Pyroshock Simulation for qualification of space electronic equipments

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Date: 14/05/08
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- ETCA pyroshock test facilities
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- Pyroshock model
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Sensitive components of electronic units

- Structural parts are not sensitive
- Sensitive components
  * Relays
    - Chatter, transfer
    - Permanent damage
  * Magnetic components: brittle failure, cracks
  * Crystals, brittle epoxies, glass diodes, wires, leads
    - Brittle failures, cracks
    - Bond fracture
    - Broken wires
Pyroshock testing methods

- Full scale testing using actual flight hardware
  - Drop tables
    * Velocity step instead of acceleration step (bad at low frequency)
    * One axis/one direction: six shocks instead of one
  - Electrodynamic shaker
    * Input to the test item is spatially overcorrelated, as opposed to the real uncorrelated shock excitation caused by pyro separations
    * 200 - 300 g max in time domain; one order of magnitude too low
  - Mechanically excited ringing structures
  - Pyrotechnically excited ringing structures
    * Plate testing using explosives is the best method of simulating pyro shock events where fullscale flight hardware are not available or too costly.
ETCA pyroshock test facilities

- Mechanical structure:
  - Double plate (aluminium, steel)
  - Simple plate (aluminium, steel)
  - Simple plate + square (aluminium, steel)
  - More complex set-up...

- Excitation devices:
  - Explosive (nominal)
  - Dropping hammer
  - Pneumatical jack

- Measurements:
  - Acceleration
  - Quick Calculation of the SRS's
- Using of Non-electric detonator
- Detonator and explosive charge are fixed on a steel plate
- A gun causes the explosion of the detonator and so, of the explosive charge

Charge fixed with tape to the set-up
ETCA pyroshock test facilities

Some standard configurations...

- Double plate set-up

![Double plate set-up diagram]
ETCA pyroshock test facilities

Some standard configurations...

- Double plate set-up

![Diagram showing double plate set-up with labels: Aluminium base plate, Aluminium mounting plate, Unit under test, Damping devices.](image-url)
Some results of double plate set-up…

**Specification M2 - Ariane 5**  
Out of plane axis only

**Specification S4**  
3 axes simultaneously
Some results of double plate set-up...
Main parameters to tune on double plate set-up:

- Quantity of explosive charge
- Material of base plate and mounting plate
- Dimensions of mounting plate
- Number of damping devices between the plate
- Location of damping devices
- Location of explosive charge
- …

Drawback of double plate set-up:

- Out of plane axis is over-tested
**ETCA pyroshock test facilities**

Some specific configurations...

- Steel plate
- Aluminium plate
- Third plate

Location of explosive charge

Aluminium square

Steel plate
ETCA pyroshock test facilities

Some specific configurations…

- Aluminium base plate
- Aluminium block
- Damping devices
- Steel base plate
- Aluminium block
ETCA pyroshock test facilities

Some results of specific configurations...

3 axes almost identical

With Aluminium square

With Aluminium block
ETCA pyroshock test facilities

Some results of specific configurations...

One high level axis set-up

With Aluminium square

30 000[g] !!!

3 axes almost identical
Usual way to perform a pyroshock test campaign

Specified level and unit (through mass and dimension mainly)

Empirical selection of test fixture and type

- Pneumatic piston
- Sledge hammer
- Explosive

Graph showing relationship between acceleration (g) and natural frequency (Hz), with marks for 'Lorala', 'Loralb', 's4', 's2v', 'XMM', and 'a5'.

Specified level and unit.
Usual way to perform a pyroshock test campaign

- ETCA pyroshocks data base *(more than 3000 pyroshocks)* is the main tool to choose a test fixture to start a calibration stage

- Calibration stage to reach specified levels is a very empiric process (tuning of parameters of the test facilities based mainly on ETCA know-how)

- To reduce time and cost of a pyroshock test campaign, interest to use models of the test facilities to know influence of set-up parameters

- → Collaboration between TAS ETCA and FPMs
**Goal:** develop a pyroshock model of the test facilities used by Thales Alenia Space Etca (Belgium – Charleroi) in order to predict the influence of some operating parameters on the SRS calculations

The pyroshock model requires:

