Predicting and measuring non-linear behaviour at spacecraft level

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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)

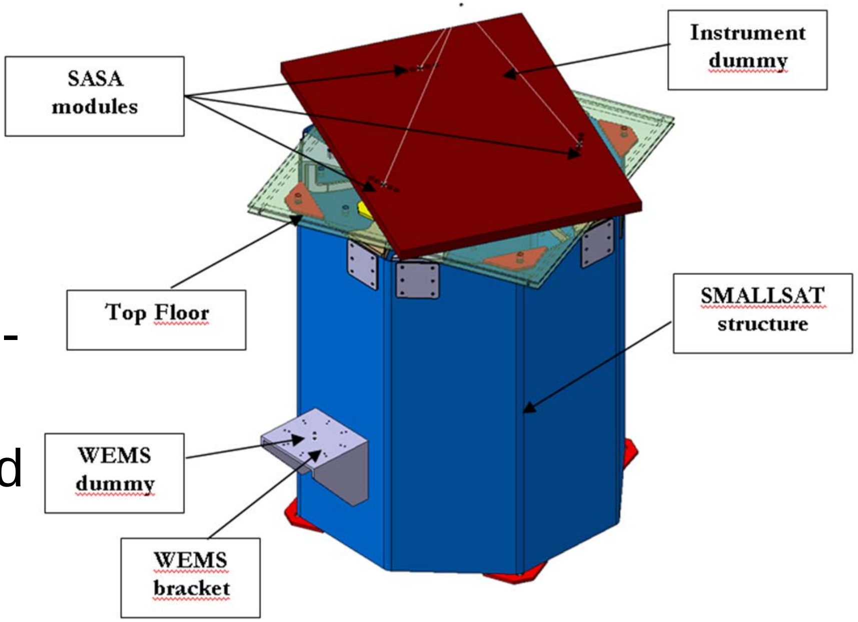
Design concept & objectives

- 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.

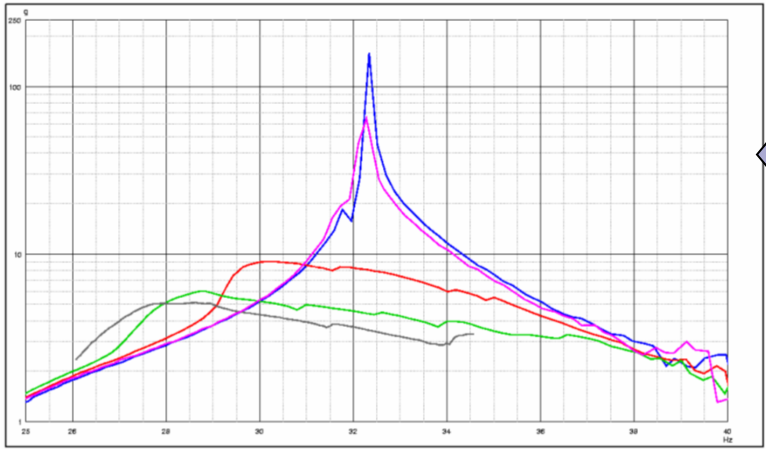
Bread-board presentation (2/5)

- 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)

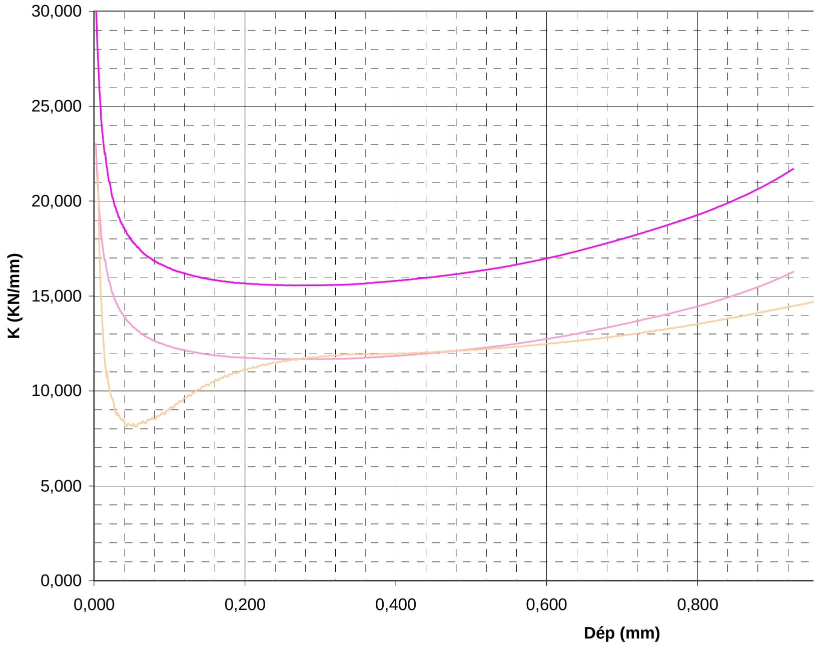
- Non-linearity #1: dummy instrument
  - Large mass (~142kg) inducing significant effect on controller;
  - Non-linear effect emphasized on previous program and linked to damping modification with input levels.

