ELIXIR Course

Structural Design

Jean-Christophe Salvignol SRE/PJ
(JWST NIRSpec & MIRI Mechanical Eng.)
• Why a structure?
• Structural Requirements & Design Drivers
• Materials
• Analyses
• Verification & Testing
Why a structure?

- ECSS says: “set of mechanical components or assemblies designed to sustain loads or pressures, provide stiffness or stability, or provide support or containment”

- So, some kind of shelf or bracket...

- Sounds trivial but not so much taking into account...
  - The launcher environment (QSL & vibrations!)
  - The space environment (temperatures, vacuum / depressurisation, radiations, micro-meteorites, re-entry, etc)
  - The very stringent requirements: mass, volume, access, stiffness, strength, stability, low WFE, etc.
Launcher Environment

- Static loads (up to ~4.5g)
- Low frequency loads (<1g, up to 100Hz)
Launcher Environment

- Acoustic noise (140dB, up to 2000Hz)
- Shocks (eg booster & fairing separations)

<table>
<thead>
<tr>
<th>Octave center frequency (Hz)</th>
<th>Flight limit level (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>31.5</td>
<td>128</td>
</tr>
<tr>
<td>63</td>
<td>131</td>
</tr>
<tr>
<td>125</td>
<td>136</td>
</tr>
<tr>
<td>250</td>
<td>133</td>
</tr>
<tr>
<td>500</td>
<td>129</td>
</tr>
<tr>
<td>1000</td>
<td>123</td>
</tr>
<tr>
<td>2000</td>
<td>116</td>
</tr>
<tr>
<td>OASPL (20 – 2828 Hz)</td>
<td>139.5</td>
</tr>
</tbody>
</table>
Structural Design

Structural Requirements & Design Drivers

- **Mass**: Limitation from the launcher lift-off capability
- **Envelope & interfaces**:
  - The spacecraft has to fit within the launcher fairing
  - The internal instruments have to fit within the S/C
  - The sub-systems have to fit within the instrument
Structural Requirements & Design Drivers

- **Stiffness & decoupling:**
  - A unit can be seen as a mass + spring system
  - Its resonance frequency shall not couple with the one of its “support”

\[ f = \frac{1}{2\pi} \sqrt{\frac{k}{m_c}} = \frac{1}{T} \]
Structural Requirements & Design Drivers

- **Strength vs design loads**
  - The S/C structure has to cope safely with the launcher static & dynamic loads
  - The Payload units as well … including the amplifications coming from the S/C
  - Thermo-elastic loads are very often very severe and can be dimensioning

- **Shocks:**
  - Are generated by the launcher (eg booster or fairing separation)
  - But also by the release of internal (S/C) devices like antennae (pyro nuts)

- **And also…**
  - Opto-mechanical (WFE), stability constrains
  - Thermal constrains
  - Micro-vibrations (eg reaction wheels)
  - EMC, magnetic constrains (P/L needs)
  - Integration & access (AIT)
  - Manufacturing limitations
  - Transportation (i/f, loads, horizontal)
  - Availability / schedule / risks / costs

Thermal cutter for Solar Array
Materials

- Strain stress law

Example Stress-Strain Curve

- Force
- Bang!
Structural Design

Materials

- Metals: recommended as far as possible, and aluminium if possible!
- Lots of experience, well characterised
- Easy to machine … and in many places
- Low safety factors (less conservative dimensioning)
- Can be repaired, modified at a late stage, etc
- Cheap and easily available
Materials

- Sandwich panels or cylinders are commonly used for the S/C structure for their favourable stiffness to mass ratio.

- If mass or performances cannot be met with standard metals, think about:
  - Fibres (CFRP, GFPP, Kevlar, etc)
  - Ceramics and glasses

