrations and multiple ground development efforts to improve designs, materials, and construction methods. HIAD articles consisting of a stacked-torus Inflatable Structure (IS) and Flexible Thermal Protection Systems (F-TPS) ranging in diameters from 3 to 6 meters with half-cone angles of 60 and 70 degree have been fabricated and tested. As an example, Figures 1 and 2 show the configuration for a 3.7 m diameter stacked torus IS design and a completed test article. The materials and construction features used for previous HIAD articles originated from inflatable beam structures that did not emphasize low mass and design efficiency. Alternate materials that offer improved strength, durability and thermal performance have been investigated as part of the HIAD technology development project. During the last few years, material property and components tests have demonstrated several materials that provide improved performance for inflatable structures. These materials as well as alternate manufacturing methods are being incorporated into the IS designs for planned fabrication and testing efforts.

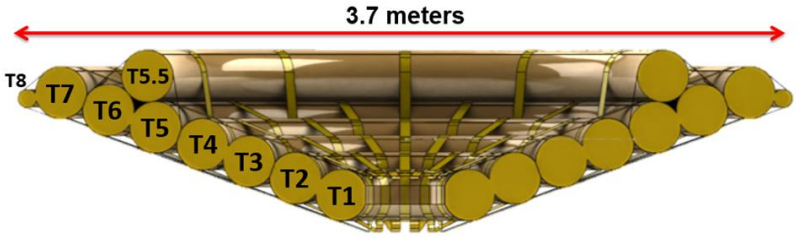

Figure 1. Cross-section of 3.7 HIAD IS

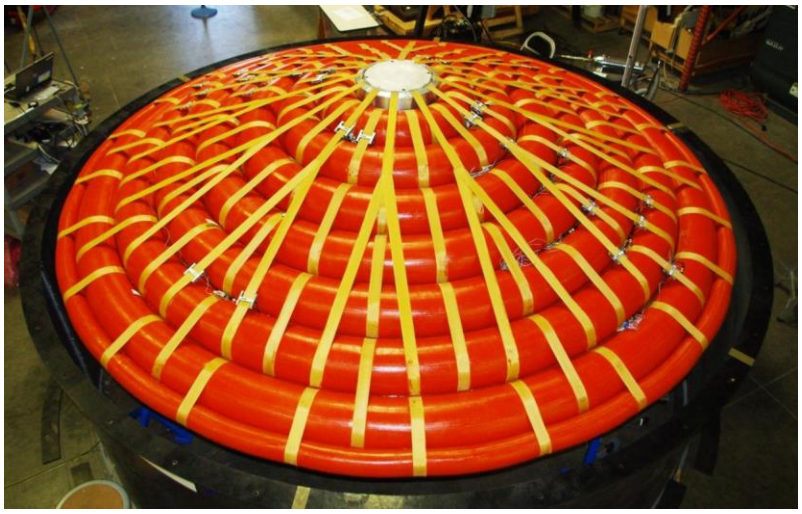

Figure 2. 3.7m Test Article

In the area of F-TPS, materials that offer improved thermal performance, durability for packing, and manufacturing are being investigated. Thermal performance of several insulating materials offering increased thermal capacity with less areal mass have been arc jet tested at relevant heat flux and total integrated heat load conditions. Improved mechanical properties and durability with incorporation of light weight textile scrims and elastomeric binders are being demonstrated through manufacturing efforts and components tests. Additionally, improved gas barriers materials with higher temperature capabilities, increased strength for load carrying capacity, and durability are being developed.

All previous HIAD articles for flight and ground testing were based on symmetrical geometries that remained fixed after inflation. EDL analysis shows that down range and cross range aerodynamic lift control efficiently improves flight control and landing accuracy for proposed Mars and Earth return missions. These studies indicate that HIADs with lift over drag (L/D) between 0.15 and 0.3 provide sufficient flight control and reduce dependency upon propulsion systems during descent and landing. Flight dynamics analyses also shows that independent lift control for down range and cross range are preferred to provide greater control. By taking advantage of the adaptable nature of soft good materials and fabrication techniques, inflatable structure geometries and features can be modified to greatly expand HIAD flight control capabilities and mission applications.

