State of the art concepts and verification strategies for passive de-orbiting systems using deployable booms and membranes

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Content

- Space Debris and Drag Augmentation Introduction

- What can we learn from precursor projects?
  - Applications for Deployable Membranes
  - Membrane Stowing
  - Membrane Design Aspects
  - Materials and Space Environment
  - Deployable Booms

- Gossamer Structures Verification Strategies
Space Debris and Drag Augmentation

• Sharp increase due to Chinese anti-satellite missile test in 2007 and a collision of two satellites (Iridium33 and Kosmos2251) in 2009
• Envisat orbiting at 790km altitude brings a risk of a new collision
• Deorbiting strategies are required, (one) solution is drag augmentation

⇒ ESA’s Deployable Membrane and ADEO Projects, will be presented in the upcoming presentations
Space Debris and Drag Augmentation

- Deorbiting strategies are required, (one) solution is drag augmentation

\[ a_D = \frac{1}{2} \rho v^2 \cdot \frac{C_D A}{m} \]

- Heavy satellites require large drag area respectively sails
- Strongly depend on the orbit, especially the altitude. Atmospheric density decreases exponentially with the altitude.
- Strongly depend on sun activity due to its influence on the atmospheric density
- In high orbits where drag forces are comparable to other disturbances like solar radiation pressure the dynamic behavior of the satellite is important
Applications for Deployable Membranes

- In former projects and missions lightweight deployable membrane technology was developed for
  - Drag Sails (mainly CubeSats)
  - Solar Sailing
  - Ultra lightweight solar photovoltaic generators
  - Membrane Antenna
  - Sun Shielding
Transferable Design Aspects for Drag Sails

• Drag Sail Projects (mainly CubeSats)
  ➢ Stowing and deployment strategies (scalability from CubeSats is difficult)
  ➢ Materials
  ➢ Membrane design

• Solar Sailing
  ➢ Stowing and deployment strategies
  ➢ Materials
  ➢ Membrane design

• Ultra lightweight solar photovoltaic generators
  ➢ Protective coatings

• Membrane Antenna
  ➢ Load introduction, surface accuracy
Membrane Stowing

- Two-dimensional folding of membranes
  - Miura-Ori pattern

- Two-dimensional wrapping of membranes
  - Hub-tangential folding lines (Oswald, Huso, Lanford)
  - Sheel’s fold pattern, Leaf-in pattern (Butterfly Folding)
  - Leaf-out pattern

- One-dimensional folding of sail segments
  - First dimension
  - Second Dimension
Membrane Design Aspects

Shape Stabilisation
- Booms
- Spin
  - Inflatable
- Circular
- Rectangular

Geometry
- Sectioning
  - Triangular

Load Transmission
- Multiple Points
  - Continuous
  - Stripped
  - Rigging

Joining Techniques
- Adhesive Bonding
- Sewing
  - Riveting
  - Welding

Layout
  - Singlelayer
  - Multi-layer
  - Coatings
Membrane Design Aspects

- Shape Stabilisation
- Geometry
- Load Transmission
- Joining Techniques
- Layout

Legend:
- sail suspension from boom
- sail surface edge
- axis / arrow direction
- boom

- Four-point suspension.
- Five-point suspension.
- Separate quadrants.
- Continuous connection.
- Stripped architecture.
Materials

• Most projects considered coated polyimide films (Kapton or Upilex) due to good mechanical behavior and thermal resistance

• Vacuum Deposited Aluminum (VDA) on polyimide is a standard product and was chosen in many former projects. Additional protective and thermo-optical coatings were considered especially for photovoltaics ($\text{SiO}_2$) and are used for various MLI materials.

  • Coatings are required as protection against space environment and for thermal design

  • Coatings need to be robust in order to stow the membranes
Space Environment in Low Earth Orbits (200 .. ~700 km)

- High concentration of Atomic Oxygen
  - Generated by solar radiation of wavelength of about 243 nm,
  - Impact energy of 5 eV
- High energetic EMR radiation
  - Bond braking e.g. C-C, C-O
    (especially hazard to polyimide films)
- Flux of solar p+/e- is negligible small comparing to the AO flux.

Experiments (e.g. MISSE) performed under real space conditions
  - Large literature database of many degraded materials.

Preliminary material selection and characterization
Coating Examples

• VDA (standard polyimide film coating):
  - Unreactive to AO exposure
  - Limited shielding of the substrate from Ultra Violet radiation
  - VUV may ionize Al. atoms => charging
  - High $\alpha/\varepsilon$ ratio => High Temperatures

• SiO2:
  - Good AO resistivity (not 100%), thick coatings for long durations
  - Good shielding of the substrate from Ultra Violet radiation
  - High electrical resistance => Spacecraft charging
  - Decreases $\alpha/\varepsilon$ ratio => Lower Temperatures

• TiO2:
  - Good AO resistivity but less than SiO2, thin TiO2 coatings crack during AO exposure, thick coatings for long durations
  - Very Good shielding of the substrate from Ultra Violet radiation
  - Prevent ESD
  - Decreases $\alpha/\varepsilon$ ratio => Lower Temperatures
Deployable Boom Technologies