- **Dynamic model of the test facility**
  - Finite Element Method (FEM)
- **Mathematical description of the excitation sources**
  - Equivalent Mechanical Shock (EMS)
Reference experimental data

Used configuration:
- square steel plate vertically suspended

Detonating cord length:
- 0, 4, 10, 20, 30, 50 cm

Acquisition parameters:
- $F_{\text{sample}} = 100$ kHz
- $N_{\text{sample}} = 8192$ pts
- Low pass filter with a cutoff frequency of 10 kHz

Characteristics of the plate:
- Steel material
- Area = 1 m²
- Thickness = 15 mm
Main experimental results

Comparison between in plane and out of plane

Influence of the length of the detonating cord

Influence of the location of measurement node

Repeatability between pyroshocks
Finite Element Model of the test facility

FE model built under ANSYS 8.1 software
- Modelling of the plate with SOLID45 elements
- Six elements per bending wavelength
- Three elements along the thickness

<table>
<thead>
<tr>
<th></th>
<th>Steel plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$</td>
<td>210 GPa</td>
</tr>
<tr>
<td>$\rho$</td>
<td>7800 Kg/m³</td>
</tr>
<tr>
<td>$\nu$</td>
<td>0.3</td>
</tr>
<tr>
<td>$h$</td>
<td>0.015 m</td>
</tr>
<tr>
<td>$f$</td>
<td>10 kHz</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>0.121 m</td>
</tr>
</tbody>
</table>

$\lambda = \sqrt{\frac{2\pi}{f}} \left( \frac{D}{Eh^3} \right)^{1/4}$

$D = \frac{E h^3}{12 (1 - \nu^2)}$

A constant damping ratio $\xi$ has been introduced in the FE model.
Model validation in the modal domain

Relative frequency difference

\[ \Delta_k = \frac{|f_k^E - f_k^S|}{f_k^S} \]

Modal Assurance Criterion (MAC):

\[ MAC_k = \frac{\left( \{ \psi_k^E \}^T \{ \psi_k^S \} \right)^2}{\left( \{ \psi_k^E \}^T \{ \psi_k^E \} \right) \left( \{ \psi_k^S \}^T \{ \psi_k^S \} \right)} \]

<table>
<thead>
<tr>
<th>(f_k^E) (Hz)</th>
<th>(f_k^S) (Hz)</th>
<th>(\Delta_k) (%)</th>
<th>MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>47</td>
<td>49</td>
<td>3.4</td>
<td>0.98</td>
</tr>
<tr>
<td>92</td>
<td>89</td>
<td>3.7</td>
<td>0.85</td>
</tr>
<tr>
<td>124</td>
<td>127</td>
<td>2.5</td>
<td>0.69</td>
</tr>
<tr>
<td>231</td>
<td>224</td>
<td>2.4</td>
<td>0.88</td>
</tr>
<tr>
<td>282</td>
<td>282</td>
<td>0.6</td>
<td>0.98</td>
</tr>
<tr>
<td>457</td>
<td>445</td>
<td>2.6</td>
<td>0.83</td>
</tr>
<tr>
<td>488</td>
<td>477</td>
<td>2.2</td>
<td>0.77</td>
</tr>
<tr>
<td>493</td>
<td>498</td>
<td>1.2</td>
<td>0.84</td>
</tr>
<tr>
<td>564</td>
<td>560</td>
<td>0.73</td>
<td>0.98</td>
</tr>
<tr>
<td>622</td>
<td>635</td>
<td>2.1</td>
<td>0.80</td>
</tr>
<tr>
<td>738</td>
<td>730</td>
<td>1.0</td>
<td>0.64</td>
</tr>
<tr>
<td>790</td>
<td>771</td>
<td>2.5</td>
<td>0.85</td>
</tr>
<tr>
<td>796</td>
<td>803</td>
<td>0.9</td>
<td>0.73</td>
</tr>
<tr>
<td>897</td>
<td>919</td>
<td>2.4</td>
<td>0.68</td>
</tr>
<tr>
<td>898</td>
<td>899</td>
<td>0.1</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Modal identification with LSCE method (TestLab – LMS)

The FE model have been validated and updated until 1000 Hz
⇒ Extrapolation at higher frequencies (until 10 kHz)
Model validation in the temporal domain

Comparison between experimental and simulated accelerations

- Graphs showing force over time and acceleration over frequency.
**Definition:** EMS corresponds to the mechanical force which has to be applied to the FE model to generate equivalent acceleration fields.