2.0 Materials and Manufacturing

Inflatable Structures Materials and Manufacturing

The stacked torus design consists of torus elements of increasing diameter with strap arrangements to maintain positions and distribute aerodynamic loads throughout structure. The torus is constructed with a braided fabric tube with a liner inserted to retain inflation gas (Figure 3). Cords are inserted into the braid to carry most of the inflation axial pressure load and to maintain shape uniformity and stability. After initial inflation of a torus, an outer coating is applied to maintain braided material organization and provide bonding between the braid and liner (Figure 4). Kevlar, Technora, Zylon, and Carbon fiber tows have been used to produce tori with the largest having sectional diameters up to 24 inches with Kevlar. Tori with larger major and sectional diameters needed for large scale HIADs begin to exceed carrier counts for braiding machines and necessitate alternate construction techniques. The 24 inch diameter braid recently produced for the HIAD project required an 800 carrier braiding machine. Use of narrow ribbons in lieu of fiber tows will allow larger braid diameters with fewer carriers for a given braid diameter and surface coverage. Using a ¼" wide ribbon would require about 100 carriers for the 24 inch braid. The HIAD project recently demonstrated braiding with ribbon at 18 inch diameter (Figure 5), which can be extended to 40 inch diameter or more that will be needed for large scale HIADs in the 15-20 meter diameter range. The HIAD project is currently working with vendors to produce high strength ribbons using Zylon to meet the high strength and thermal requirements.

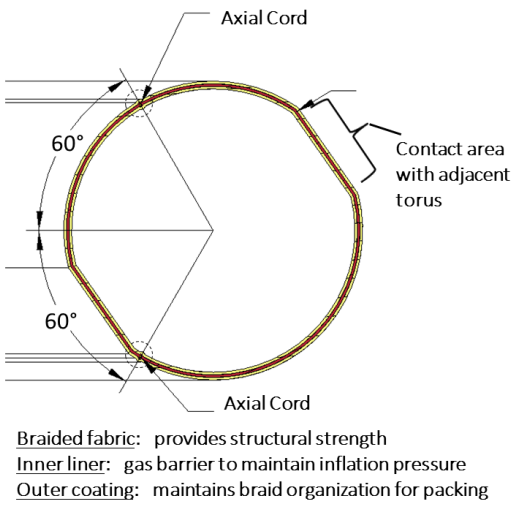

Figure 3. Torus Elements

Figure 4. Torus Coating Application

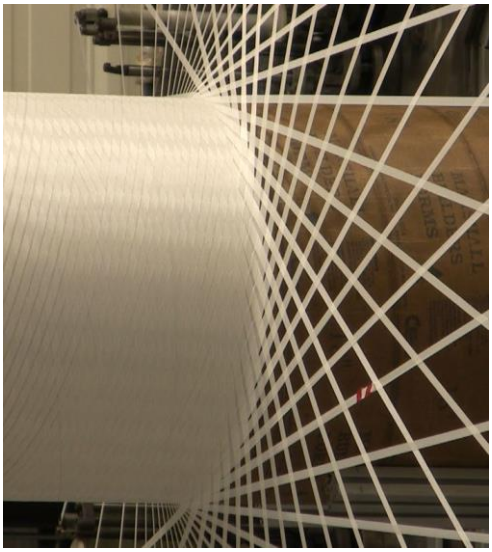

Figure 5. Demonstration of Braiding with Ribbon

Current fabrication procedures require a significant amount of hand work to assemble the torus components and achieve a torus within the tolerance requirements. Extreme care must be taken to avoid damage to materials during handling, particularly the liner which is very thin and must be carefully fed through the braid. As torus sizes increase the material handling processes require special fixtures for lifting and become much more difficult and labor intensive. Combining several steps with the braiding process can significantly decrease labor and improve product quality. One step to simplify the process is to place the liner over a cylindrical mandrel and then perform the braiding operation with ribbons laid over the liner and mandrel. A further improvement would be to include an operation to bond the braid to the liner using adhesives or heat fusing as part of a continuous braiding process. Recent advancements in braiding technology incorporates programming of braiding operations to tailor fiber angles and densities to produce variation in diameters and shapes for complex designs. An example of these advance braiding methods, referred to as 3D braiding, is the production of fuselage ring frames for the Airbus A350 over a special mandrel to match the specified fuselage diameter. The 3D braiding approaches can be applied to produce the HIAD torus shape with a curved braided tube matching the torus diameter. Ultimately, a continuous process of braiding over the liner with a curved mandrel that includes a process to adhere the braid to the liner is envisioned. The curved composite would then be cut to the appropriate length and closed out to form the torus. This more complex operation will require incremental development efforts but can result in increased productivity and repeatability with higher quality, tighter tolerances and more efficient torus design and construction.

