Thermal-Structural Analysis of Sunshield Membranes

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Future IR Space Telescopes

• There are several large infrared (IR) space telescopes planned for the coming decades...
  – James Webb Space Telescope (JWST)
  – Single Aperture Far Infrared (SAFIR)

• The JWST consists of a cryogenic telescope and instruments, a room temperature spacecraft, and a deployable sunshield.

• The sunshield provides passive radiative cooling to cryogenic operating temperatures, stability at operating temperature, and stray light control.

Reference Concept (NASA)

Current Design (TRW/Ball)
Sunshields for Large Space Telescopes

- Typical deployable sunshield concepts consists of:
  - Multiple layers of thin-film membranes
  - Deployable booms to support the film layers
  - Membrane management hardware to position and tension the films:
    - Ladder structures
    - Constant force springs
  - Container for the stowed structure

NASA Reference Concept:
- Overall size = 30 m x 15 m
- Total Mass = 200 kg

Thin film layers:
- Material: Kapton
- Thickness = 0.0005-0.001 in
- Global stresses ~ 10 psi
- Local stresses ~ 100 psi
Sunshield Temperatures

- Mean temperatures will vary widely from layer-to-layer:
  - Sun-side film layer ~ 400 K
  - Cold-side film layer ~ 100 K.

- In-plane temperature variations within the film layers are predicted to be large (up to 100 K) due to:
  - Greater view to deep space at the edges than at the center
  - Presence of the room temperature spacecraft at the center

- Membrane layers must be maintained in their nominal geometry (both spacing and flatness) when subject to thermal strain effects due to both layer-to-layer temperature differences and in-plane temperature gradients.
Accommodating Thermal Strains

- Post-deployment structural performance of the sunshield is a concern since it may impact observatory thermal performance.

- A constant-force preloading scheme is typically implemented to accommodate thermal expansion/contraction of the membrane layers and is effective in compensating for uniform temperature changes and layer-to-layer bulk temperature differences.

- Even with constant-force preloading, large radial temperature gradients could lead to a loss of tensile preload within the film layers:
  - Results from over-contraction of the cold film perimeter relative to the warmer center of the film.
  - The formation of a slack region would result if the tensile preload drops to zero.

- Reduced preload or slackness in the films is a concern since any resulting sagging of the films could lead to “thermal shortcuting” if adjacent membrane layers come into contact.
Objective

• The objective was to study the effects of temperature on the structural behavior of preloaded sunshield film layers utilizing recent developments in finite element modeling of partially wrinkled thin-film membranes.

• The problem of a single film layer from the NASA reference concept JWST sunshield is used to demonstrate the analysis process and study sensitivities to:
  – In-plane temperature variations
  – Film preload level
Thermal-Structural Analytical Process

• Multi-step, sequentially coupled thermal-structural analysis:

1. Thermal analysis predicts temperatures

2. Temperature mapping used to interface thermal and structural models

3. Structural analysis predicts displacements/stresses/etc. due to combination of mechanical preloads and prescribed temperatures
Thermal Analysis

- Thermal analysis performed using:
  - Thermal Synthesis System (TSS) to calculate radiation interchange factors
  - SINDA85 to solve for model nodal temperatures

- Sunshield cold-side (layer 6) temperatures:
  - Tmean = 73.9 K
  - Tmax = 111.7 K
  - Tmin = 44.3 K
  - In-plane gradient = 67.4 K
Temperature Mapping

- Since thermal and structural models typically have dissimilar meshes, it is necessary to perform a “mapping” of the temperatures from the thermal model mesh to the structural model mesh.

- Temperature mapping approaches:
  - Pair corresponding thermal and structural model nodes, then prescribe these temperatures in a steady-state heat transfer analysis performed using the FEM.
  - Fit a function to the thermal results, then map this function to the structural model mesh (i.e. MATLAB “griddata” function)
Structural Analysis

• The structural analysis was performed using ABAQUS.

• The baseline analysis consisted of three nonlinear static analysis steps:
  1. Apply constant force spring preloads, Specify uniform temperature = 294 K (room temperature)
  2. Specify uniform temperature = 74 K (mean cold-side temperature)
  3. Specify mapped temperature distribution (mean temperature + gradient)
Thin-Film Modeling

• Thin-film membrane layer modeled using membrane elements (M3D3) in conjunction with a wrinkling material model:
  – Material model is a finite element implementation of Stein-Hedgepeth membrane wrinkling theory.

• Membrane element stiffness iteratively modified to account for the effects of wrinkling:
  – Element state determined using a mixed stress-strain criteria
  – Stiffness matrix formulation based on the element state
  – Approach predicts stress distributions corrected for wrinkling and slackness as well as wrinkled/slack regions, but not wrinkling details.

• Shell element overlay provides small artificial stiffness:
  – Allows slack regions to become taut when preload is increased despite zero in-plane stiffness in slack membrane elements
  – Studies showed minimal effect on the membrane stresses

• Additional numerical stabilization provided by ABAQUS *STABILIZE
Finite Element Model

- **Mesh:**
  - 5146 Nodes
  - 19800 Elements

- **Components:**
  - Film (M3D3 membrane elements)
  - Corner reinforcements (STRI3 shell elements)
  - Spreader Bars (B31 beam elements)
  - Constant Force Springs (B31 beam elements)

- Central cut-out in film representative of attachment to spacecraft

- Assumed uniform, temperature independent CTE for all materials (2.0E-5 /K)
FEM – Load & Constraints

• Loads:
  – 2 CFS per corner
  – 14.25 N total per corner
  – Applied constant force preload using ABAQUS *PRE-TENSION SECTION

• Constraints:
  – Fixed at spreader bars (interface with deployment booms)
  – Pinned around the perimeter of central cut-out
Uniform Temperature = 294 K

<table>
<thead>
<tr>
<th>Preload (N)</th>
<th>Temperature (K)</th>
<th>Stresses (Pa)</th>
<th>Area (%)</th>
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<td>Major - Max</td>
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Thermal Strains

Uniform Temperature = 74 K

Mapped Temperature Distribution (Tmean = 74 K, Tmax-Tmin= 67 K)

Difference (i.e. thermal strain due to radial gradient)
Uniform Temperature = 74 K

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### Mapped Temperature Distribution

**(Tmean = 74 K, Tmax-Tmin = 67 K)**

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Effects of Varying Temperature Gradient

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Effects of Varying Preload

![Graph showing the effects of varying preload on the fraction of film surface area.](image)

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Summary

• Results from an analysis of the cold-side film layer of the NASA reference concept JWST sunshield were used to demonstrate a thermal-structural analysis approach and provide insight into the response of the membrane to thermo-mechanical loading.

• For the problem considered, the film was shown to develop slack regions when subject to a large in-plane temperature gradient. Subsequent analyses showed that the slack region could be eliminated by increasing the magnitude of the mechanical preload by a factor of four.

• These studies demonstrate the importance of including thermal effects in thin-film membrane structural analyses when significant temperature variations are expected within the structure.

• Topics for future study include: thermal model refinement, temperature-dependent material properties, mismatches in coefficient of thermal expansion, and additional approaches to film tensioning.