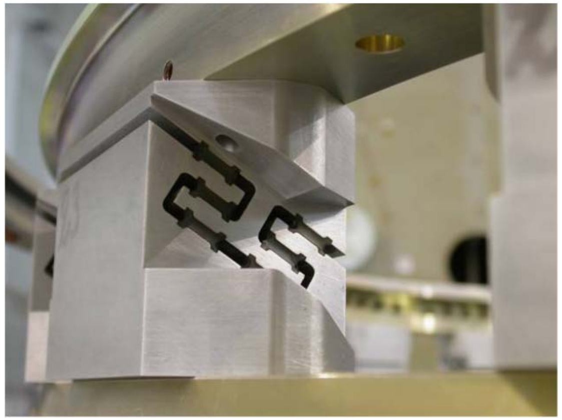


Level	Curve	Frequency	Amplification	Base input
low	(blue line)	32	150	0.1g
intermediate	(red line)	30	9	0.5g
qualification	(green line)	29	6	1g
Augmented qualification	(grey line)	28	5	1.5g
Control low level	(magenta line)	32	60	0.1g

Bread-board presentation (4/5)

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

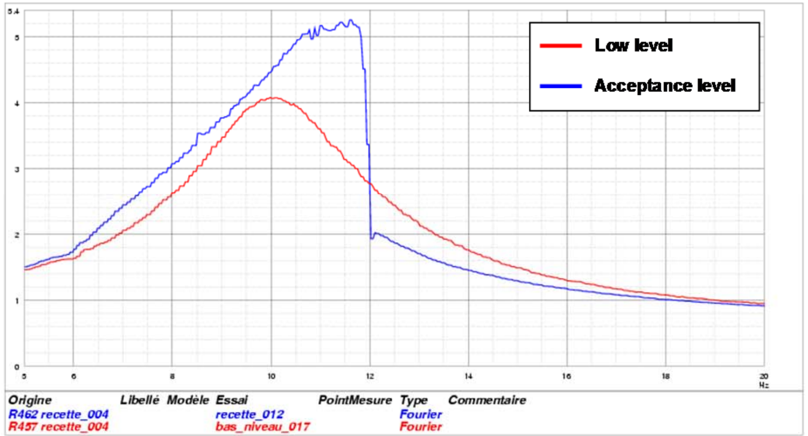


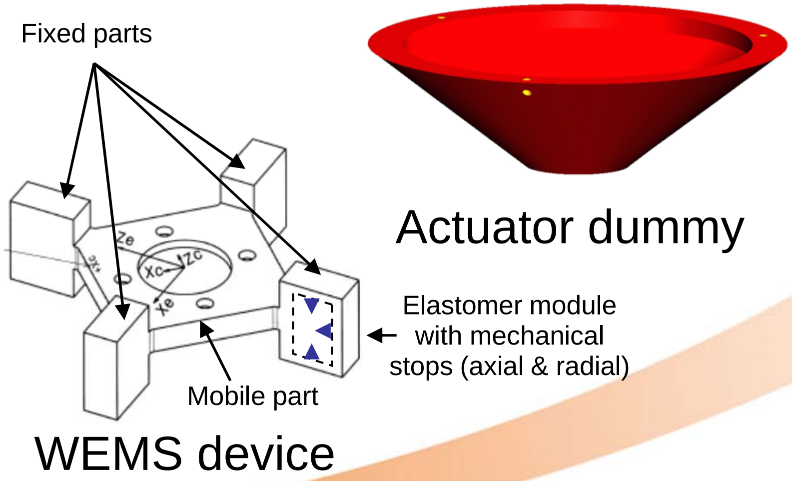


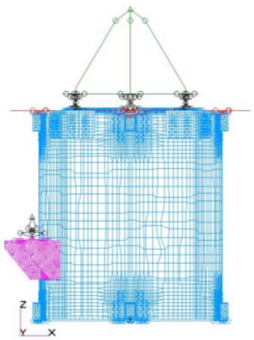
Bread-board presentation (5/5)

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.