The stacked torus design requires a large number of strap to maintain geometry and distribute aerodynamic loads. Figure 6 shows a typical strapping arrangement that was designed for the 6m test article. Pairing straps wrap around adjacent tori and are evenly distributed throughout the structure to maintain relative torus positions and the stack cone angle. Radial strap are anchored to the vehicle centerbody and attach to outer tori in the stack to improve distribution of aerodynamic loads throughout the structure. The radial straps shown in Figure 6 attach to three straps, referred to as chevron straps, which attach to two outer tori. The number and arrangement of radial and chevrons straps are tailored to meet specific structure geometry and load requirements. Standard Mil spec webbing with widths of 2 inch and 1-3/4 inch have been used for prior HIAD test articles. For more efficient loads transfer and construction, alternate structural ties are being investigated. These high strength ties will be thinner and have greater widths that can be contoured

to the torus curvature. Advanced textile manufacturing approaches with thin woven material and coatings to provide durability and bondable surfaces are being developed with textile vendors.

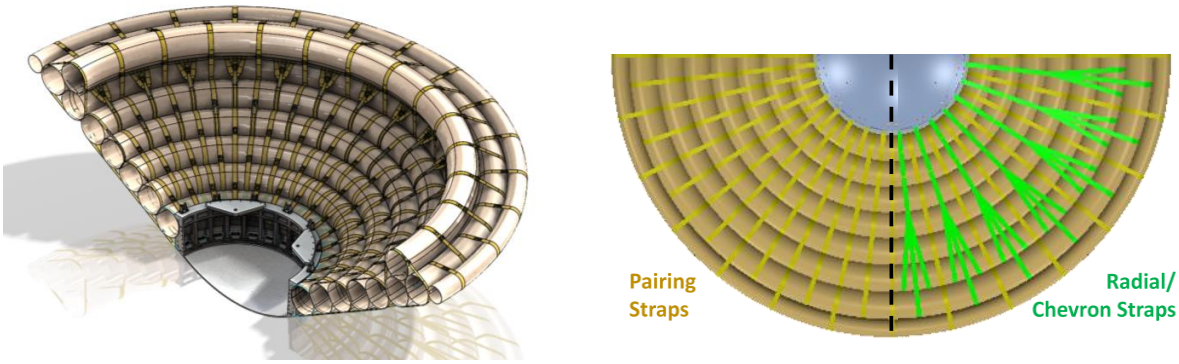

Figure 6. Current Strap Configuration

Flexible Thermal Protection Systems Materials and Manufacturing

The F-TPS must protect the IS from very high temperatures during entry flight while being tolerant to system packing and deployment. The F-TPS is comprised of multiple layers of materials specifically selected for the thermal loads and temperatures as shown in Figure 7. The outer layers must withstand the highest temperatures and aerodynamic pressure and shear loads. Insulating layers are selected for thickness and number of layers to meet specific mission thermal load requirements. The gas barrier layer is impermeable to block flow of hot gases to the IS and includes a high strength cloth for mechanical loads and attachment of structural members that integrate the F-TPS to the vehicle centerbody. Early designs for HIAD F-TPS primarily utilized off-the-shelf materials and were demonstrated during the IRVE flight experiments and several test campaigns at arc jet test facilities [2]. To improve thermal performance and reduce areal mass, alternate materials and state-of-the-art manufacturing processes are being developed. Insulating layers contribute most to the TPS mass and are consequently the primary focus for development. A separate NASA project, Entry Systems Modeling (ESM), investigated a set of advanced insulators suitable for peak heat fluxes up to 75 W/cm^2. FTPS layups using various insulator layers were tested and evaluated including materials fabricated from Saffil alumina fibers, opacified fibrous insulators, and intumescent insulators. The most promising candidates from the ESM project will be advanced by HIAD to increase scale and incorporate the materials into F-TPS fabrication. Methods to improve durability of these materials and alternate seaming and stitching for assembly are currently being developed and tested. Advanced gas barrier materials with higher thermal properties and improved strength have recently been developed using custom manufacturing processes in collaboration with textile vendors.

