Laboratory Test of Vibration of Micro/Nano Satellite for Environment Test Standardization

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5th Nano-Satellite Symposium, November 20-23, 2013, Tokyo, Japan
Background

• Micro/Nano satellite: Low-cost and fast-delivery using COTS.
• Existing testing standard not suitable for micro/nano satellites.
• The unit QT(Qualification Test) for large/medium satellite require too many margins.
• Needs to Define an adequate level of the unit test level.

• KIT initiated NETS (Nano Satellite Environment Test Standardization) project in 2011.
• Proposing affordable and reliable tests to the space community.
• Various environment tests according to NETS projects.
• Basic research- QT level vibration test.
Unit QT level strategy

• Existing QT- too much margins
• QT-guarantee design for space
• Products- no test history

• Unit QT level in this standard - give minimum assurance
• Buyers get minimum assurance
• Customer may test again to their specification
Approach

• Statistics of experimental data
  20-300Hz : Statistics of various satellites
  300-2000Hz : Vibration test measure at various internal points
• Amplification factor of base vibrations
• Identify the minimum amplification factor
• Propose Unit QT level by multiplying PSD by AF.
Experimental System
Outline of vibration test

• Test article: Dummy satellite
  (the Hodoyoshi-3 satellite AT test data was used for update dummy satellite test results)
• Size: 50cm x 50cm x 50cm
• Weight: 50kg class
• Vibration: Random vibration.
• Base acceleration: Adopted from SMC–S-016 (US Standard)
• Peak PSD levels and resonant frequencies were identified.
• To compute Normal tolerance limit, followed the ”Dynamic Environment Criteria”, NASA-HDBK-7005.
Test article

- RF transmitter
- PCU (Power Control Unit)
- OBC (On board computer)
- Battery

Dummy satellite
Size: 50cm x 50cm x 50cm

DM (Dummy masses) with heater inside

Structure - flight quality

Hodoyoshi-3 satellite vibration test data are also used for update.
Test article

- “Four quarter tatami” - viewed from the top
- Seen as the popular layout of tatamis
- *yo-jou-han*
  4.5 tatami room

www.uemura-tatami.com/archives/491
Test procedure

Satellite fixed to vibration machine
Accelerometers attached
Random vibration tests

Peak PSD and resonant frequency
Finding vibration modes

Statistical methods to find Unit QT level

Testing

Raw Data Analysis

Final Statistical Analysis
Random vibration spectrum profile

- Power Spectral Density (PSD) plot: Mean square acceleration per unit bandwidth
- Random vibration excites all the frequencies in a defined spectrum at any given time.

For the experiment:
Adopted from SMC –S-016 (US Standard)
Amplification Factor (AF)

\[ AF = \left( \frac{PSD_m}{PSD_b} \right)^{\frac{1}{2}} \]

- **AF**: Amplification factor
- **PSD_m**: Measured PSD value
- **PSD_b**: Base level

If AF=1, no amplification
If AF>1, vibration amplified
If AF<1, attenuated vibration
Test results and data analysis
Test result: PSD waveform

- Measured at 18 points
- Position: +x internal panel
- Base level: 9Grms
- Vibration: Vertical
- Accelerometer: z axis
Example of Test results: Amplification Factor

Sensor position: DM1, vertical

Amplification Factor

Peak, AF=1.69

Frequency [Hz]

100 300 1000
Test data statistics of dummy satellite(300-1000Hz)

- The **peak amplification factors** and **resonant frequencies** were deduced within three frequency ranges.
- Approximated these data by **lognormal distribution**.