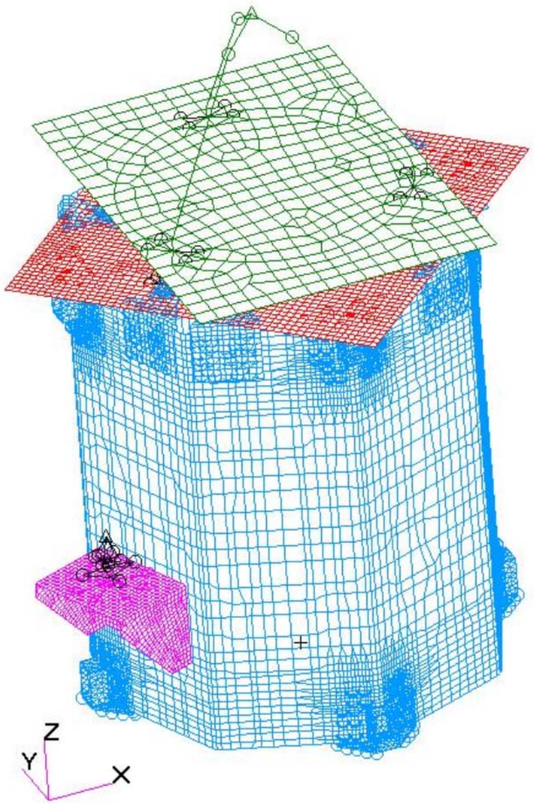






Tests predictions (1/5)

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)

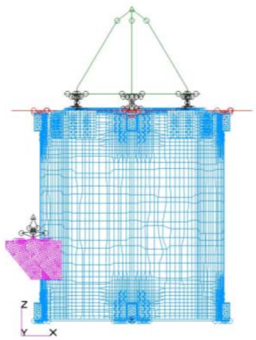
- Input base acceleration:
  - Lateral / axial directions
  - From low level (0.1g) to high level (up to 1g, notched locally for structure protection)
  - Sine sweep in the range [5-100Hz]

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

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

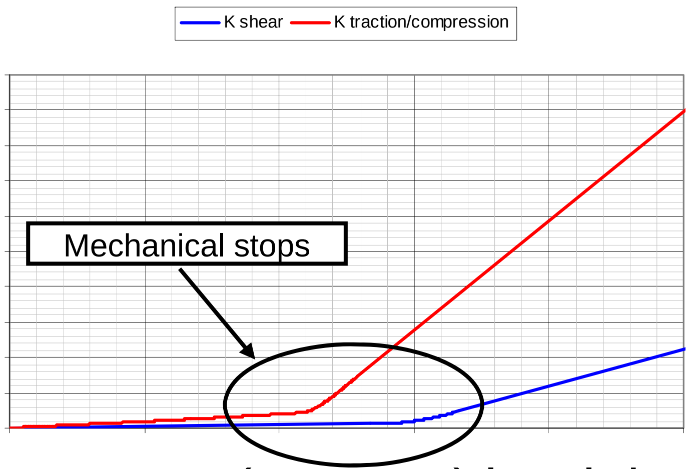
(*) only mentioned for completeness but no further results presented hereafter.

Tests predictions (3/5)

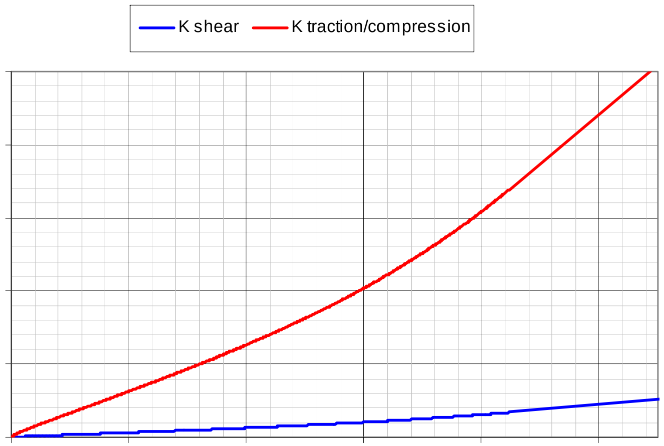


- Non-linear stiffness modelling
  - CBUSH1D cards (rod type spring/damper connection)
  - Symmetrical curves (only positive displacements presented)

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

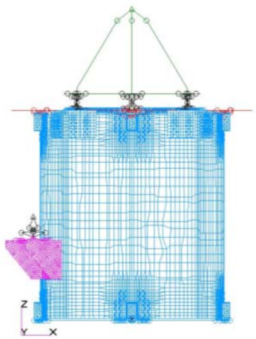


Non-linear stiffness at SASSA module (Force vs displacement)



