Coupled Aero-Structural Modelling and Optimisation of Deployable Mars Aero-Decelerators

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Deployable Aero-Decelerators

- Enable large masses to be delivered to Mars surface
  - Also enable higher elevation landing sites and more precise landing

- Other advantages
  - Can be deployed and restowed
  - Resilient to micrometeoroid impact
  - Can withstand dual heat pulse
  - Could enable guidance by individual control of ribs
  - Could use ribs as landing gear

Savino et al. (2015)
Wiegand & Konigsmann (1996)
Akin (1990)
Venkatapathy et al. (2011)
Mass Estimation

- Widely varying mass assessments for all concepts
  - 8% - 46% of entry vehicle mass
  - Different margin assumptions
  - Hard to compare against inflatables and rigid bodies

- Robust mass estimates are key for determining performance
  - A coupled aero-structural tool will improve deployable rib mass estimation process

- Enables assessment of different architectures/concepts
Coupled Aero-Structural Model

6DOF entry trajectory simulator + Structural model of deployable ribs
- Geometry mesh of any shape/size
- European Mars Climate Database
- Modified Newtonian method
- Equations of motion integrated
- Aerodynamic forces & coefficients updated at each timestep
- Aerodynamic forces across TPS summed and applied to rib nodes
- Euler-Bernoulli beam model
- Numerical integration method
- Individual ribs deform separately
- Updated shape passed back

Undeformed Mesh

Mesh at Peak Deformation
Correlation and Validation

• Trajectory Simulator
  • Correlated against results from internal Airbus tool BL43
    • Schiaparelli-based rigid entry vehicle
  • Validated against published NASA flight data

• Structural Model
  • Correlated against deflection results from Abaqus FEA model
  • 5% deflection error with mesh points > 15 along rib length
Reference Mission

<table>
<thead>
<tr>
<th>Mission</th>
<th>Human Cargo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Payload</td>
<td>20 tonnes</td>
</tr>
<tr>
<td>Stowed Diameter</td>
<td>4.5 m</td>
</tr>
<tr>
<td>Entry Strategy</td>
<td>Direct entry from transfer trajectory</td>
</tr>
<tr>
<td>Entry Velocity</td>
<td>6 km/s</td>
</tr>
<tr>
<td>Descent Strategy</td>
<td>Supersonic retropropulsion at Mach 3.5 above 3 km altitude</td>
</tr>
<tr>
<td>Landing Site Elevation</td>
<td>0 km MOLA</td>
</tr>
</tbody>
</table>

Credit: NASA
Deformation Animations

Variable parameters include:

- All 6DOF trajectory initial conditions
- Entry vehicle size and shape
- Number of ribs
- Rib cross-section, dimensions and material properties
- Support strut location
- Payload centre of gravity
Rib Stiffness Variation

- Varied bending stiffness of ribs
  - $EI$ range: $4-84 \times 10^6 \text{ Nm}^2$
  - Reference Human Cargo mission assumed

- Clear effect on drag coefficient

- Only very flexible ribs show significant effect on trajectory
  - $EI \leq 7 \times 10^6 \text{ Nm}^2$
  - 25% higher velocity at 10 km
  - 7% increase in peak heat flux
  - 13% decrease in peak g-load
Rib Stiffness Variation

• Increasing rib flexibility damps attitude oscillations more effectively
  • New deformed shape is more stable
  • e.g. similar to 45° sphere-cone having greater stability

• Flexibility alone does not lead to beneficial effects on trajectory
Rib Tapering Effect

• Mass savings from flexible tapered ribs => increase entry vehicle diameter
  • Maintained entry vehicle mass
  • Balanced decreased rib mass with increased TPS mass
• Beneficial trajectory effect
  • Larger diameters decelerate more effectively at higher altitudes
  • Lowers peak heat flux significantly (42 => 30 W/cm²)
• Reallocating the mass gained from flexibility is very beneficial
Number of Ribs

• Maintained total rib mass by balancing rib size/stiffness with number of ribs
• Very large effect on trajectory
  • Drag coefficient varies significantly
  • Fewer stiffer ribs deform less but give lower drag coefficient initially
  • Prefer larger number of more flexible ribs – to a limit
    • e.g. 16 ribs in this case
• Optimise number of ribs for each specific mission – more flexible ribs generally preferred

![Diagram showing drag coefficient and altitude for different number of ribs](image-url)
Support Strut Location

- Strut can be located at any point along deployed element
  - Investigated for **one rib design case**
  - Improvement in drag coefficient with strut distance from hinge
  - Minor (< 3%) change in peak heat flux, g-load, velocity at 10 km
- => Strut location should be based on maximum principal stress
  - Ensure material yield strength including safety factor is not exceeded
- Optimise with rib flexibility for lowest mass design
Conclusions and Next Steps

• Aero-structural simulator tool developed to assess deployable aero-decelerator concepts and improve mass estimates
  • Continue using tool to investigate variables and optimise designs
• Flexible deployable ribs are beneficial if resulting mass savings are reallocated to increase vehicle diameter
  • Decreases peak heat flux significantly
  • Attitude damping increases with flexibility
• Number of ribs has a large effect on the drag properties and must be optimised for each mission
• Next steps: validation of aero-structural effects via experiment
  • Lab-scale test to investigate TPS flexure/wrinkling as ribs deform
  • High-speed wind tunnel test to investigate stability
Backup Slides
Mesh Convergence

![Graph showing mesh convergence]

- **Maximum Deflection [m]**
- **No. of Mesh Elements**
- **Matlab**
- **Abaqus**
- **Converged Solution**