Predicting and measuring non-linear behaviour at spacecraft level

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Laurent SOULA (ASTRIUM Satellite France)
Alfred Newerla (ESTEC)
Agenda

- Purpose of the study
- Bread-board presentation
- Test predictions
- Tests results
- Test-Analysis Correlation
- Synthesis
Purpose of the study (1/2)

- **Context**
  - This project is part of ESA study contract 21359/08 “Advancement of Mechanical Verification Methods for Non-linear Spacecraft Structures” (NOLISS) for which Astrium SAS is prime contractor. Sub contractors involved are:
    - Astrium ST (impact on launcher coupled load analysis);
    - Astrium Stevenage (breadboard design, test facilities);
    - LMS (tests piloting and measurements);
    - University of Liege (advanced non-linear identification methods).
  - The general approach still applied in practice today is to use a linearized model around the mechanical level expected. Non-linearity is characterised by sub-system tests.
Purpose of the study (2/2)

- **Objectives**
  - There is an increasing need to have a well-defined process to handle structural non-linearities since more and more non-linearities are intentionally introduced inside the spacecraft to fulfil specific functions (vibration isolation, damping effects…). As a result, these non-linearities are to be added to other (sometimes unexpected) non-linearities inherent in the spacecraft structure.
  
  - The objective of this study is to verify relevant ideas how to handle structural non-linearities in load prediction analyses and mechanical verification tests. For that purpose a bread-board model is developed.
Bread-board presentation (1/5)

- Design concept & objectives
  - The bread-board model is representative of a flight model configuration: it includes several non-linearity types, representative of what could be implemented in typical spacecraft structures.
  
  - The bread-board has two main objectives:
    1) Identify the effects on the non-linear behaviour.
    2) Identify at which level the non-linear effects impact on the spacecraft behaviour.
Bread-board presentation (2/5)

- **Assembly**
  - The SMALLSAT structure: octagonal filament wound-single monocoque thick walled CFRP structure;
  - A dummy instrument (base-plate + tripod + mass);
  - A SASSA device composed by 3 modules interfacing the dummy instrument and the SMALLSAT Top Floor;
  - An actuator dummy suspended on WEMS device.
Bread-board presentation (3/5)

- Non-linearity #1: dummy instrument
  - Large mass (~142kg) inducing significant effect on controller;
  - Non-linear effect emphasized on previous program and linked to damping modification with input levels.

<table>
<thead>
<tr>
<th>Level</th>
<th>Curve</th>
<th>Frequency</th>
<th>Amplification</th>
<th>Base input</th>
</tr>
</thead>
<tbody>
<tr>
<td>low</td>
<td>blue</td>
<td>32</td>
<td>150</td>
<td>0.1g</td>
</tr>
<tr>
<td>intermediate</td>
<td>red</td>
<td>30</td>
<td>9</td>
<td>0.5g</td>
</tr>
<tr>
<td>qualification</td>
<td>green</td>
<td>29</td>
<td>6</td>
<td>1g</td>
</tr>
<tr>
<td>Augmented qualification</td>
<td>grey</td>
<td>28</td>
<td>5</td>
<td>1.5g</td>
</tr>
<tr>
<td>Control low level</td>
<td>magenta</td>
<td>32</td>
<td>60</td>
<td>0.1g</td>
</tr>
</tbody>
</table>
Bread-board presentation (4/5)

- **Non-linearity #2: instrument isolation**
  - SASSA isolator (developed by Astrium for ESA) implemented at instrument / top floor interface.
Bread-board presentation (5/5)

- Non-linearity #3: suspended actuator
  - Actuator dummy (8kg) suspended by elastomer isolator based on concept developed for several Astrium programs;
  - Isolation system is based on mechanical stop concept;
  - Variation of frequency for low-levels input and contact for higher levels.
Tests predictions (1/5)

- **FEM overview**
  - Mass: ~215kg
    (~64kg for SMALLSAT structure)
  - Modal behaviour:
    - Main lateral mode (SASSA): 31.5Hz
    - Main axial mode (SASSA): 52Hz
    - WEMS modes: 11Hz / 28Hz / 31Hz
      (bending/axial/lateral)
Tests predictions (2/5)

- **Input base acceleration:**
  - Lateral / axial directions
  - From low level (0.1g) to high level (up to 1g, notched locally for structure protection)
  - Sine sweep in the range [5-100Hz]

- **NASTRAN modal frequency response (SOL111) and non-linear transient response (SOL129)**

<table>
<thead>
<tr>
<th>NASTRAN</th>
<th>Excitation</th>
<th>Sine sweep</th>
<th>Local stiffness</th>
<th>Damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOL111 (*)</td>
<td>Frequency dependent</td>
<td>Up</td>
<td>Linearized</td>
<td>Variable modal damping (mixed rule)</td>
</tr>
<tr>
<td>SOL129</td>
<td>Time dependent</td>
<td>Up/Down</td>
<td>Non-linear</td>
<td>Rayleigh damping (global) + viscous damping (local)</td>
</tr>
</tbody>
</table>