  - Lower (constant) local damping considered for SASSA and WEMS devices with elastomer parts

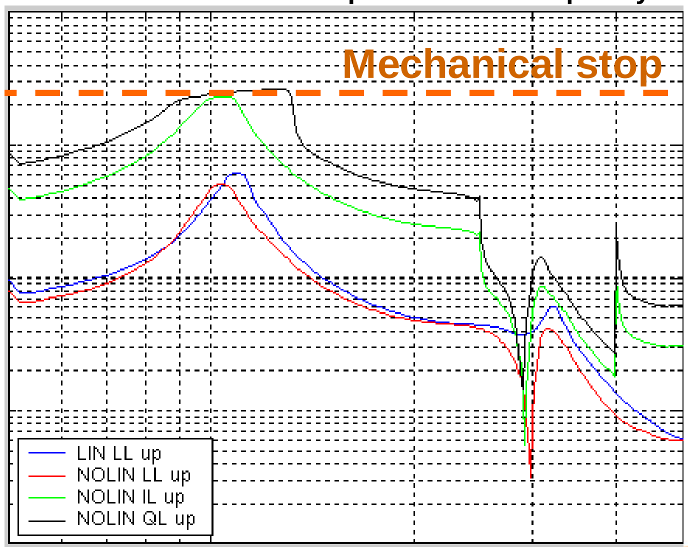
Tests predictions (4/5)



Non-linear analysis

- Severe non-linearity at WEMS level due to the presence of mechanical stops.

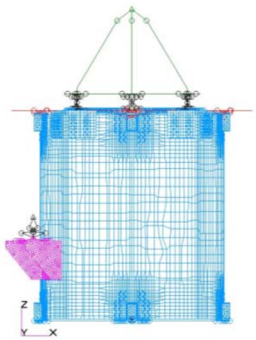
Internal axial relative displacement vs frequency



- Quite linear SASSA behaviour: only slight shift in frequency due to very small internal displacements.

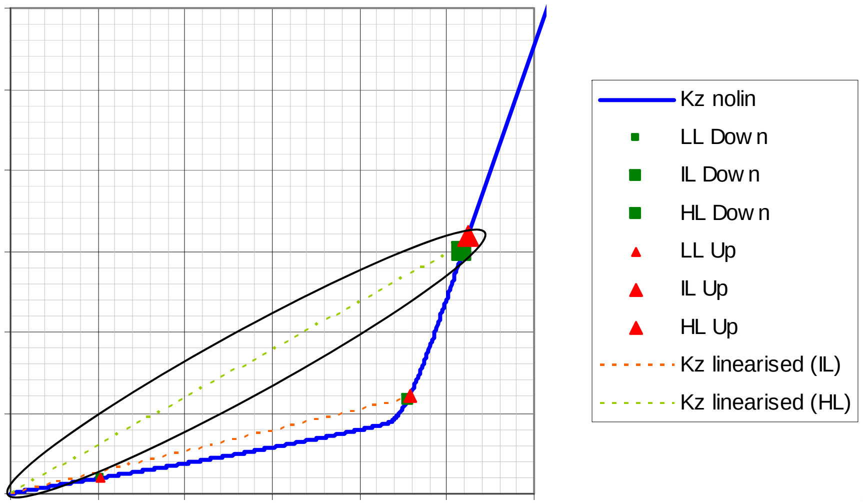
- Damping non-linearity of the dummy instrument cannot be highlighted by simulation (model not representative of various interface components).

Tests predictions (5/5)