<table>
<thead>
<tr>
<th></th>
<th>Resonant frequency[Hz]</th>
<th>Amplification factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Horizontal1</td>
<td>Horizontal2</td>
</tr>
<tr>
<td>DM1</td>
<td>566.4</td>
<td>546.9</td>
</tr>
<tr>
<td>PCU</td>
<td>820.3</td>
<td>517.6</td>
</tr>
<tr>
<td>BATTERY</td>
<td>463.9</td>
<td>546.9</td>
</tr>
<tr>
<td>DM6</td>
<td>546.9</td>
<td>927.7</td>
</tr>
<tr>
<td>OBC</td>
<td>561.5</td>
<td>302.7</td>
</tr>
<tr>
<td>RF</td>
<td>546.9</td>
<td>493.2</td>
</tr>
<tr>
<td>DM4</td>
<td>551.8</td>
<td>542.0</td>
</tr>
<tr>
<td>DM2</td>
<td>571.3</td>
<td>498.1</td>
</tr>
<tr>
<td>DM5</td>
<td>561.5</td>
<td>546.9</td>
</tr>
<tr>
<td>DM3</td>
<td>571.3</td>
<td>498.1</td>
</tr>
<tr>
<td>DM9</td>
<td>537.1</td>
<td>996.1</td>
</tr>
<tr>
<td>DM7</td>
<td>566.4</td>
<td>961.9</td>
</tr>
<tr>
<td>DM10</td>
<td>537.1</td>
<td>493.2</td>
</tr>
<tr>
<td>DM8</td>
<td>566.4</td>
<td>659.2</td>
</tr>
</tbody>
</table>
Vibration response modes

**Local vibration mode**
- 300-2000Hz
- Internal panel structure

**Whole satellite mode**
- 20-300Hz
- Entire satellite structure
Example of Vibration modes of micro/nano satellite

- Noticed two vibration modes: “Whole satellite mode” and “Local vibration mode”.

- The measurement data were divided into three frequency range:
  1. 20-300Hz: Whole satellite mode
  2. 300-1000Hz: Local vibration mode
  3. 1000-2000Hz: Local vibration mode

Horizontal Vibration response at internal panel
Vibration modes of micro/nano satellite

“Local vibration mode” due to mostly internal panels arrangement

Vertical Vibration response at internal panel
Statistical method to deduce Normal tolerance limit

- To compute Normal tolerance limit, followed NASA methodology: NASA-HDBK-7005
- The Handbook says:
  - “there is evidence that the logarithm of the spectral values for any motion parameter describing the response from one to another have an approximate normal distribution”
  - “The spatial distribution of structural response spectra in a specific frequency resolution bandwidth approximately fits a lognormal distribution”.

- Examined whether our test data follow normal or lognormal distributions.
- $\chi^2$ (Chi squared) goodness of fit statistics were used to check normality.
After evaluating normality, we decided to choose lognormal as the distribution of Amplification factor.
Normal Tolerance Limit (NTL) calculation

\[ y = \log_{10} x \]

\[ NTL_y(n, \beta, \gamma) = \bar{y} \pm k_{n,\beta,\gamma} s_y \]

- \( x \): data value (e.g. AF, frequency)
- \( k_{n,\beta,\gamma} \): normal tolerance factor.
- \( n=18 \) and \( k_{n,\beta,\gamma} =1.67 \) for tested data.
- 95/50 limit
- \( \beta=0.95, \gamma=0.50 \)
Normal tolerance limit of amplification factor in logarithm of the dummy satellite in the range: 300-1000Hz

<table>
<thead>
<tr>
<th></th>
<th>Resonant frequency[Hz]</th>
<th>Amplification factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Horizontal (x)</td>
<td>Horizontal (y)</td>
</tr>
<tr>
<td>Average</td>
<td>566.4</td>
<td>586.5</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>281</td>
<td>760.4</td>
</tr>
<tr>
<td>Lower value</td>
<td>97.3</td>
<td>-683</td>
</tr>
<tr>
<td>Upper value</td>
<td>1035.7</td>
<td>1856.4</td>
</tr>
<tr>
<td></td>
<td>Horizontal (x)</td>
<td>Horizontal (y)</td>
</tr>
<tr>
<td>Average</td>
<td>0.39(2.4)</td>
<td>0.49(3.1)</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.20(1.6)</td>
<td>0.28(3.1)</td>
</tr>
<tr>
<td>NTL (Min)</td>
<td>0.06(1.15)</td>
<td>0.02 (1.05)</td>
</tr>
<tr>
<td>NTL (Max)</td>
<td>0.72(5.25)</td>
<td>0.96 (9.12)</td>
</tr>
</tbody>
</table>

- **1.15**: maximum value of minimum Normal tolerance limit among all direction.
- **1.15** was chosen as the unit QT level in the range: 300Hz and 1000Hz.
## Amplification factor, 20-300Hz