SMART Primary Structure
**Structural Design**

**Dimensional stability**

- **Zerodur**
- **Carb/Carb (T300)**
- **C-SiC**
- **Aluminium**
- **Beryllium**

**Specific stiffness**

- **SiC (NIRSpec)**

### Materials

<table>
<thead>
<tr>
<th>Materials</th>
<th>CTE RT → 30K [m/m/K]</th>
<th>CTE at 30K [m/m/K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiC-100</td>
<td>1.1 $10^{-6}$</td>
<td>0.2 $10^{-6}$</td>
</tr>
<tr>
<td>Zerodur</td>
<td>-0.19 $10^{-6}$</td>
<td>-0.4 $10^{-6}$</td>
</tr>
<tr>
<td>Invar</td>
<td>1.6 $10^{-6}$</td>
<td>-0.8 $10^{-6}$</td>
</tr>
<tr>
<td>Titanium</td>
<td>6.3 $10^{-6}$</td>
<td>1.0 $10^{-6}$</td>
</tr>
<tr>
<td>Aluminium</td>
<td>15.10$^{-6}$</td>
<td>1.0 $10^{-6}$</td>
</tr>
</tbody>
</table>
~60% of the NIRSpec mass in SiC-100
CAD = Computer Aided Design

3D geometrical modelling software
The accommodation is done with CAD S/W like CATIA

Very powerful tool to ensure proper interface allocations, integration access, etc ... but some surprises can be seen on the actual hardware!
Analyses

- **FEM & Types of analyses (NASTRAN)**
  - Predictions are made with **finite element models** (FEM) - NASTRAN is the most common tool
  - Static, modal, dynamic, acoustic, shocks can be predicted for the dimensioning, for the test campaign and for flight (CLA)

- **CLA** = Coupled Loads Analysis: Dynamic analysis of the S/C inside the Launcher with all the flight events like ignition of engines, booster ejection, gust, etc. Predicts the flight loads against which the S/C has to be qualified (= safely survive with margins)
Analyses

- Strength analyses: the parts shall not distort and even less break under transportation, handling, test, and launch loads.
- Safety factors & Margin of Safety (MoS)
  - The ESA standards (ECSS) requires the structures to show positive margin of safety including factors that are material dependant:

\[
\text{MOS} = \frac{\text{design allowable load}}{\text{design limit load} \times \text{FOS}} - 1
\]

<table>
<thead>
<tr>
<th>Structure type and sizing case</th>
<th>FOS Yield</th>
<th>FOS Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metallic structures</td>
<td>1.1</td>
<td>1.25</td>
</tr>
<tr>
<td>Composite structures. Uniform material, brittle</td>
<td>-</td>
<td>1.25</td>
</tr>
<tr>
<td>Sandwich structures</td>
<td>-</td>
<td>1.25</td>
</tr>
<tr>
<td>Glass &amp; Ceramic structures</td>
<td>-</td>
<td>2.5</td>
</tr>
<tr>
<td>Composite structures discontinuities</td>
<td>-</td>
<td>1.5</td>
</tr>
<tr>
<td>Joints and inserts</td>
<td>-</td>
<td>1.25</td>
</tr>
<tr>
<td>Global buckling</td>
<td>-</td>
<td>2.0</td>
</tr>
</tbody>
</table>

- Allowable load: allowable load under specified functional conditions (e.g. yield, buckling, ultimate)
- Limit load: computed or measured load under defined load condition (e.g. design limit load, vibration load, thermal load)
- FOS: Factor of safety applicable to the specified functional conditions including the specified load conditions (e.g. yield, ultimate, buckling) as defined in Table 11
Verification & Testing

- Static tests or very low frequency vibration test
  - Done on a dedicated jig with hydraulic pullers / pushers, masses & pulleys, or on a shaker

- Sinusoidal vibration tests
  - Done on a shaker
  - Excites (sweeps) the structure up to typically 100Hz to cover the low freq launcher excitations

- Random vibration tests
  - Done on a shaker, all freq excited simultaneously, 20Hz to 2000Hz
  - Typically not done at S/C level (high freq are covered by the acoustic test) but very common at unit level

Rosetta S/C
Verification & Testing
- Sinusoidal vibration tests
Verification & Testing

- **Acoustic test**
  - Done in a dedicated acoustic chamber, typically up to 2000Hz

- **Shock test**
  - Clampband release done at S/C level, sometimes a SHOGUN test is also performed to address the L/V shocks
  - For units, a shock test on a ringing table can be performed

- **Thermo-elastic tests**
  - Covered as part of the thermal vacuum test → See Thermal Design Presentation

- **Proof tests**
  - For some critical parts (e.g. kinematic mounts / flexures) or for fragile materials like glass or ceramics
  - Generally done at part level

- **Micro-vibrations**
  - Done at unit level for sensitive units, not very common
Now, you cannot probably make a S/C or Payload structure yet...