(*) only mentioned for completeness but no further results presented hereafter.
Tests predictions (3/5)

- Non-linear stiffness modelling
  - CBUSH1D cards (rod type spring/damper connection)
  - Symmetrical curves (only positive displacements presented)

Non-linear stiffness at WEMS module (Force vs displacement)
- Mechanical stops

Non-linear stiffness at SASSA module (Force vs displacement)
- Lower (constant) local damping considered for SASSA and WEMS devices with elastomer parts
Tests predictions (4/5)

- Non-linear analysis
  - Severe non-linearity at WEMS level due to the presence of mechanical stops.
  - Quite linear SASSA behaviour: only slight shift in frequency due to very small internal displacements.
  - Damping non-linearity of the dummy instrument cannot be highlighted by simulation (model not representative of various interface components).
Tests predictions (5/5)

- Linearization of stiffness
  - Linearized stiffness is increased wrt expected displacements (correlation with high level input results)
  - Same damping assumption

Traction/Compression stiffness for WEMS module
(Force vs displacements)

WEMS dummy base lateral acceleration vs frequency
Test results (1/4)

- **Test plan**
  - Lateral / axial sine excitations in the range [5-100Hz];
  - Two successive sweeps, up then down;
  - Low / Intermediate / High levels.

- **Piloting strategy**
  - Control taking into account the average filtered (fundamental) response of two pilot accelerometers located near shaker I/F;
  - Other control channels associated with limitations or abort values are added.

- **Test instrumentation**
  - 76 channels.
Test results (2/4)

- At WEMS level (1)
  - “Wave effect” highlighted, characteristic of non-linear stiffness
  - Mechanical stops reached

WEMS dummy base lateral acceleration vs frequency

- Sweep up versus sweep down
- Non-symmetrical behaviour in axial direction

Analyses non linéaires et conception des structures
Test results (3/4)

- At WEMS level (2)
  - High frequency content
    - Acceleration response on lateral mode (8.5Hz)
  - SRS (3D) on axial response

15Hz low pass filter
15Hz high pass filter
Test results (4/4)

- At instrument level
  - Non-linearity highlighted: damping and softening

- Poor HF content

[Image of test results]

- Lateral excitation
  - Top of instrument dummy acceleration vs frequency

- Axial excitation
  - Top of instrument dummy acceleration on main SASSA mode at ~57Hz

- Frequency (Hz) vs Amplification
  - LL1AX, LL1BX, IL2AX, IL2BX, LL3AX, LL3BX, IL4AX, IL4BX, LL5AX, LL5BX, QL6AX, QL6BX

- Analyses non linéaires et conception des structures
Test-analysis correlation (1/3)

- **FEM modifications**
  - At WEMS level:
    - Update local stiffness at I/F between the structure and WEMS support bracket
    - Adjust WEMS module traction/compression stiffness parameters
  - At Instrument/SASSA level:
    - Update global and local positions and/or orientations regarding the differences between both FEM and bread-board configuration.
Test-analysis correlation (2/3)

- Comparison at WEMS level
  - Lateral excitation/response
    - Much better predictions, even on the second lateral mode. Amplification still under-predicted due to early wave drop.
  - Axial excitation/response
    - Predicted internal displacement far below mechanical stop.
Test-analysis correlation (3/3)

- **Comparison at Instrument/SASSA level**
  - Lateral excitation/response
    - Overall shape matches well with test results despite two predicted peaks versus only one peak being measured.
  - Axial excitation/response
    - Still some shifts in frequency and amplitude
Synthesis (1/2)

- Predictions versus tests
  - At WEMS level:
    - Non-linear behaviour predicted and revealed by tests;
    - Amplification and frequency shifts due to inaccurate local modelling.
  - At SASSA level:
    - Quite linear behaviour predicted and experienced;
    - Filtering of most of the high frequency content propagating through the structure from WEMS.
  - At instrument level:
    - Non-linear behaviour expected (not predicted) and revealed by tests.
Synthesis (2/2)

- Correlation
  - Thanks to FEM modifications (particularly the WEMS axial non-linear stiffness definition) the simulations correlate well with the tests results;
  - Sensitivity analyses might be helpful in order to define a more representative WEMS support bracket interface stiffness for improved dynamic behaviour predictions;
  - Adjustments of the damping assumptions would also contribute to more accurate amplification predictions. Not critical: orders of magnitude are correct on main modes.

- Classical spacecraft test specification (sine excitation) suitable for non-linearity characterization.