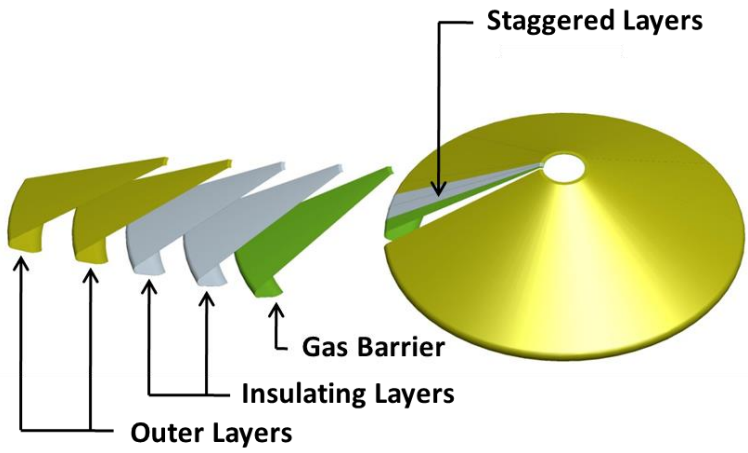

Figure 7. F-TPS Layer Definition

3.0 Alternate and Asymmetric HIAD Designs

By incorporating asymmetric shapes and features, HIAD technology applications and flight performance can be expanded to meet a much broader range of planetary missions. Development of alternate HIAD designs have been mostly untapped as efforts have primarily focused on symmetric fixed inflatable geometries. Trajectory analysis and flight simulations show that a lift to drag ratio (L/D) between 0.15 and 0.3 provides control authority to significantly improve landing accuracy and reduce dependency upon propulsion systems during entry and descent. Ideally, the asymmetric aerodynamic features provide independent down range and cross range lift control with rapid response times for actuation. The IRVE-3 flight experiment demonstrated the effectiveness of generating lift with a symmetrical 3 m diameter HIAD from a radial CG offset. A trim angle of up to 16 degrees was obtained providing a L/D ratio of 0.2 near peak dynamic pressure [1]. However, CG offset approaches have limitations as larger masses are needed for higher L/D and integration of the mass translation and mechanisms with a vehicle become problematic. By taking advantage of the adaptable nature of soft good materials and fabrication techniques, inflatable structure geometries and features can be incorporated into HIAD designs for flight control authority to meet proposed Mars missions as well as Earth return missions.

A design trade study approach is used to evaluate and select viable concepts. Assessment of a concept begins with analysis of aerodynamic performance over the hypersonic and supersonic flight regimes. After the general shape, functions and features are identified, a structural design using soft goods and integration with the HIAD is developed. To fully evaluate each concept other key performance and system parameters must be considered. To be suitable for mission applications and vehicle integration, key performance parameters are: flight dynamics, control authority response, structural load capability, aeroheating, TPS integration, vehicle integration, manufacturability, and packing, stowage and deployment efficiencies.

Various HIAD asymmetric configurations, including fixed geometry concepts and concepts with actively controlled features have been investigated. Promising approaches that include a canted stacked torus design, addition of trim tabs, and morphing configurations that allow active shape manipulation are being investigated and are summarized below.

Fixed Geometry

Many previous research programs and studies have considered modification of the simple blunted cone shape into asymmetric geometries to provide lift for flight control. In the 1980s, a significant amount of analysis, design, and testing was conducted for the Aeroassist Flight Experiment (AFE) configuration shown in Figure 8 [3]. Wind tunnel measurements at Mach 6 and 10 for AFE agreed very well with the inviscid-flow computer codes for aerodynamic coefficients, shock shapes and lift-to-drag ratio [4]. More recent research has considered several geometry variation with canted and truncated cone shapes. The shifted nose configurations shown in Figure 9 were analyzed and found to provide L/D between 0.1 and 0.4 with angles of attack ranging from -30° to 20° while maintaining flight stability [5] [6].

