Summary of Ultralightweight Ballute Technology Advances

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***Abstract* – Ultralightweight ballutes offer the potential to provide the deceleration for entry and aerocapture missions at a fraction of the mass of traditional methods. From April 2003 through December 2006, a team consisting of Ball Aerospace, ILC Dover, NASA Langley, NASA JSC, and the Jet Propulsion Laboratory has been addressing the technical issues associated with ultralightweight ballutes for aerocapture missions under funding provided by the In-Space Propulsion Office at NASA MSFC. Significant technology advances have been made in the areas of ballute materials, aerothermal analysis, trajectory control, aeroelastic modeling, hypersonic test, and overall ballute system design processes. The results show that ultralightweight ballutes provide excellent performance and packaging benefits not only for aerocapture, but also for de-orbit, entry, descent, and landing missions to planetary bodies with a sensible atmosphere. Additional ground testing followed by flight demonstration represents a critical validation step before this technology is used in operational mission applications.**

INTRODUCTION

A ballute (a compound word combining balloon and parachute) is a deployable, inflatable drag device designed to provide deceleration at high altitudes and high velocities. Ballutes have been used in several terrestrial applications, and can also provide aerodynamic deceleration for aerocapture, entry, descent, and landing missions in space.

Traditional aerocapture technology relies on an aeroshell or heat shield to provide aerodynamic deceleration and protect the spacecraft from high entry-heating rates. The innovative concept behind using ballutes for aerocapture centers on deployment of a lightweight ballute with sufficient drag area to decelerate the spacecraft at very low densities high in the atmosphere. By flying higher in the atmosphere, deceleration required for aerocapture is achieved with relatively benign heating rates. The low heating rates experienced during atmospheric entry and deceleration enable the use of ultralightweight construction techniques for the ballute. This 'fly higher, fly lighter, fly cooler' approach to aerocapture results in revolutionary mass performance compared to traditional technologies.

In addition to providing mass performance advantages, ballutes are stored in a relatively small volume and then deployed shortly before use. This packaging benefit enables aeroassist to be used where constraints imposed by structurally fixed aeroshells are prohibitive. For example, spacecraft component packaging is not constrained by the aeroshell structural envelope. The spacecraft center of gravity does not have to be strictly controlled to maintain aerodynamic stability. Because the ballute is not deployed until use, the ballute does not interfere with communications, instrument pointing, and spacecraft thermal control during interplanetary cruise.

Over the past four years, a team of engineers from Ball Aerospace, ILC Dover, NASA Langley, JSC, and JPL has been carrying out a systems analysis and test program to mature ultralightweight ballute technology for aerocapture under funding provided by the In-Space Propulsion Office at NASA MSFC. Ball Aerospace led the overall effort and was responsible for systems engineering and system wide analyses. ILC Dover provided expertise in materials testing, inflatable design, and fabrication processes. NASA Langley led hyper-

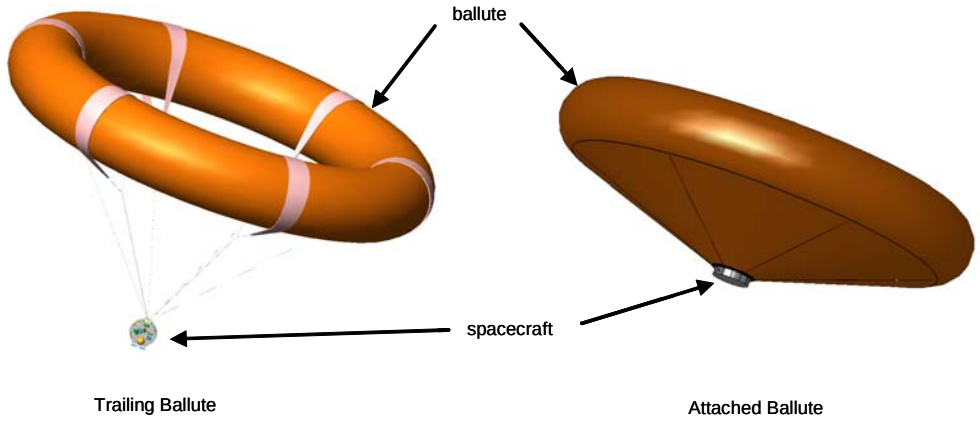

Fig. 1. 'Fly higher, fly lighter, fly cooler' approach to aerocapture can be accomplished with trailing and clamped ballute configurations.

sonic aerothermal analysis and test efforts. NASA JSC provided validation of trajectory control algorithms developed by Ball. JPL provided support in mission and system design.

