SHOCK QUALIFICATION METHODS FOR EQUIPMENTS

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ABSTRACT

The currently used process for equipment qualification to shock uses Shock Response Spectra (SRS) calculated from acceleration test measurements at spacecraft level. This method looses some information, especially concerning the shock duration. Moreover the final specification is usually an envelope of one or more SRS, resulting in a simplified SRS.

The test benches used to qualify the equipments generate particular excitation, which may be incompatible with the specified SRS shape. This can lead to either under- or over-qualification.

Thus this shock qualification process is not completely satisfactory and could be improved. A CNES-funded R&D activity has been lead by EADS Astrium in this way.

Real shock acceleration measurements at equipment interfaces have been compared to acceleration measurements during their qualification shock test in order to point out their differences.

Two new data processing tools have been developed by RMS. These tools were designed to give a simple but reliable description of the shock signal. One of them has been chosen for the last step of the study. The aim is to use this developed tool to define adequate specifications.

1. A CRITICAL APPROACH OF THE CURRENT METHOD

This part is based on a comparative study between the real shock environment at S/C level and the qualification shock environment.

1.1 Methodology

The shock environment at system level comes from measurements achieved on the Structural and Thermal Model STM3000 in 2001 at Intespace facilities. Four different shock events were measured: Clampband release, Shogun (Shock Generator Unit), Ariane 5 Fairing Separation and Ariane 5 VEB (Vehicle Equipment Bay) Separation.

Four equipments were chosen to have a panel of different masses and dimensions: the smallest weights 7.5 kg and has a typical interface dimension of 150 mm whereas the biggest weights 25 kg and has a typical interface dimension of 400 mm. All of them are located in the lowest part of the structure where the shock levels are quite high.

These equipments have been tested on the same mechanical shock test bench with different input according to their own shock qualification levels given by the mean of Shock Response Spectra (SRS).

![Fig. 1. Shock qualification of an equipment on a mechanical shock test bench](image)

The comparison between qualification and real environment at S/C (spacecraft) level has been made using directly the acquired time histories, or using data processing tools to study in the frequency domain (SRC techniques with varying amplification factor Q) or the time-frequency plane (Morlet wavelets techniques).

The frequency range of interest extends from 100 Hz to 10 kHz and has been arbitrarily divided in LF (Low Frequency) from 100 to 800 Hz, MF (Medium Frequency) from 800 Hz to 2 kHz and HF (High Frequency) from 2 kHz to 10 kHz.
1.2 General characteristics of the system environment

Shock measurements at system level have a very complex frequency content over the entire frequency range. It is the superposition of two physical phenomena.

The response is due to local phenomena such as a modal response of the equipment itself or of its supporting plate. Such components are highlighted by responses on a given equipment at constant frequencies for different shock events. An example is given in Fig. 2, where the encircled areas show common frequencies for different shock sources.

Fig. 2. Local responses at system level (same response location for different tests)

The response is also due to components that propagate directly from the S/C-launcher I/F (interface). Therefore such components can be found at different locations for a given shock source. An example is given in Fig. 3 where the dotted lines show precise frequencies common to different places in the S/C.

Fig. 3. Propagation components at system level (different response location for the same test)

The measured acceleration at S/C level are therefore a combination of these two phenomena. This explains the abundance of responding frequencies, which cover the entire frequency band, and therefore the complexity of the environment at system level.

A typical response at system level can be formally described as follows.

In LF range, the global levels and the main responding frequency bands are mainly driven by the characteristics of the excitation. The precise frequencies and levels are rather due to local phenomena. These components are quite long, lasting for 40 to 50 ms. There are usually several successive pulses at neighbouring frequencies that contributes to a response in a frequency band.

In MF range, the levels are usually high. They are directly induced by the excitation at the launcher I/F which main component is in this frequency range. The signal is composed of several pulses of varying frequency typically lasting for 40 to 50 ms. Moreover the magnitude profile of the succeeding pulses may be either descending or ascending then descending. The response is thus far more complex than what is generally admitted.

In HF range, the signal is composed of a complex superposition of very short pulses of varying frequencies. The HF components are lasting for a shorter time than the other frequency ranges, typically for 10-15 ms. Their magnitude is usually rather low compared to MF range levels as they are well filtered during the propagation throughout the structure.

Two examples of such a decomposition can be seen in Fig. 4.

Besides, the initial profile of a response at system level is always progressive. Consequently the maximum is not reached during the very first oscillations of the time history, which can be seen in Fig. 4.

1.3 General characteristics of the qualification environment

Shock measurements on a mechanical shock test bench present easily recognisable time history shapes and frequency compositions.
The signal is mostly dominated by high frequency components, especially for in-plane excitation. The only LF responses appear for out-of-plane excitations. They appear pretty well defined in frequency compared to what has been observed at system level. An example of the frequency content of a response to a mechanical shock test bench is given in Fig. 5.