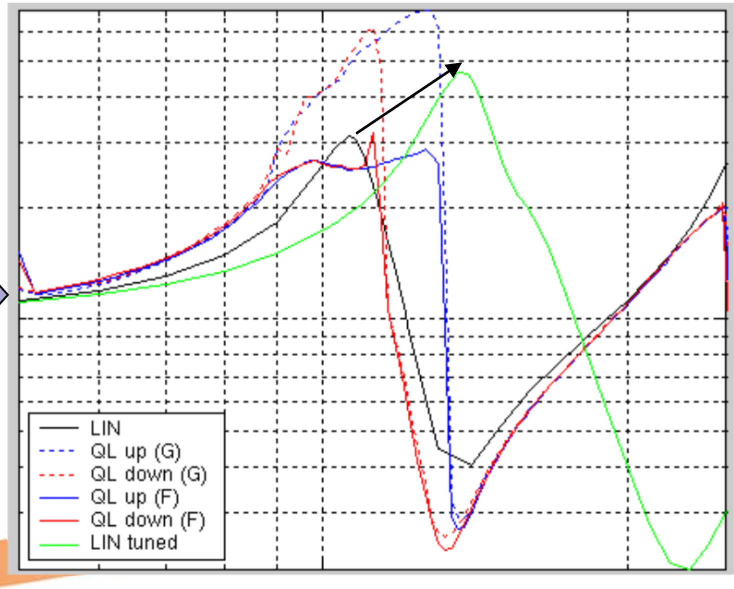


- Linearization of stiffness
  - Linearized stiffness is increased wrt expected displacements (correlation with high level input results)
  - Same damping assumption

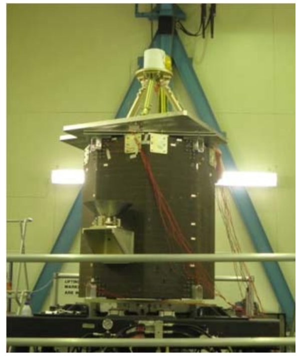
Traction/Compression stiffness for WEMS module (Force vs displacements)



WEMS dummy base lateral acceleration vs frequency



Test results (1/4)



Test plan

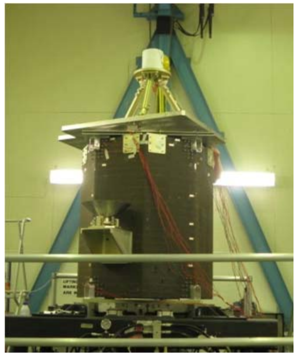
- Lateral / axial sine excitations in the range [5-100Hz];
- Two successive sweeps, up then down;
- Low / Intermediate / High levels.

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

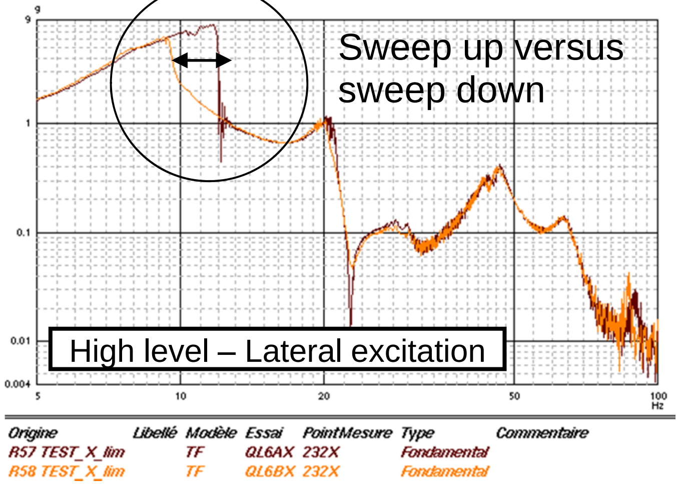
- 76 channels.



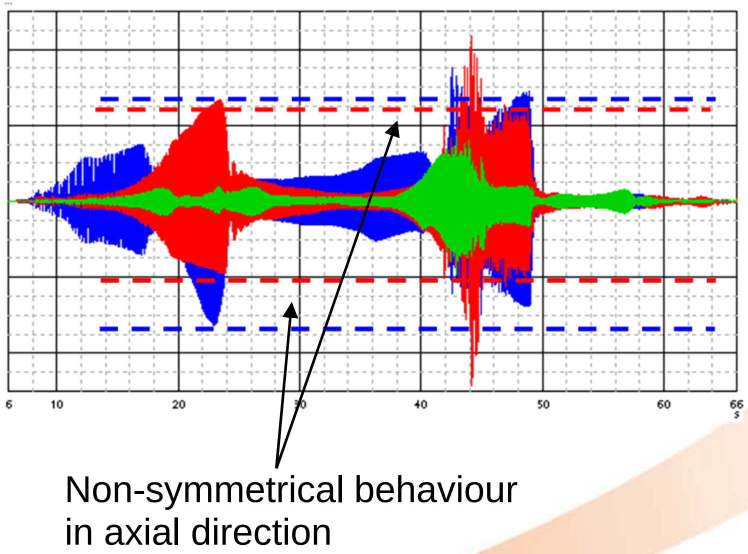
Test results (2/4)