Two different configurations with the ballute trailing the spacecraft were investigated: a tethered trailing ballute, and an aft attached, or clamped ballute. Both are illustrated in Fig. 1. The two concepts represent the extremes for trailing ballute design configurations, with the clamped ballute essentially a trailing distance of zero. Over the course of the technology development effort, advantages and disadvantages have been identified with each configuration, but both configurations offer the benefits ascribed to the 'fly higher, fly lighter, fly cooler' methodology for aerocapture.

The ballute technology development effort focused on and made significant progress in the following areas:

- Ballute materials and construction techniques
- Aerothermal analysis and hypersonic testing
- Aeroelastic modeling
- Trajectory control
- Integrated system performance and design

This paper provides a brief summary of the work accomplished. The details of the technology development effort have been published in a series of papers and conference presentations [1], [2], [3], [4], [5], [6], [7]. [8], [9], [10], as well as a NASA Contractor Final Report [11].

Ballute Materials and Construction

In the area of ballute materials and construction techniques, a broad variety of lightweight films were tested to determine and evaluate properties at relevant temperatures (see Fig. 2). Testing of pristine and creased material samples at room and elevated temperatures (up to 600 C) was completed. Key parameters evaluated include material strength, flexibility, manufacturability, and mass. The results from the material testing efforts were factored into nonlinear finite element models for ballute structural analysis. An array of seaming adhesives and materials combinations was also evaluated through testing of pristine and creased seamed samples at room and elevated temperatures. Flexibility, manufacturability, tear strength, and tensile strength of the seams were evaluated. A new high temperature adhesive was developed that meets all requirements for the ballute application. Based on the material testing and evaluation efforts, Upilex and PBO thin films, and Zylon tether materials were selected for use in the inflatable ballute system.

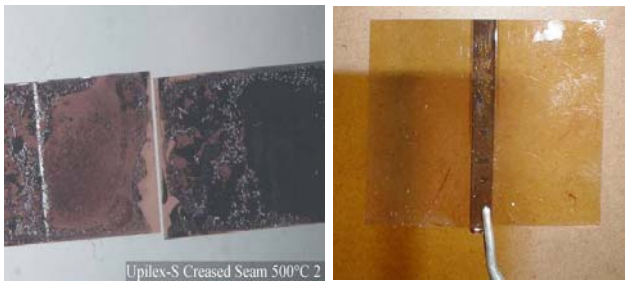

Fig. 2. Several thin film materials, including creased and seamed samples, were tested and characterized for the ballute application.

Hypersonic Aerothermal Analysis

Computational Fluid Dynamics (CFD) models were used to compute drag efficiency, aerodynamic loads, aeroheating, and investigate flow stability for candidate ballute configurations. Analysis results were used in structural and thermal analysis and ballute sizing. Aerothermal CFD models were validated with hypersonic test conditions that were conducted during the program. Significant progress in the aerothermal analysis area includes confirmation that CFD tools can be used to predict steady or unsteady flow for the trailing ballute configuration. Another significant first is the use of unstructured grid methods to accurately model widely variant feature sizes associated with ballute systems, as shown in Fig. 3.

Hypersonic Testing

Experiments were conducted in continuum and rarefied hypersonic flows to evaluate critical ballute geometry parameters and capture flow/ballute interactions for aerothermal analysis model validation. Continuum flow testing occurred in NASA Langley's air and CF4 wind tunnels up to Mach 10. Models tested included those made from flexible thin film materials, with rotational and translational degrees of freedom to simulate flight like conditions (see Fig. 4 and 5). Tests were also conducted in a hypersonic, low density facility at the University of Virginia to provide a good match for design Knudsen numbers. Test cases in the low density facility provided data for two body interactions, and for tether/ballute interfaces (see Fig. 6).

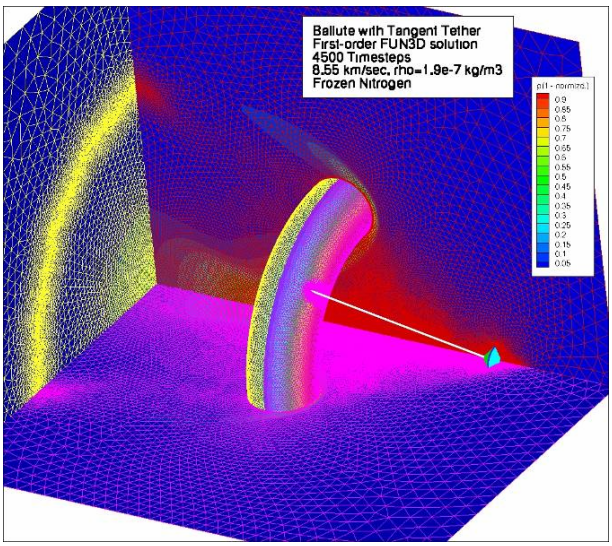

Fig. 3. Simulation of spacecraft-tether-ballute interaction using unstructured flow solver FUN3D with hypersonic option.