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Horizontal x</th>
<th>Horizontal y</th>
<th>Axial direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite-A</td>
<td>8.2</td>
<td>10.4</td>
<td>8.0</td>
</tr>
<tr>
<td>Satellite-B</td>
<td>4.21</td>
<td>5.18</td>
<td>5.86</td>
</tr>
<tr>
<td>Satellite-C</td>
<td>6.52</td>
<td>5.75</td>
<td>7.56</td>
</tr>
<tr>
<td>Satellite-D</td>
<td>7.31</td>
<td>7.27</td>
<td>5.05</td>
</tr>
<tr>
<td>Satellite-E</td>
<td>5.73</td>
<td>6.92</td>
<td>3.39</td>
</tr>
<tr>
<td>Satellite-F</td>
<td>6.78</td>
<td>5.19</td>
<td>3.27</td>
</tr>
</tbody>
</table>
Normal tolerance limit of amplification factor in logarithm in the range: **20-300Hz** (real values are shown in bracket).

<table>
<thead>
<tr>
<th>Resonant frequency [Hz]</th>
<th>Horizontal 1</th>
<th>Horizontal 2</th>
<th>Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>54</td>
<td>49</td>
<td>172</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>27</td>
<td>28</td>
<td>56</td>
</tr>
<tr>
<td>Lower value</td>
<td>6.7</td>
<td>0</td>
<td>74</td>
</tr>
<tr>
<td>Upper value</td>
<td>101.2</td>
<td>98</td>
<td>270</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Amplification factor</th>
<th>Horizontal1</th>
<th>Horizontal2</th>
<th>Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>0.80 (6.3)</td>
<td>0.82 (6.6)</td>
<td>0.72 (5.2)</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.10 (1.2)</td>
<td>0.12 (1.3)</td>
<td>0.17 (1.5)</td>
</tr>
<tr>
<td>NTL (Min)</td>
<td>0.62 (4.2)</td>
<td>0.61 (4.1)</td>
<td>0.42 (2.6)</td>
</tr>
<tr>
<td>NTL (Max)</td>
<td>0.97 (9.3)</td>
<td>1.03 (10.7)</td>
<td>1.0 (10)</td>
</tr>
</tbody>
</table>

- **4.2**: maximum value of minimum Normal tolerance limit among all direction.
- **4.2** was chosen as the unit QT level between **20Hz and 101Hz**.
The amplification factor and resonance frequency range for unit QT test level (20-2000Hz)

- Results of three frequency ranges merged.
- Amplification factor of unit QT level between 20Hz and 2000Hz.
Unit QT level (20-2000Hz)

Unit QT level = PSD(AT level) x Amplification factor^2

- RMS
  - SMC : 12.9Grms
  - Rocket B : 11.8Grms
  - Rocket C : 8.4Grms

- Propose Rocket B as Unit QT level.
Conclusion

• Basic research has been carried out to find Unit QT level.
• Amplification factor and range of resonant frequencies were considered.
• Unit QT test level has been proposed.

Future work:
• Finite Element Analysis (FEA) of small satellites structures will be carried out to update experimental results.
Appendix
Mounting of the Accelerometers

Accelerometers attached at positions of internal and external panels.
Flowchart of Data analyzing

Accelerometer data

Charge amplifier
(output-10V+10V)

A/D conversion
5000 sample/sec

FFT

PSD

Amplification Factor

RMS

Resonant frequency

Time domain

Frequency domain

Flowchart of Data analyzing

Accelerometer data

Charge amplifier
(output-10V+10V)