Fig. 5. Typical response to a mechanical shock test bench excitation (in-plane at the top, out-of-plane at the bottom)

The density of responding frequencies also appear largely lower than for a measurement at system level, even in HF range.

Contrary to what has been observed at system level, the beginning of the acceleration time history shows a very steep slope corresponding to the impact of the hammer on the anvil. As a result this kind of shock can be easily described:

- The response to an in-plane excitation looks like HF components superimposed to a half-sine MF pulse. An example is given in Fig. 6.

Fig. 6. Response to an in-plane excitation and its half sine model for LF and MF range

- The response to an out-of-plane excitation looks like HF components superimposed to several (typically 3 to 5) synchronous damped sine (usually called Prony modes) in LF and MF ranges. An example is given in Fig. 7.

Fig. 7. Response to an out-of-plane excitation and two damped sines models for LF and MF range
1.4 Comparison

The comparison between the two environments is summed up in Table 1.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>At system level</th>
<th>At qualification level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>Long signal</td>
<td>Short signal</td>
</tr>
<tr>
<td>Magnitude</td>
<td>Low maximum</td>
<td>High maximum values</td>
</tr>
<tr>
<td>Frequency range</td>
<td>Mostly MF (1-3 kHz) and LF (&lt;1 kHz)</td>
<td>Mostly HF</td>
</tr>
<tr>
<td>Density of responding frequencies</td>
<td>Very high over the entire frequency range</td>
<td>Very low in LF or MF ranges, high in HF</td>
</tr>
<tr>
<td>Damping of the identified modes</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Time-frequency</td>
<td>Successive pulses with different magnitude schemes</td>
<td>Synchronous pulses at the beginning of the signal</td>
</tr>
</tbody>
</table>

Table 1. Comparison between system and qualification environments

2. AN ALTERNATE METHOD TO REPLACE SHOCK RESPONSE SPECTRA

In the frame of this study two new data processing tools have been developed by RMS. The aim was to have a tool that could successfully describe the complexity of a pyrotechnic shock with only a limited number of parameters. The global scheme relies on a superposition of several pulses with different arrival dates. The two methods differ by the model adopted for the description of an individual pulse. The first method is based on a second order autoregressive method (AR) while the second one is based on Prony modes (i.e. damped sine) with limited bandwidth (LBP).

Both methods have been tested. One of them has been chosen in order to be intensively analysed and to see its applicability in terms of specification tool. The AR method proved to be not mature enough whereas the LBP method gives interesting results. As a consequence only the LBP method is presented in the following paragraphs.

2.1 Methodology

A LBP mode is the convolution of a damped sine with a Gaussian pulse. The Gaussian pulse is used to limit the frequency bandwidth of the Prony mode.

A LBP model is described using the following parameters:
- the number of modes n;
- the Gaussian frequency bandwidth parameter k_p;
- the magnitude of the LBP modes (A_i)_{i=1,n};
- the frequencies of the LBP modes (f_i)_{i=1,n};
- the damping of the LBP modes (ξ_i)_{i=1,n};
- the arrival dates of the LBP modes (t_i)_{i=1,n}.

The extraction of the LBP modes uses a deflation algorithm which tends to prefer energetic high frequency components. A specific method has been developed to avoid this: it consists in reducing a signal to its main components over the global frequency band. This step is done in the time-frequency plane which allows to isolate properly the main components.

![Image](CU131Z_extrait_BF_rsp_W)

Fig. 8. Reduction of a signal to its main components

Such a method allows to describe a complex pyrotechnic shock environment with only 6 to 15 LBP modes (25 to 61 parameters). An example is given on Fig. 9. and Fig. 10., showing the acceleration measurement and its model in the frequency-time plane and in term of SRS.

![Image](CU131Y_extraction_RSP_W)

Fig. 9. Wavelet diagram for pyroshock measurement at system level (blue curve and top diagram) and its model using 12 LBP modes (red curve and bottom diagram)
Fig. 10. SRS for a pyroshock measurement at system level (blue curve) and for its model using 12 LBP modes (red curve)

The model achieve to represent all the main feature of the measurement, covering a wide frequency bandwidth, as seen on Table 2. The main innovation of this method is that it takes the sequential arrival of the frequency components. Thus the model respect the time-frequency structure of the measurement, which means that it preserves its physical content.