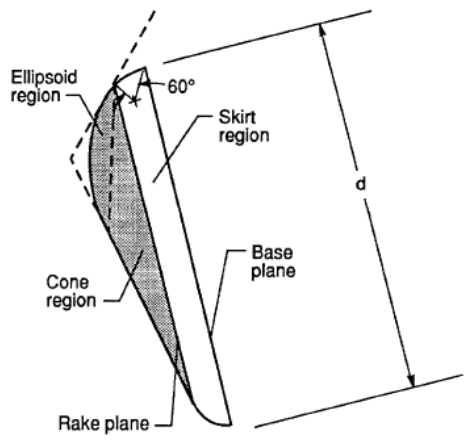

Figure 8. Lifting shape for Aeroassist Flight Experiment

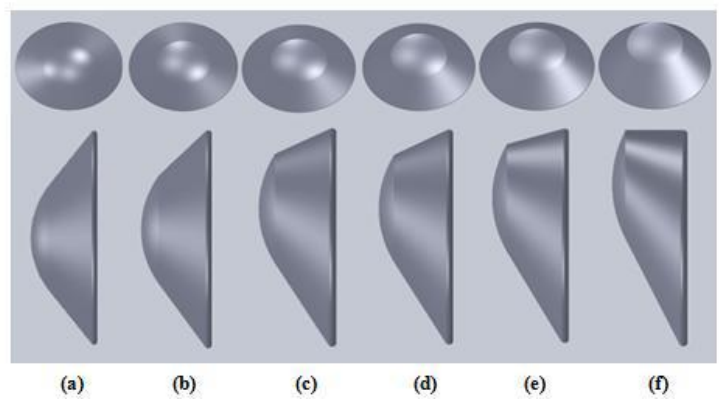

Figure 9. Top and Side Views of Shifted Nose Geometries at (a) symmetric, (b) 20%, (c) 40%, (d) 60%, (e) 80%, (f) 100%

To achieve these non-axisymmetric geometries, inflatable structure designs must be developed with structural capacity that accommodates the non-uniform aerodynamic loads. One concept is to modify the current stacked torus design by canting the stack as shown in Figure 10. This approach is relatively simple extension of current stacked torus manufacturing methods with a modified strapping arrangement. The amount of cant, windward and leeward angles, can be selected to provide L/D up to 0.3 to suit the specific trajectory and flight control requirements.

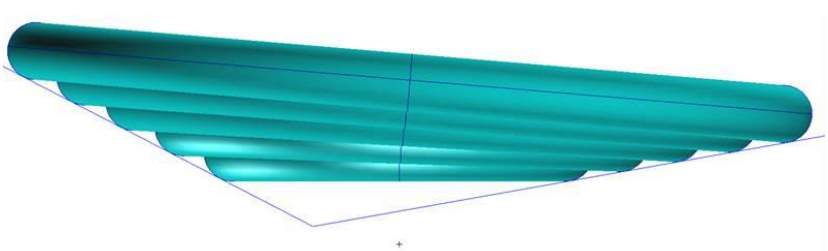

Figure 10. Canted Stack Torus

Trim tabs

Addition of control surfaces to the traditional sphere cone blunt body for aerodynamic lift have been extensively studied. Trim tabs are potentially low mass devices that provide lift over a broad range of Mach numbers without requiring a radial offset of the vehicle's center of gravity. L/D can be modulated by

actively controlling tab angle. Various trim tab configurations at hypersonic and supersonic Mach numbers have been tested and correlated with CFD code [7-12]. Trim tabs as shown in Figure 11 with cant angles of 0 to 90 degrees relative to the forebody surface and various areas and aspect ratios were tested to measure force and moment coefficients. The most significant parameters affecting performance were found to be the trim tab area and cant angle. Since high cant angle configurations introduce high localized heating that must be accommodated with the TPS, concepts for initial HIAD applications will consider cant angles of 0 and 20 degrees. Based on test results for a 70 degree cone angle aeroshell, a trim tab with a 0 degree cant angle and 6% of the base aeroshell drag area, achieves an L/D of approximately 0.3.