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

WEMS dummy base lateral acceleration vs frequency



WEMS module internal displacement vs time



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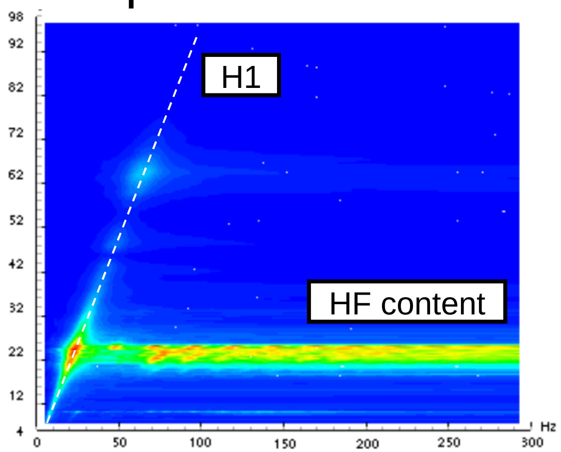
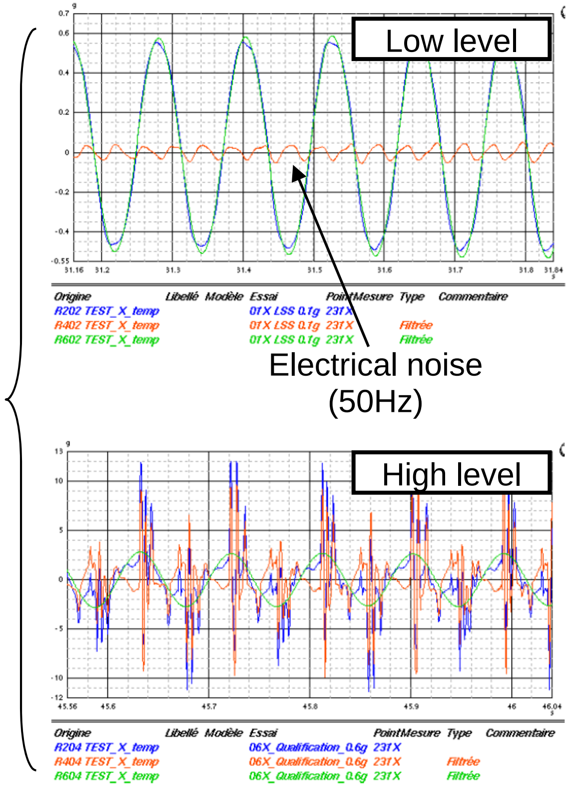
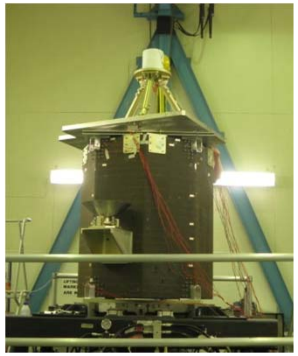
Test results (3/4)

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



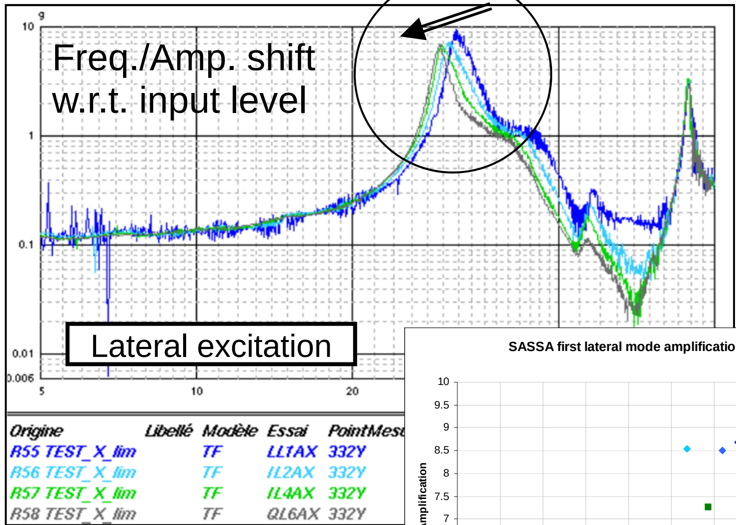




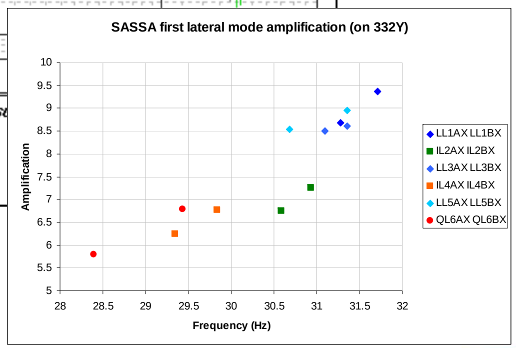
Original
15Hz low pass filter
15Hz high pass filter