<table>
<thead>
<tr>
<th>Mode #</th>
<th>Frequency (Hz)</th>
<th>Damping (%)</th>
<th>Normalised magnitude</th>
<th>Arrival date (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>586</td>
<td>1.05</td>
<td>6.12</td>
<td>0.0026</td>
</tr>
<tr>
<td>2</td>
<td>1130</td>
<td>4.91</td>
<td>1.00</td>
<td>0.0119</td>
</tr>
<tr>
<td>3</td>
<td>1370</td>
<td>4.85</td>
<td>5.18</td>
<td>0.0003</td>
</tr>
<tr>
<td>4</td>
<td>1540</td>
<td>3.04</td>
<td>2.89</td>
<td>0.0006</td>
</tr>
<tr>
<td>5</td>
<td>2140</td>
<td>2.98</td>
<td>2.74</td>
<td>0.0013</td>
</tr>
<tr>
<td>6</td>
<td>2460</td>
<td>3.04</td>
<td>2.13</td>
<td>0.0026</td>
</tr>
<tr>
<td>7</td>
<td>3420</td>
<td>4.11</td>
<td>15.97</td>
<td>0.0043</td>
</tr>
<tr>
<td>8</td>
<td>4440</td>
<td>1.89</td>
<td>13.10</td>
<td>0.0013</td>
</tr>
<tr>
<td>9</td>
<td>5280</td>
<td>3.98</td>
<td>6.81</td>
<td>0.0023</td>
</tr>
<tr>
<td>10</td>
<td>5540</td>
<td>3.72</td>
<td>15.88</td>
<td>0.0007</td>
</tr>
<tr>
<td>11</td>
<td>5570</td>
<td>1.91</td>
<td>-8.58</td>
<td>0.0008</td>
</tr>
<tr>
<td>12</td>
<td>6920</td>
<td>2.62</td>
<td>6.06</td>
<td>0.0008</td>
</tr>
</tbody>
</table>

Table 2: Model associated parameters

2.2 Influence of the model parameters

To get a better knowledge of this new tool, a campaign of analyses has been lead to study the influence of the parameters of a given model.

The Gaussian frequency bandwidth global parameter influences the shape of an individual modes (Fig. 11). The higher the parameter value is, the higher is the frequency bandwidth and the higher is the maximum level on time history.

In terms of SRS, this impacts the level at high frequency (maximum level of the time history) and the slope at lower frequency than the mode frequency: the higher the Gaussian frequency bandwidth parameter value is the lower is the slope, which means the closer to damped sine SRS slope it is (Fig. 12)

Fig. 11. LBP shape wrt. Gaussian frequency bandwidth parameter

Fig. 12. LBP mode SRS wrt. Gaussian frequency bandwidth parameter

The influence of magnitude is intuitive: it does not modify the time-frequency content of the model in any way. The model allows to modulate the effect of a magnitude variation over a parameter such as frequency.

The damping influences the duration of the signal. In terms of SRS, the effect is globally similar to the effect of magnitude except that it is localised in the vicinity of the frequency of the considered mode. The higher is the damping, the shorter is the signal duration and the lower are the SRS levels.

To study the influence of the frequency, a random variation of frequency has been introduced in the model (±5%). This limited variation does not change a lot the time-frequency structure of the signal. However it may have an impact on its SRS levels, especially if the model has several modes at close frequencies. An example of this variability is shown on Fig. 13.

Fig. 13. SRS variability due to random frequency variation

The arrival date, the main innovation of the model, has a very complex role in the model, which cannot be mathematically explained in a simple way. To grasp its influence, several methods have been tested:
Synchronisation of all the modes. The arrival date is then just an identification parameter, as the sequential arrival is just put aside. It results in a simplified model showing a simplified SRS with surprisingly limited variations of levels compared to the original model (Fig. 14). Such a method results in a widely changed time-frequency structure which is no more physical. However the excitation duration for each mode remains physical as the modal parameters are quite precisely identified thanks to the new tool; this still constitutes an improvement compared to the standard SRS shock characterisation tool and may explain the correct conservation of SRS levels.

Dilatation / condensation of the temporal distance between two modes. It consists in multiplying this temporal distance by a given factor without modifying the arrival order. This shows the high impact of the temporal superposition of the modes: the SRS levels may be modified by -2.5/+5 dB for a multiplication/division by a factor 2 of their temporal distance.

Random variation of the arrival dates. A ±10% random variation of the relative time distances has been introduced on the model. The time-frequency structure of the signal is highly changed. This study highlights the great impact of this parameter on the signal (up to 12dB of variation on the main response peak in term of SRS). The driving parameter proved to be the relative phasing of the modes: a constructive summation can give significantly higher levels than a destructive summation (see Fig. 15).

As a conclusion, the new parameter of arrival date has a great influence on the model on its temporal structure but also on its frequency response seen by the mean of SRS. Nevertheless no simple rule drive this influence.

2.3 Using the LBP method as a specification

A pyroshock acceleration measurement at system level can be correctly modelled with a limited numbers of LBP modes. Such a formulation respects the measured temporal structure which is a major test compared to the previously used representation.

Using a tool as specification tool requires to be able to take margins and to combine elementary specifications to derive a global one. As a consequence it is necessary to study the LBP tool ability in these fields: taking margins and combining LBP models just as specification could be combined. These two aspects are tackled in this part.