A structural model using Abaqus was developed for a 16.7m diameter IS for preliminary analysis of aerodynamic loading and inflatable structure response. The 16.7m diameter corresponds to a HIAD aeroshell being considered in a Mar human scale EDL mission study. The model incorporated design features and materials properties that were correlated to structural load tests of previous 3m and 6m test articles. Figure 12 shows the aerodynamic pressure distribution for L/D of 0.2 for the 16.7m IS with 6% tab area and the deformed IS from the Abaqus structural model. Although the IS is a relatively stiff structure it allows some increased displacement in the tab area as a result of the moment applied by the tab surface pressure. Displacement of the tab augmented by the aerodynamic loads can be accounted for in the tab design, its integration with primary structure, and an initial slight cant angle to provide the desired cant angle at peak loading.

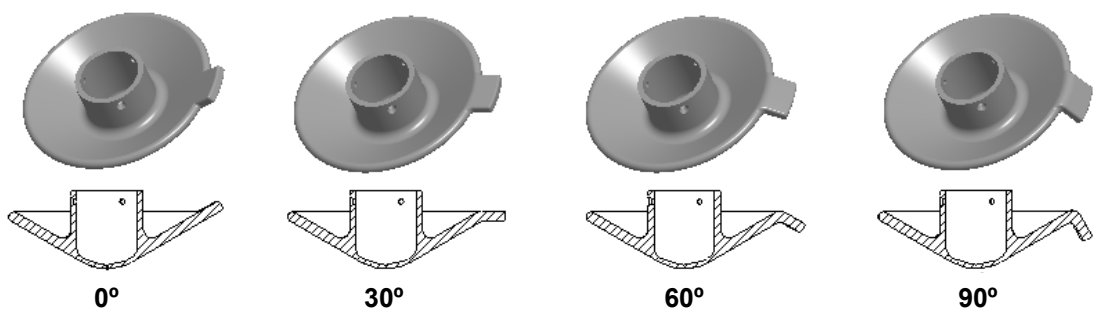

Figure 11. Sphere Cone with Trim Tab at Various Cant Angles

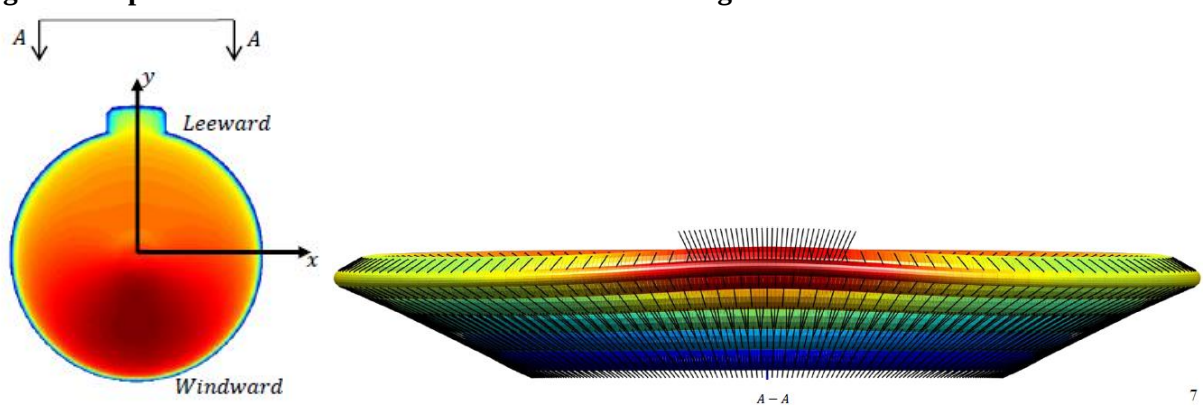

Figure 12. Trim Tab Aerodynamic Pressure Distribution and Structural Model Results

Ongoing efforts are developing tab designs to meet requirements for load capacity, attachments, activation, and construction. Atmospheric entry trajectory analysis shows that tab the response time needs to be on the order of 10-15 seconds to provide sufficient flight control. Additionally, multiple trim tabs can be positioned around the shoulder to provide independent cross range and down range control. Further

aerodynamic performance and structural analysis of tab concepts will be used to develop trim tab design and materials for fabrication and testing demonstrations.