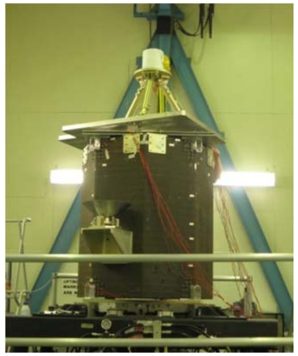
Test results (4/4)

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

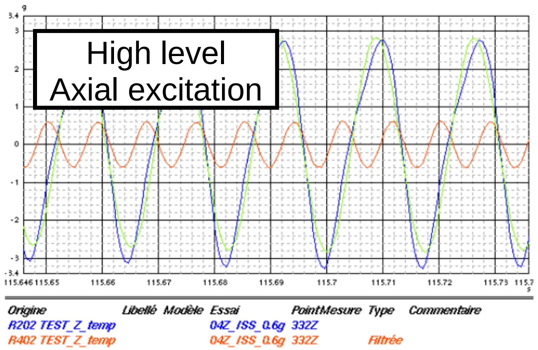


Top of Instrument dummy acceleration vs frequency





- Poor HF content



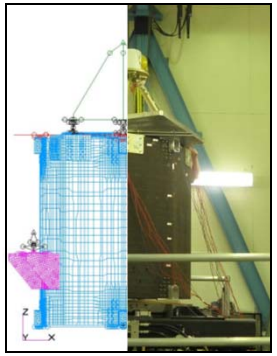
Top of Instrument dummy acceleration on main SASSA mode at ~57Hz

Original

70Hz low pass filter

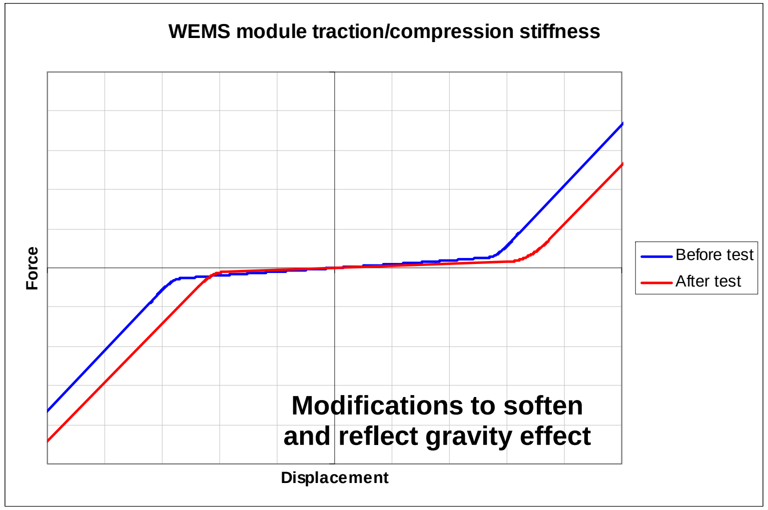
70z high pass filter

Test-analysis correlation (1/3)



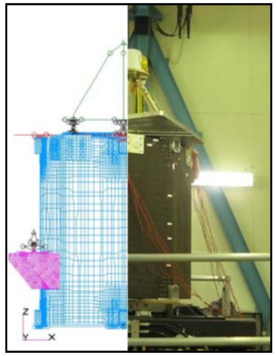
FEM modifications

- At WEMS level:
  - Update local stiffness at I/F between the structure and WEMS support bracket
  - Adjust WEMS module traction/compression stiffness parameters



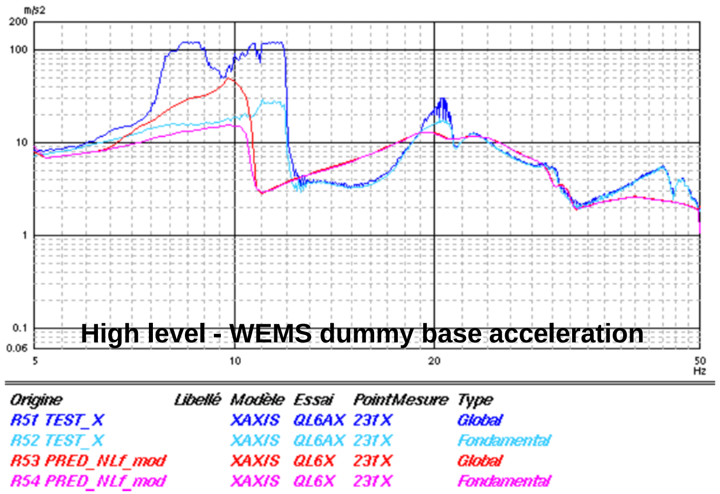
- At Instrument/SASSA level:
  - Update global and local positions and/or orientations regarding the differences between both FEM and bread-board configuration.