The margin aspect is directly linked to the influence of each parameter as it has been presented previously. In order to have a meaningful link to the actually used SRS method, SRS has been widely used to evaluate the obtained margins. As SRS describes the response to a signal, it is interesting to see it as a margin validation tool.

Taking margins in amplitude or in damping is quite simple: it consists in multiplying the required parameter by a given factor, globally for the entire model or locally for chosen modes. The margin are taken directly on the individual modes – which means in a discrete way. As the SRS levels at a frequency are also due to neighbouring frequencies, the margin calculated on the SRS is never the required margin on the modes. An
example where a magnitude margin has been defined on the LBP modes by frequency ranges is given in Fig. 16.

![Fig. 16. Magnitude margin by frequency band](image)

Taking margin in frequency is more complex than for the current method as frequency is a discontinuous parameter in the LBP model. The idea to take margins on a given mode frequency is described hereafter: it consists in duplicating the mode as many times as needed to cover the required frequency uncertainty, while dividing their magnitude to keep a constant energy in the signal. An example is given in Fig. 17.

This solution appeared to be feasible and efficient. Nevertheless it is needed to precisely correlate the number of required modes to the desired frequency uncertainty in order to reach a robust method. Besides there is an impact over the entire frequency band in terms of SRS, which is not mastered.

![Fig. 17. Frequency margin of ±20% by mode duplication](image)

As there is no simple rule to describe the effect of an arrival date variation on the signal, there is no obvious way of taking margins on this parameter. Moreover it is important to keep the temporal structure of the signal as it is one of its main physical property.

The last point concerns the combination of LBP models. The idea is to be able to combine LBP models as SRS specification are combined for different situations such as:

- Case 1: Combining specifications at the same point for the same excitation in different response directions (for instance in-plane specification);
- Case 2: Combining specifications at different points for the same excitation (a given equipment located at different places on the S/C);
- Case 3: Combining specifications at the same point for different excitations.

The main difficulty comes from the way to combine LBP models in time, as this dimension is a new feature in the description of a shock environment. Two methods have been studied to combine such models: juxtaposition or synchronisation of 2 LBP models.

The juxtaposition method is the simplest and the more robust method. It consists in joining side by side the two considered time histories, keeping the time interval between them sufficient so that they do not interact with each other. An example is given in Fig. 18.

![Fig. 18. Temporal juxtaposition of 3 LBP models](image)

The main advantage of this method is that there is no loss of information and the time-frequency structure of each individual excitation is conserved. Therefore it is well adapted to the 3rd case of combination (as exposed above) but its applicability is more disputable for the two other cases. Its main drawback is that such a juxtaposed model can easily become hard to manage as the number of parameters increases with the number of juxtaposed models.

The second method takes advantage from the observed fact that a synchronised model remains very similar to the original model in terms of SRS (see 2.2). A first step consist in simplifying the global PBL model: the prevailing modes are selected by frequency range, using SRS as a criterion. This allows reducing the number of modes by a factor 2. The second step is to synchronise all the modes, setting their arrival date to a common value. An example is given in Fig. 19. The studied case is the same than the previous so that Fig. 18. and Fig. 19. are comparable.

![Fig. 19. Synchronisation of the reduced LBP models](image)
In order to evaluate the difference between the two methods the SRS of the two resulting models have been compared (Fig. 20.). This comparison shows limited difference, despite the loss of physical time-frequency content.

Another method could consist in phasing the modes so that all temporal maximum values occur at the same time. This would result in an overestimating combination with unknown margins. In more specific cases, such as the 1\textsuperscript{st} and 2\textsuperscript{nd} cases of model combination (as presented previously), some similarities between the individual LBP models could be expected as there is either a common excitation and/or a common location in the S/C. It could be interesting to take advantage from these expected similarities to define a combined model. However it is difficult to identify similarities with a great confidence, which makes such methods difficult to implement.

3. CONCLUSION

This CNES-funded R&D activity lead by EADS Astrium has shown the limits of the current method of shock qualification methods for equipments. Comparing qualification measurements and real shock measurement at system level, fundamental differences in shock duration and time-frequency have been pointed out.

To provide alternative methods a new data processing tool has been developed by RMS. Based on a multipulses damped sine scheme called LBP model, it brings an adequate description of a shock measurement especially in the temporal domain. Such a shock measurement at system level can therefore be described with about 6 to 15 pulses. A wide analysis has been lead to characterise a LBP model and especially to identify the influence of the model parameters. Finally, specific aspects of a potential use of the model as a specification toll have been studied such as margins and combination of LBP models.

This tool proves to be an efficient and powerful tool to characterise shock measurements. It could be used as a specification tool, even if this needs further studies to refine and standardise the method.