**EMS is defined by two parameters**
- The intensity $F_{\text{max}}$ of the impact
- The duration $\tau$ of the impact
The parameters $F_{\text{max}}$ and $\tau$ of the EMS are deduced by an optimization process that minimize the gap between experimental and numerical results in terms of SRS:

$$\epsilon = \min_{F_{\text{max}}, \tau} \sum_{f=0 \text{ Hz}}^{10 \text{ kHz}} \sum_{j=1}^{N_{\text{SRS}}} \left| SRS_j^{\text{Measured}} - SRS_j^{\text{Simulated}}(F_{\text{max}}, \tau) \right|^2$$

Identification process costly in calculation time

In practice,

- Quantification of $\tau$: [20:20:200] $\mu$s
- For each $\tau$, calculation of the SRS to an unitary intensity $\Rightarrow SRS^{\text{ref}}$

$$\epsilon(\tau) = \min_{F_{\text{max}}} \sum_{f=0 \text{ Hz}}^{10 \text{ kHz}} \sum_{j=1}^{N_{\text{SRS}}} \left| SRS_j^{\text{Measured}} - F_{\text{max}} SRS_j^{\text{ref}} \right|^2$$
\( \Delta_i(f) \): represents the difference at frequency \( f \) between experimental and simulated SRS in terms of frequency for node number \( i \)

\[
\Delta_i(f) = |SRS_i^{simulated}(f) - SRS_i^{Measured}(f)|
\]

\( \mu(\Delta_i) \) et \( \sigma(\Delta_i) \): correspond to the mean and the standard deviation of the indicator \( \Delta_i(f) \) along the frequency range \([1 – 10 \text{ kHz}]\)

\[
\mu(\Delta_i) = \frac{\sum_f |\Delta_i(f)|}{N}
\]

\[
\sigma(\Delta_i) = \sqrt{\frac{1}{N} \sum_f (\Delta_i(f) - \mu(\Delta_i))^2}
\]

\( \mu_G \) et \( \sigma_G \): represent the mean and the standard deviation respectively of the frequency difference between experimental and simulated SRS considered on the whole set of measured nodes.
Influence of the damping ratio $\xi$

Damping ratio $\xi$ corresponds to the mean value measured during the experimental modal analysis in the frequency range [0-1000 Hz].

### EMS identified from a zero detonating cord length

<table>
<thead>
<tr>
<th>$\xi$ (%)</th>
<th>$F_{max}$ (N)</th>
<th>$\tau$ (µs)</th>
<th>$F_{max} \times \tau$ (Ns)</th>
<th>$\mu_G$ (dB)</th>
<th>$\sigma_G$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>60612</td>
<td>80</td>
<td>4.85</td>
<td>0.82</td>
<td>0.64</td>
</tr>
<tr>
<td>0.1</td>
<td>83518</td>
<td>60</td>
<td>5.01</td>
<td>0.80</td>
<td>0.61</td>
</tr>
<tr>
<td>0.2</td>
<td>88344</td>
<td>60</td>
<td>5.3</td>
<td>0.84</td>
<td>0.61</td>
</tr>
<tr>
<td>0.3</td>
<td>92091</td>
<td>60</td>
<td>5.52</td>
<td>0.87</td>
<td>0.61</td>
</tr>
<tr>
<td>1</td>
<td>112070</td>
<td>60</td>
<td>6.72</td>
<td>1.07</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Damping ratio influences significantly the SRS at low frequencies.
Identification of the EMS