Morphing HIADs

Another approach is to use shape morphing to deform the HIAD from its symmetrical shape to create a non-uniformity for aerodynamic lift. This can accomplished by distorting the stacked torus structure with actuators to modulate the lift vector during entry and descent. Two concepts are currently being investigated.

One approach is to morph the aeroshell shapes by displacing a quadrant of the structure as shown in Figure 13. Modified Newtonian Impact Theory was used to evaluate the shape changes and the amount of displacement to estimate aerodynamic coefficients, lift to drag, and trim angle. For a 12 m diameter 70 degree cone half-angle aeroshell, the aft displacement in a quadrant of 42 inches (1.1 m) at the shoulder provides an L/D of about 0.2. This displacement can be achieved with tension elements attached to the shoulder of the IS controlled by actuators attached to the vehicle centerbody. Concepts using electric motors or pneumatic muscle actuators with associated sensors and controls are being developed. Structural analysis using Abaqus finite element modeling software provides estimates of actuation forces and response of the inflatable structure**.** Initial structural analysis for HIAD morphing uses the 16.7 m 70 degree 5 torus inflatable structure for a Mars EDL Pathfinder architecture study. Figure 14 shows the displaced structure corresponding to an L/D of 0.2 for the 16.7m design. With active control, actuators provide quick response to modulate the amount of shape change for lift and flight control. Separate lift and bank control is achieved with independent actuation systems for each quadrant of the aeroshell.