A/D conversion
5000 sample/sec

FFT

PSD

Amplification Factor

RMS

Resonant frequency
Peak amplification factor, 1000-2000Hz

<table>
<thead>
<tr>
<th>position</th>
<th>normal (X)</th>
<th>normal (Y)</th>
<th>normal Axial (Z)</th>
<th>lognormal Log(x)</th>
<th>lognormal Log(y)</th>
<th>lognormal Log(z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM1</td>
<td>2.27</td>
<td>1.07</td>
<td>1.83</td>
<td>0.36</td>
<td>0.03</td>
<td>0.26</td>
</tr>
<tr>
<td>PCU</td>
<td>3.36</td>
<td>1.44</td>
<td>2.07</td>
<td>0.53</td>
<td>0.16</td>
<td>0.32</td>
</tr>
<tr>
<td>BATTERY</td>
<td>2.86</td>
<td>1.42</td>
<td>2.60</td>
<td>0.46</td>
<td>0.15</td>
<td>0.41</td>
</tr>
<tr>
<td>DM6</td>
<td>1.72</td>
<td>2.17</td>
<td>1.76</td>
<td>0.24</td>
<td>0.34</td>
<td>0.25</td>
</tr>
<tr>
<td>OBC</td>
<td>1.96</td>
<td>4.35</td>
<td>2.94</td>
<td>0.29</td>
<td>0.64</td>
<td>0.47</td>
</tr>
<tr>
<td>RF</td>
<td>2.12</td>
<td>2.98</td>
<td>2.93</td>
<td>0.33</td>
<td>0.47</td>
<td>0.47</td>
</tr>
<tr>
<td>DM4</td>
<td>2.49</td>
<td>1.50</td>
<td>1.41</td>
<td>0.40</td>
<td>0.18</td>
<td>0.15</td>
</tr>
<tr>
<td>DM2</td>
<td>3.86</td>
<td>1.83</td>
<td>2.23</td>
<td>0.59</td>
<td>0.26</td>
<td>0.35</td>
</tr>
<tr>
<td>DM5</td>
<td>2.61</td>
<td>1.90</td>
<td>1.87</td>
<td>0.42</td>
<td>0.28</td>
<td>0.27</td>
</tr>
<tr>
<td>DM3</td>
<td>4.53</td>
<td>3.07</td>
<td>1.35</td>
<td>0.66</td>
<td>0.49</td>
<td>0.13</td>
</tr>
<tr>
<td>DM9</td>
<td>1.28</td>
<td>3.29</td>
<td>2.14</td>
<td>0.11</td>
<td>0.52</td>
<td>0.33</td>
</tr>
<tr>
<td>DM7</td>
<td>1.58</td>
<td>2.42</td>
<td>2.27</td>
<td>0.20</td>
<td>0.38</td>
<td>0.36</td>
</tr>
<tr>
<td>DM10</td>
<td>1.62</td>
<td>2.66</td>
<td>2.63</td>
<td>0.21</td>
<td>0.42</td>
<td>0.42</td>
</tr>
<tr>
<td>DM8</td>
<td>2.44</td>
<td>3.29</td>
<td>1.94</td>
<td>0.39</td>
<td>0.52</td>
<td>0.29</td>
</tr>
</tbody>
</table>
Normal tolerance limit of amplification factor in logarithm of the dummy satellite in the range: 1000-2000Hz

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<th>Resonant frequency[Hz]</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Horizontal (x)</td>
</tr>
<tr>
<td>Average</td>
<td>1798.2</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>864.7</td>
</tr>
<tr>
<td>Lower value</td>
<td>354.1</td>
</tr>
<tr>
<td>Upper value</td>
<td>3242.2</td>
</tr>
<tr>
<td>Average</td>
<td>0.33(2.1)</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.68(4.8)</td>
</tr>
<tr>
<td>NTL (Min)</td>
<td>-0.81 (0.15)</td>
</tr>
<tr>
<td>NTL (Max)</td>
<td>1.47(29.5)</td>
</tr>
</tbody>
</table>

- No amplification in 1000-2000Hz range.
- We simply take the amplification is uniform at unity between 1000Hz and 2000Hz
Calculation of vibration transmittance apart from resonant frequency range

\[ \tau = \sqrt{\frac{1 + (2\xi\kappa)^2}{(1 - \kappa^2)^2 + (2\xi\kappa)^2}} \]

\[ \kappa = \frac{f}{f_0} \]

\[ Q \approx \frac{1}{2\xi} \]

- \( \tau \): Transmittance, \( \xi \): damping rate, \( \kappa \): frequency rate, \( f \) and \( f_0 \): base and resonant frequency.

- In our case, transmittance is equal to the amplification factor.

- For calculating the gradient value from 270Hz to higher, amplification factor and frequency were extrapolated until the amplification factor became 1.15.

- The amplification became 1.15 at 390Hz. Assumed \( \xi = 0.1 \).