**Strain Energy**
- Flexible structures
- Stowage by elastic material deformation
- Deployment by stored strain energy

**Inflatable**
- Thin walled, highly deformable shells
- Stowage by shell folding
- Deployment by inflation gas
- Rigidization may be necessary

**Articulated**
- Rigid structural members
- Stowage by use of hinges
- Deployment by additional mechanism

**Telescopic**
- Segmented rigid shell structure
- Stowage by use of telescopic segments
- Deployment by additional mechanism

Courtesy of University of Surrey

Courtesy of ATK/ABLE Engineering

Courtesy of Northrop Grumman
Strain Energy Deployment

- Thin-walled **shell booms** or **trusses with flexible members**
- Deformation of the structure within the **elastic region of the material**
- **Maximum elastic strain** limits shell/rod thickness
- Deployment by **stored strain energy**
- Deployment may require support and control by additional mechanism

Four loner on deployable CoilABLE truss (Courtesy of ATK/ABLE Engineering)

Bi-stable CFRP-booms (Courtesy of RolaTube)

Deployed De-Orbit Sail drag sail using DLRS CFRP boom technology
Inflatable Structures

- **Tubular structures** made of **laminated foils** or thin walled **composites allowing plastic deformation** (thermoplastic or uncured resins)
- Stowage by **membrane-like folding** of the structure
- Gas-tight tubular structure allows **deployment by inflation**
- **Rigidization mechanism** required to maintain structural stability after venting of the inflation gas
Articulated Structures

- **Trusses or linkages** with rigid structural members connected by hinges
- **Deployment by springs** at the hinges or **additional mechanisms** like motor driven cable/pulley systems
- **Latches may be required** to lock hinges in deployed state

dragNET de-orbit system using pantograph type deployable booms for support of the sails (Courtesy of MMA Design)

Telescopic Structures

- Segmented, telescopic structure made of rigid elements with mainly tubular cross-section
- Linear deployment driven by additional mechanism

Telescopic composite mast deployed by an internal metal STEM boom
(Courtesy of Northrop Grumman)
Boom Evaluation Criteria

- **Boom evaluation criteria for de-orbiting applications:**
  - Stowage Volume, Mass (including deployment mechanisms), Structural performance (stiffness, strength), Scalability, Long term stowage capability, Complexity, MMOD resistance, Thermal characteristics, Material degradation

- **Evaluation of entire boom categories is necessarily defective** as properties among representatives of the same category may vary strongly.
  - Therefore, **individual evaluation of boom concepts is necessary**.

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<td>Structural performance (stiffness, strength)</td>
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**SUM**
- 613
- 463
- 436
- 487
- 444
- 377
- 378
- 500
- 474
- 464
DLR’s Development of Deployable Membrane Spacecraft Structures

- Design
- Structural Analysis
- Thermal Analysis
- Manufacturing
- Shaker Tests
- Centrifuge Test
- Fast Decompression
- Deployment Test

- Degradation (e⁻, p⁺, EMR)
Membrane Verification on the example of DLR’s Gossamer-1 project

- Shaker
- Centrifuge
- Fast Decompression
- Deployment
Verification – Shaker

- **Sine**

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<td>6 - 100 Hz</td>
<td>2.5 g</td>
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<tr>
<td>Z</td>
<td>2 - 6 Hz</td>
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<tr>
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<td>6 - 100 Hz</td>
<td>3.5 g</td>
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- **Random**

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<th>Overall level [g&lt;sub&gt;rms&lt;/sub&gt;]</th>
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<td>215 Hz</td>
<td>7 g&lt;sup&gt;2&lt;/sup&gt;/Hz</td>
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</table>

duration | 2 min per axis
Verification - Centrifuge

- All axes tested with 30g
- It is difficult to test vibration and static loads at the same time in a laboratory environment
  => Centrifuge testing with very high g-levels
- $2\sigma$ standard deviation of the maximum vibration accelerations were covered (83.29g)
Verification - Fast Decompression

- Venting 99% of the air within the first 75 seconds
- Test was consistent to our reference launch of a Steel2.1 rocket, providing time-altitude correlations
- Employing atmosphere model NRLMSISE-00 and ideal gas law the pressure was calculated
Verification – Laboratory deployment test

- Final laboratory deployment testing, including measurement of deployment forces
Verification – Further Aspects

- Microscope investigations, package verification (e.g. coatings)
- Degradation experiments (e.g. VUV and ATOX)
- Boom characterization (e.g. Stiffness, creeping)
- .....
Summary

- State of the art review in the field of
  - Drag Sails, Solar Sails, Thin-film Photovoltaics, Membrane Antenna, Sun Shielding
  - Summary membrane stowing strategies
  - Summary membrane design aspects
  - Space Environment in LEO and impact on Materials
  - Exemplarily three different coatings were presented (Al, SiO2, TiO2)

- Membrane Verification
  - Qualification testing on the example of DLR’s Gossamer-1 Project
  - Shaker, Centrifuge, Fast Decompression and laboratory Deployment
Bibliography


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