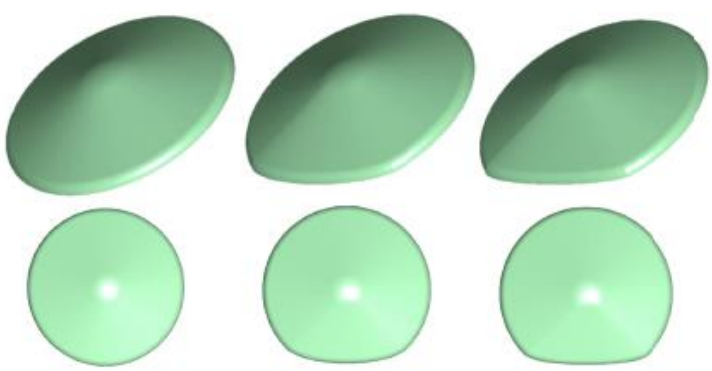

Figure 13. Morphing of an Aeroshell Quadrant

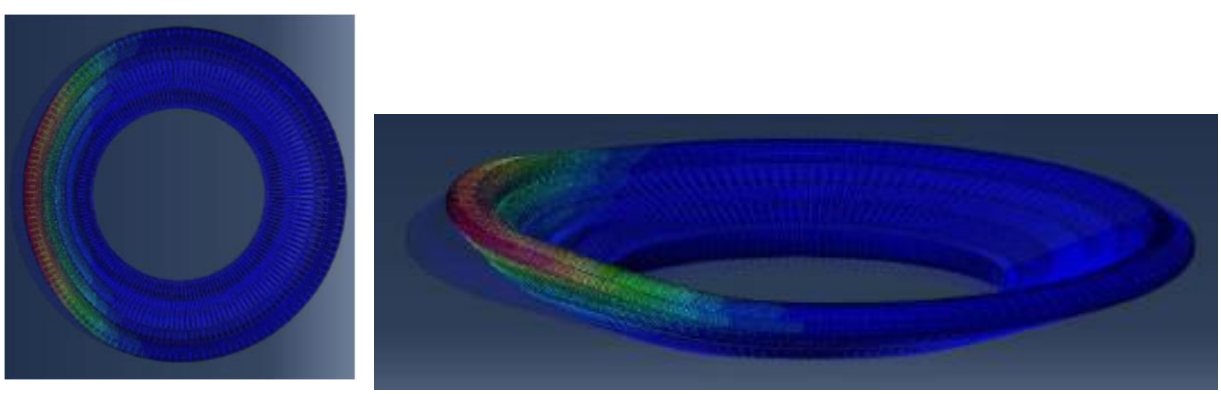

Figure 14. Structural Model of 16.7 m HIAD for L/D of 0.2

Another shape morphing concept being investigated uses displacement of only the outer torus. This approach will initially compress the outer torus from its normal unrestrained position as represented in Figure 15. From this intermediate position, the outer torus is released in one area and pulled in further on the opposite side to provide non-symmetry for lift. To make the outer torus more compliant its inflation pressure is much lower than the rest of the torus stack. A pressure of 2 psi for the outer torus provides sufficient structural stiffness for the aerodynamic loads near the shoulder. The rest of the stack would likely be maintained between 15 and 20 psi which has been demonstrated to carry the required peak aerodynamic loads from previous HIAD tests. Figure 16, shows results from the structural modeling to study the distortion of the torus with a load member (strap, membrane, etc.) attached to the torus and pulling towards the vehicle centerbody. Sufficient flight control authority and response rates requirements are met with customized actuators and associated controls. With separate actuation of each quadrant the torus can be radially manipulated by releasing and compressing for independent down-range and cross-range flight control.

Figure 15. Outer Torus Compressed and Uncompressed

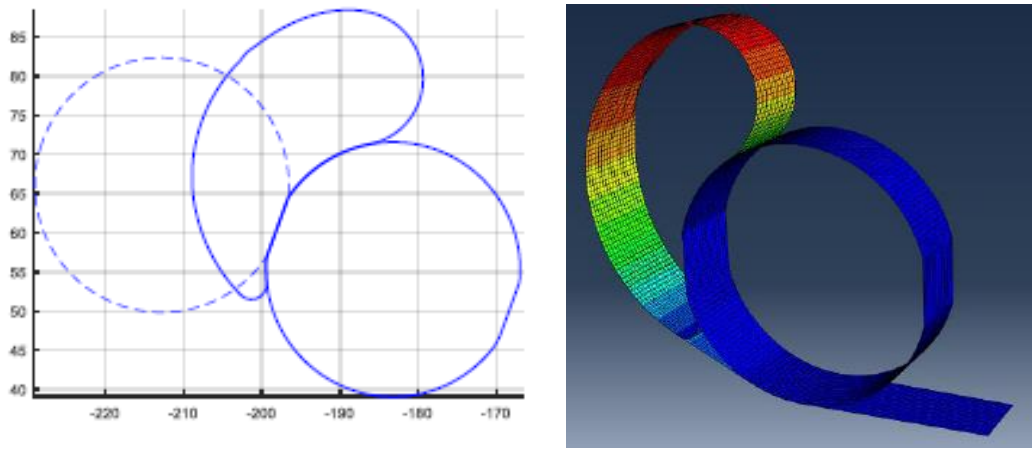

Figure 16. Structural Modeling of Torus Displacement

4. Summary and Future Work

Successful flight demonstrations and ground development efforts over the last decade have established the stacked torus HIAD as leading EDL technology for delivery of large payloads and expanded landing capabilities for atmospheric planetary missions. Recent efforts have focused on broadening HIAD capabilities with asymmetric geometries and features to provide flight control to provide greater landing accuracy and reduce dependency upon propulsion systems during descent and landing. The concepts

described herein are being developed for L/D between 0.15 and 0.3 which meets objectives derived from trajectory analysis. Initial aerodynamic analysis and structural modeling confirm that these concepts can provide performance needed for down range and cross range control during hypersonic flight. Next steps will include design of features and actuation methods and functional testing to demonstrate operation. Previous HIAD tests articles will be utilized for integration of trim tab and morphing concepts for testing. Non-axisymmetric fixed geometries will be demonstrated with fabrication of torus elements and subscale articles. As the concepts mature, other design and performance parameters will be investigated and included in a trade study to evaluate each concept. Key performance parameters include flight dynamics, control authority response, structural load capability, aeroheating, TPS integration, vehicle integration, manufacturability, and packing, stowage and deployment efficiencies. The most promising designs will be advanced through additional test article fabrication, testing, and correlation with aerodynamic, aerothermal and structural models. Ongoing efforts to improve materials and construction methods will increase HIAD structural and thermal performance while reducing mass. Many of the IS material and fabrication improvements will be utilized for the asymmetric geometries and features. Advancements in insulating materials will be required to tailor the F-TPS for non-symmetrical aerothermal loads and localized heating associated with features such as trim tabs.

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