Advances in Aircraft and Spacecraft Science, *Vol. 5, No. 2 (2018) 177-186*
DOI: https://doi.org/10.12989/aas.2018.5.2.177

Transient testing from LV / SC coupled analysis by new shock synthesis

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(Received November 8, 2016, Revised September 9, 2017, Accepted October 4, 2017)

Abstract. This paper deals with the idea to replace the usual high-level sine sweep test on shaker at system level, very severe, by a low level one completed by a transient test in the same configuration, in order to be more representative of the real environment, thus limiting over testing and improving the payload comfort. The problem of the transient test specification is first discussed. The proposed solution is to derive from LV/SC coupled analyses a shock response spectrum corresponding to two damping ratios. Then, the question of adequate shock synthesis is tackled. A new method with a given spectrum is considered for better potential and accuracy than the usual wavelets. A campaign on the Intespace bi-shaker devoted to system level showed its capability to perform the resulting test with one spectrum. First investigations to extend this approach to two spectra are in progress.

Keywords: SRS; shock synthesis; transient testing; fast sine sweep

1. Introduction

Spacecraft structures need to be qualified with respect to their dynamic environments. Various events can provide significant levels which must be taken into account. To cover the low frequency range, the current practice at system level is the sine sweep test which requires the use of notching to avoid over testing in the vicinity of the main resonances (see discussion in Girard *et al*. 2012).

This practice is appropriate to cover sustained vibrations, but not the transients which generate the most severe levels for the spacecraft primary structure. Replacing one environment by another whose nature is very different always involves risks related to the assumptions used to define the equivalence.

In order to be more representative of the real environment, the idea here is to replace the usual high-level sine sweep test on shaker at system level by a low level one covering residual sustained vibrations (noise), completed by a transient test in the same configuration to cover the real expected transients. This should limit over testing in the low frequency range, thus improving the payload comfort.

Some illustrations are given in Sec. 2 to show the gap between real and simulated environments in the current practice. The problem of the transient test specification is then discussed in Sec. 3, followed by the question of adequate shock synthesis in Sec. 4, and test results obtained on the

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http://www.techno-press.org/?journal=aas&subpage=7 ISSN: 2287-528X (Print), 2287-5271 (Online)

Intespace bi-shaker devoted to system level in Sec. 5.

2. Real and simulated environments

Concerning the real environment of a spacecraft structure, let us consider an illustrative example using the first qualification flight of the ARIANE launcher which took place on Dec. 24 1979 (see ESA-ESTEC, ECSS-E-HB-32-26A 2013 § 5). Fig. 1 shows the acceleration time history at the LV/SC (Launch Vehicle/zSpacecraft) interface during the 1^{st} and 2_{nd} stage (N2O4/UDHM) flight segments in the axial and lateral directions. Only the lower and upper envelopes are plotted in order to simplify the responses.

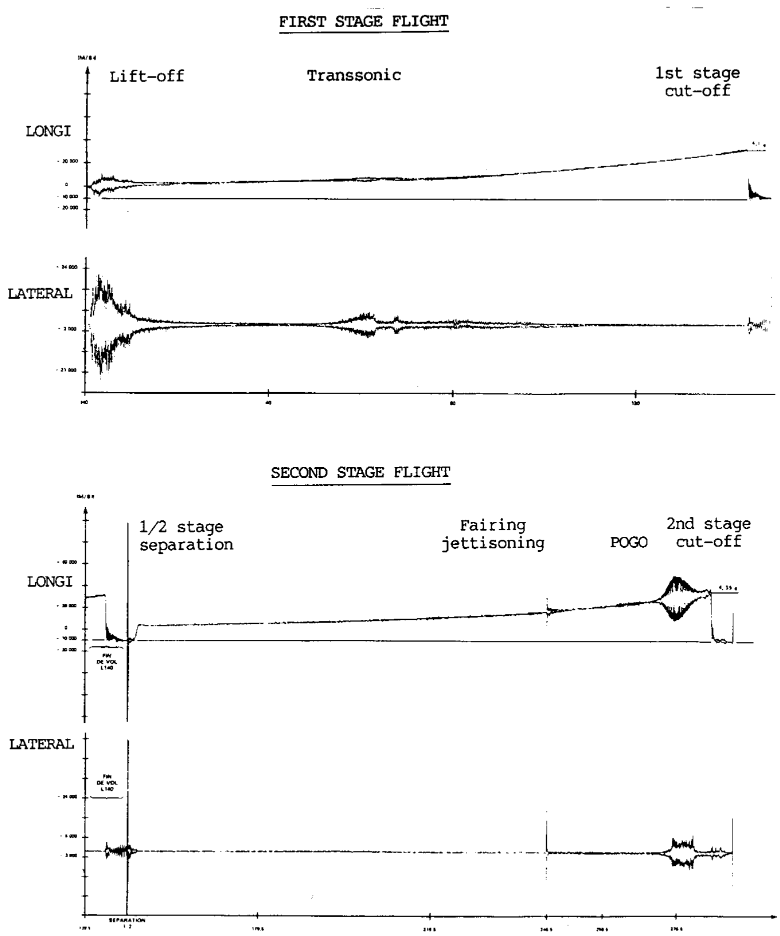


Fig. 1 The LV/SC Flight Interface Acceleration

All the possible regimes are present. We can distinguish:

• Quasi-static regime-The axial acceleration which slowly increases due to fuel consumption.