"Bob will be Godzilla in this structural integrity test."

... but you should be able to talk with better confidence to a structural engineer!
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Mechanisms

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Mechanisms

- Rule number 1
- Why using mechanisms?
- Design drivers
- Analyses
- Verification and Testing
**Mechanisms**

**Design Rule № 1:**

**Do not use mechanisms**

(as far as you can...)

It’s a source of problems, delays, costs...
Forget about flight heritage in 99% of the cases!
Mechanisms

Why using mechanisms?
- Because there is no other choice
- Examples: SADM, APM, FWA, RMA
Mechanisms

2009 JWST HD Animation B-Roll

Deployment #1
Solar Array & HGA

Runtime: 00:20:00
Resolution: HD 1920x1080
Mechanisms

Design drivers

- Same as for structures (stiffness, strength)
- Motorisation margins (shall move)
- Lifetime (shall move ... up to the end!)
- Power consumptions
- Performances including opto-mechanical, stability, position accuracy, repeatability, etc.
- Available technologies (e.g. sensors, motors, bearings, tribology/lubricants)
- Reliability (redundancy!)
- Cleanliness
- Costs (expensive!)
Design drivers

- Motorisation margins (extract of ECSS for Mechanisms):

The minimum actuation torque ($T_{\text{min}}$) shall be derived by the equation:

$$T_{\text{min}} = 2 \times (1,1 I + 1,2 S + 1,5 H_{M} + 3 F_{R} + 3 H_{Y} + 3 H_{A} + 3 H_{D}) + 1,25 T_{D} + T_{L}$$

where:

- $I$ is the inertial torque applied to a mechanism subjected to acceleration in an inertial frame of reference (e.g. spinning spacecraft, payload or other).
- $TD$ is the inertial resistance torque caused by the worst-case acceleration function specified by the customer at the mechanism level.
- $TL$ is the deliverable output torque, when specified by the customer.

<table>
<thead>
<tr>
<th>Component of resistance</th>
<th>Symbol</th>
<th>Theoretical Factor</th>
<th>Measured Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inertia</td>
<td>$I$</td>
<td>1,1</td>
<td>1,1</td>
</tr>
<tr>
<td>Spring</td>
<td>$S$</td>
<td>1,2</td>
<td>1,2</td>
</tr>
<tr>
<td>Motor mag. losses</td>
<td>$H_{M}$</td>
<td>1,5</td>
<td>1,2</td>
</tr>
<tr>
<td>Friction</td>
<td>$F_{R}$</td>
<td>3</td>
<td>1,5</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>$H_{Y}$</td>
<td>3</td>
<td>1,5</td>
</tr>
<tr>
<td>Others (Harness)</td>
<td>$H_{A}$</td>
<td>3</td>
<td>1,5</td>
</tr>
<tr>
<td>Adhesion</td>
<td>$H_{D}$</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>
Design drivers
- Lifetime (extract of ECSS for Mechanisms):

a. The lifetime qualification shall be verified using the factored sum of the predicted nominal ground test cycles and the in-orbit operation cycles.

b. For the test verification, the number of expected cycles shall be multiplied by the factors in Table 4-3.

<table>
<thead>
<tr>
<th>Type</th>
<th>Number of expected cycles</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground testing (minimum 10 cycles to be tested)</td>
<td>1 to 1000 cycles</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>1001 to 100 000 cycles</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>&gt; 100 000 cycles</td>
<td>1,25</td>
</tr>
<tr>
<td>In-orbit</td>
<td>1 to 10 cycles</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>11 to 1000 cycles</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>1001 to 100 000 cycles</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>&gt; 100 000 cycles</td>
<td>1,25</td>
</tr>
</tbody>
</table>
Mechanisms

• Analysis
  – Same as for structures: FEM used to assess the structural performances
  – Kinematics - Deployments: risks of hitting something on the way (eg antenna), definition of envelopes (eg shutters, doors)
  – Kinematics - Characterisation of motions: ex reactive torque due to the rotation of the wheel can impact a fine pointing system

• Verification & Testing
  – Same as for structures (vibrations, shock, thermal cycling)
  – Lifetime test
  – Functional & Performance tests
Reminder of Design Rule № 1:

Do not use mechanisms!

(as far as you can...)

QUESTIONS?