Test-analysis correlation (2/3)



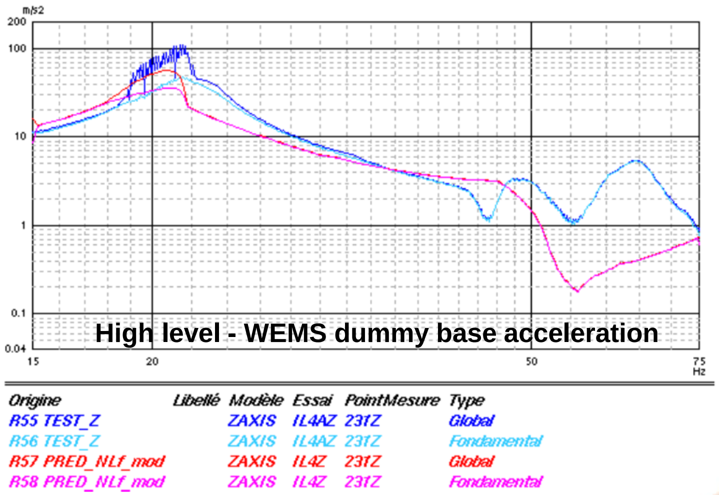
Comparison at WEMS level

- Lateral excitation/response



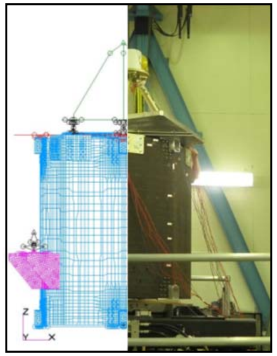
- Much better predictions, even on the second lateral mode. Amplification still under-predicted due to early wave drop.

- Axial excitation/response

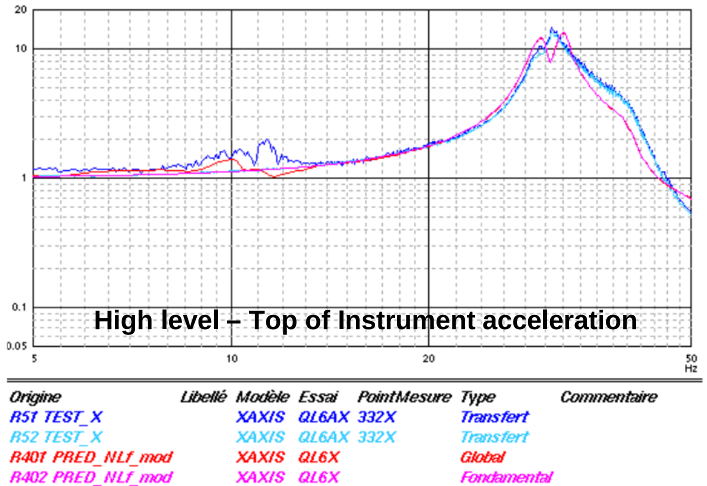


- Predicted internal displacement far below mechanical stop.

Test-analysis correlation (3/3)

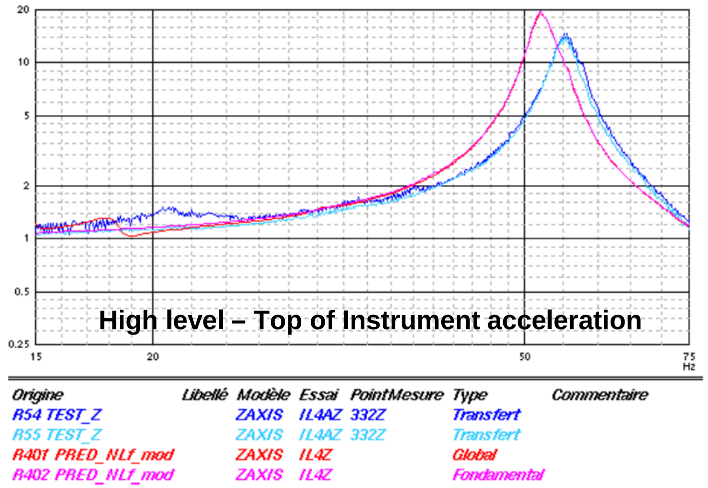


- Comparison at Instrument/SASSA level
  - Lateral excitation/response



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

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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.