Aeroelastic Modeling and Analysis

Significant progress was made in aeroelastic modeling and analysis of ultralightweight ballutes. The aeroelastic problem involves non-linear structures and hypersonic flow through continuum to rarefied flow conditions, which required development of a new analysis capability. The approach taken was to couple together existing validated tools for the individual disciplines. LS-DYNA was used for the structural analysis, and aerothermal codes included DAC and NASCART-GT. The coupled tool set was used to obtain solutions for the ballute problem, and comparison of the solutions with wind tunnel test data of flexible ballute models shows good agreement (see Fig. 7).

Trajectory Control

Successful ballute aerocapture relies on critical timing of the ballute separation under dispersions in navigation, atmospheric density, aerodynamics, and other ballute design parameters. A predictor-corrector algorithm, that uses on-board accelerometer measurements, was developed. Monte-Carlo trajectory simulations showed that the algorithm provides excellent performance, with 100 percent successful capture under realistic dispersions. The algorithm was independently coded and tested at NASA JSC, where the performance results were verified. The delta-V required for orbit circularization after ballute aerocapture is shown in Fig. 8. These results were compared to those for aerocapture using a rigid aeroshell and lift modulation [12]. The comparison shows that post-aerocapture delta-V required for ballute aerocapture is equal to that required for using a rigid aeroshell.

System Design and Performance

A systems analysis effort was used to derive key technology issues and put them in context for use on a realistic aerocapture mission. The effort focused on Titan as a characteristic target, with additional work conducted to assess performance at other potential aerocapture targets. For the Titan aero-

Fig. 4. Several thin film and free flying ballute wind tunnel models of various configurations were constructed and tested at NASA Langley.

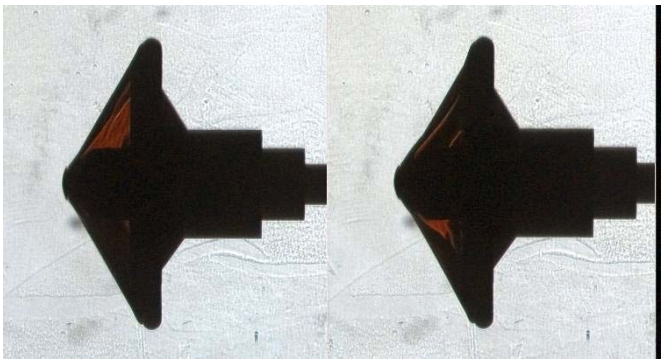

Fig. 5. Hypersonic wind tunnel testing of thin film ballute articles provides flow field and deformation data for CFD and aeroelastic model validation.

Fig. 6. Mach 12, low density flow over 3-D model of the trailing ballute configuration provides additional CFD model validation data.

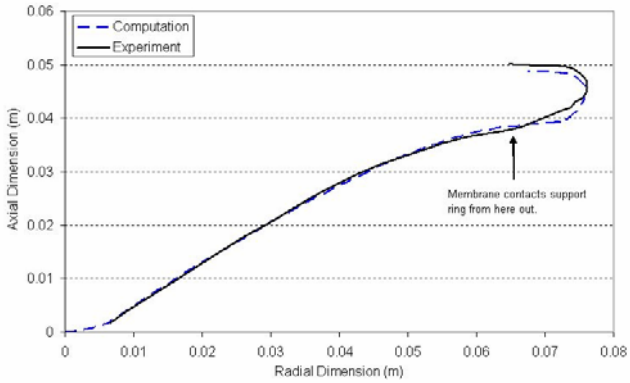

Fig. 7. Aeroelastic modeling tool shows good agreement with deformations seen in hypersonic wind tunnel tests.