Damping ratio $\xi = 0.1\%$

<table>
<thead>
<tr>
<th>length cord</th>
<th>$F_{max}$ (N)</th>
<th>$\tau$ (μs)</th>
<th>$F_{max} \times \tau$ (Ns)</th>
<th>$\mu_C$ (dB)</th>
<th>$\sigma_C$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 cm</td>
<td>83518</td>
<td>60</td>
<td>5.01</td>
<td>0.80</td>
<td>0.62</td>
</tr>
<tr>
<td>4 cm</td>
<td>129830</td>
<td>60</td>
<td>7.79</td>
<td>0.76</td>
<td>0.57</td>
</tr>
<tr>
<td>10 cm</td>
<td>203980</td>
<td>60</td>
<td>12.24</td>
<td>0.88</td>
<td>0.68</td>
</tr>
<tr>
<td>20 cm</td>
<td>199260</td>
<td>80</td>
<td>15.94</td>
<td>0.84</td>
<td>0.67</td>
</tr>
<tr>
<td>30 cm</td>
<td>191210</td>
<td>100</td>
<td>19.12</td>
<td>1.32</td>
<td>1.83</td>
</tr>
<tr>
<td>50 cm</td>
<td>240870</td>
<td>100</td>
<td>24.09</td>
<td>1.27</td>
<td>1.16</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>length cord</th>
<th>$\mu(\Delta_i)$</th>
<th>$\sigma(\Delta_i)$</th>
<th>$\mu(\Delta_i)$</th>
<th>$\sigma(\Delta_i)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>node 1</td>
<td>1.30</td>
<td>0.89</td>
<td>3.13</td>
<td>4.02</td>
</tr>
<tr>
<td>node 14</td>
<td>0.70</td>
<td>0.52</td>
<td>0.86</td>
<td>0.61</td>
</tr>
<tr>
<td>node 11</td>
<td>0.67</td>
<td>0.44</td>
<td>0.83</td>
<td>0.54</td>
</tr>
<tr>
<td>node 6</td>
<td>0.76</td>
<td>0.48</td>
<td>1.15</td>
<td>0.94</td>
</tr>
<tr>
<td>node 15</td>
<td>0.67</td>
<td>0.53</td>
<td>0.88</td>
<td>0.65</td>
</tr>
<tr>
<td>node 12</td>
<td>0.70</td>
<td>0.66</td>
<td>0.83</td>
<td>0.63</td>
</tr>
<tr>
<td>node 5</td>
<td>0.91</td>
<td>0.65</td>
<td>1.58</td>
<td>0.98</td>
</tr>
</tbody>
</table>

EMS reproduces in a satisfactory way, in terms of SRS, the dynamic behaviour of the plate in the orthogonal direction because the mean frequency difference is inferior than the usual tolerances ($< 3 \text{ dB}$)
Energy injected by the EMS

![Graph showing the relationship between the product of the maximum force and the explosive cord length and the length of the explosive cord.](image)
Comparison between experimental and simulated SRS

Accelerations measured in orthogonal direction of the plate

At node 1

At node 6
Comparison between experimental and simulated SRS

Accelerations measured in the plane of the plate

At node 6

At node 11

The moment arm induced by the measure cube amplifies acceleration levels in-plane directions ⇒ introduction of the dynamic effects of the cube in the FE model
Modelling of the measure cube (1)

- Modelling of the moment arm with help of CERIG elements
- Cube has been represented by an undeformable pyramid having equivalent geometric dimensions (same base and same height)

Characteristics of the cube
- \( M_{\text{cube}} = 47 \text{ g (steel)} \)
- \( h_{\text{cube}} = 20 \text{ mm} \)
- \( S_{\text{cube}} = 400 \text{ mm}^2 \)
Modelling of the measure cube (2)

Accelerations measured in the plane of the plate

At node 6

At node 11
When we apply to these 3 configurations the EMS identified on the reference test facility, we obtain similar results.
Comparison between experimental and simulated SRS

Configuration 2
Steel plate

Configuration 2
Aluminium plate

Difficulties to reproduce the SRS at high frequencies => Modelling of the screw bolts with element beam isn’t appropriated?
Parametric analysis

Influence of the thickness of the plate

Influence of the material of the plate

Influence of the location of excitation sources

Addition of a localized mass
Conclusions

- Ability of Thales Alenia Space ETCA pyroshock test facilities to cover a large range of SRS
- Equivalent mechanical shock + FEM of the test facilities = new way to reduce time spent during calibration stage
- Parametric analysis can be performed to know the influence of main parameters of the test set-up
- Development of new mechanical tools to reach high level specifications in, at least, two axes simultaneously, with reduced overtesting
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