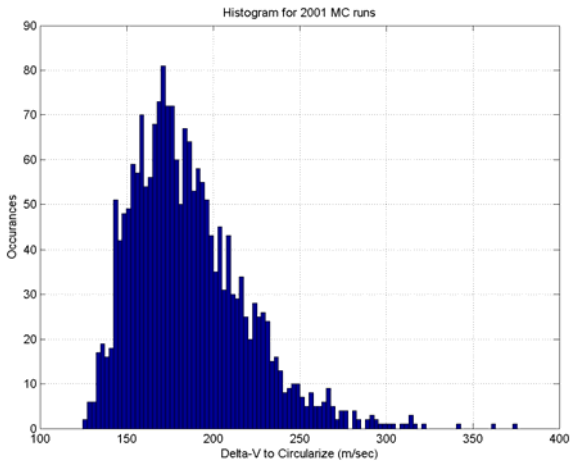

Fig. 8. Circularization delta-V from Monte Carlo simulations shows excellent performance for ballute aerocapture.

capture mission, two reference ballute system concepts were developed: one for a trailing torus ballute configuration, and one for an aft attached configuration. Fig. 9 and Table I show the characteristics for the two ballute designs. Trajectory, aerothermal, structural, and thermal analyses were used along with the testing efforts to develop the ballute system designs, mass estimates, and characterize design performance. The results show that ballute system designs provide an aerocapture mass fraction (ballute system mass divided by total vehicle mass) of 9 to 12 percent for aerocapture of a 1000 kg spacecraft at Titan. This compares very favorably to the 40 percent mass fraction for traditional rigid aeroshell technology [13].

CONCLUSION

Significant progress was made across several key areas during the ballute technology program, and systems analysis shows that excellent performance and packaging benefits are possible compared to traditional aerocapture technology. Ultralightweight ballute technology benefits a broad set of mis-

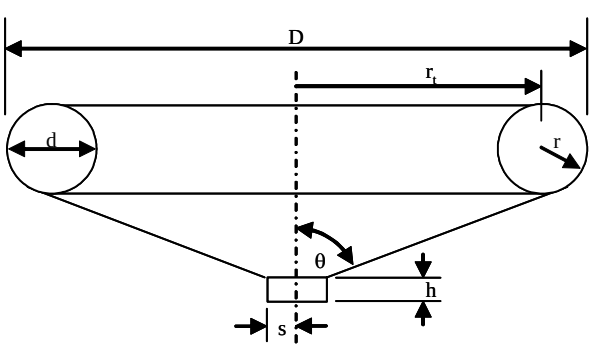

Fig. 9. Characteristic dimensions for ballute configurations.

TABLE I
CHARACTERISTIC VALUES FOR TRAILING AND CLAMPED BALLUTE FOR AEROCAPTURE OF 1000 KG SPACECRAFT AT TITAN.

Parameter	Trailing	Clamped
Torus radius, r_t	17.27 m	12.1 m
Torus cross sectional radius, r	3.45 m	1.73 m
Aspect ratio, AR = r_t / r	5	7
Ballute diameter, D	41.44 m	27.66 m
Half cone angle, q	42 deg	70 deg
Ballute attach radius, s	0 m	1.5 m
Spacecraft protruding height, h	N/A	0.5 m
Ballute aerodynamic reference area, A	748 m^2	600.8 m^2
Ballute drag coefficient, free molecular limit	2.19	2.10
Ballute drag coefficient, hypersonic	1.25	1.489
Hypersonic ballistic coefficient (1000 kg entry mass)	1.07 kg/m^2	1.12 kg/m^2

sion types, including aerocapture, de-orbit missions and entry, descent and landing systems to planetary bodies with a sensible atmosphere. Additional ground based testing followed by flight demonstration represents a critical validation step before this technology is used in operational mission applications.

ACKNOWLEDGEMENT

The work described in this paper was funded in whole, or in part, by the In-Space Propulsion Technologies Program, managed by NASA's Science Mission Directorate in Washington, D.C., and implemented by the In-Space Propulsion Technology Projects Office at Marshall Space Flight Center in Huntsville, AL. The authors would like to thank Les Johnson, Bonnie James, Michelle Munk, and Erin Richardson at the MSFC In-Space Propulsion Project office for their sponsorship and direction of these efforts.

The technology development work was carried out by a team of people at Ball Aerospace, ILC Dover, NASA Langley, NASA JSC, the Jet Propulsion Laboratory, the University of Virginia, and the Georgia Institute of Technology. The authors wish to acknowledge contributions from Fred Hausle, Duffy Morales, Maureen Riesco, Deepti Sharma, Bill Trochman, Reuben Rohrschneider, and Chris Zeller at Ball Aerospace; Jim Stein, Jody Ware, John Lin, and Cliff Willey at ILC Dover; Peter Gnoffo, Greg Buck, Tom Horvath, Chris Glass, Jim Moss, and Richard Wilmoth at NASA Langley; Carlos Westhelle at NASA JSC; Dan Lyons at JPL; Jim McDaniels and Eric Cecil at the University of Virginia; Robert Braun, Jin-Wook Lee, and Stephen Ruffin at Georgia Tech.

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