• Harmonic regime-The POGO effect (PrOpulsion Generated Oscillations) at the end of the 2nd stage flight (see zoom in Fig. 2) due to an interaction between the structure, the hydraulics and the propulsion. It excites the first axial mode of the launcher whose frequency slowly increases, again due to fuel consumption, resulting in a swept sine from 28 to 32 Hz over a period of approximately ten seconds. The anti-POGO system was intentionally deactivated during this flight in order to observe this effect, making this example quite unique.

• Transient regime-Comprising the thrust transients lasting several tenths of seconds (the most severe occurring at engine burn-out) and the separation shocks (stages and fairing) lasting several milliseconds.

• Random regime-t lift-off and transonic flight lasting between 10 and 20 seconds. With a frequency content of up to 2000 Hz, this corresponds to tens of thousands of (non-reproducible) oscillations, therefore precluding a deterministic analysis.

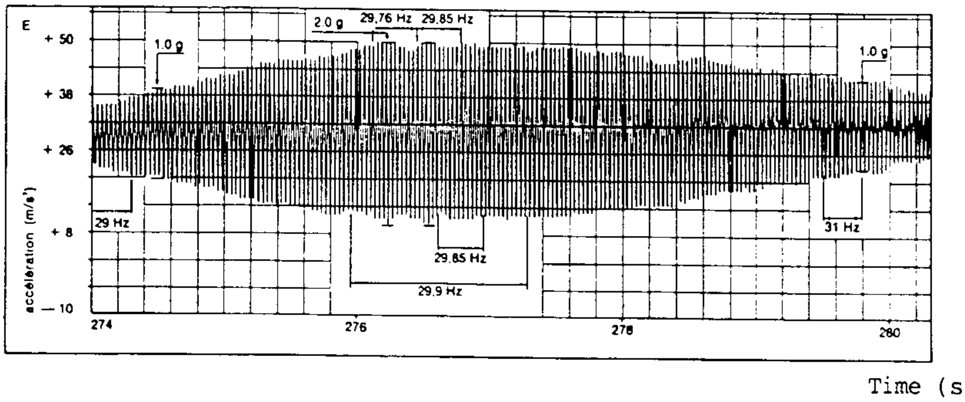


Fig. 2 Zoom on POGO effect

In the present context, it is clear that sine testing in the low frequency range is appropriate only for noise and residual POGO if any, lasting several seconds or more. The transient events such as thrust transients, having a limited number of oscillations, can be represented by a sine only using equivalence. The current use is the well-known concept of the shock response spectrum (SRS) which is by definition the maximum response of a 1-DOF system as a function of its natural frequency and for a given damping ratio ξ. In this case, the equivalent sine is approximately given by the SRS divided by the factor $Q = 1/(2\,\xi)$. Note that it depends closely on the choice of ξ.

This enables us to compare LV/SC coupled analysis results with the sine levels applied during qualification tests. An example is given in Fig. 3 (from ESA-ESTEC, ECSS-E-HB-32-26A 2013 § 6).

The difference between the coupled analysis results and the sine test actual profile sine illustrates the potential profit of a transient test for the payload qualification. Except in some frequency bands in the vicinity of the main resonances controlled by the notching procedure, the margins are unnecessarily high. This is why it is worthwhile to investigate transient testing.

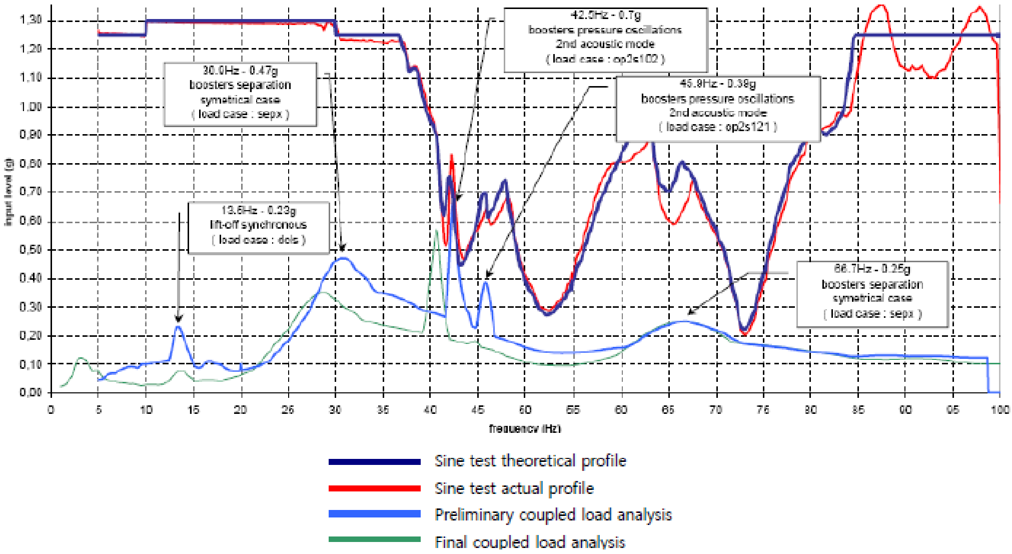


Fig. 3 Example of Ariane 5 LV/SC longitudinal acceleration profile (Q = 20)

3. Transient test specification

For transient testing, the first problem to be solved is the test specification. The solution generally adopted is the SRS presented in the previous section. It contains directly the notion of severity required to elaborate specification and it allows envelopes to cover several transients. One of its main drawbacks is to be irreversible, contrary to Fourier transform: a given SRS relates to an infinity of time histories. This is due to the fact that it provides only an amplitude, without a kind of phase which can be interpreted here by the notion of duration: for example, any SRS can be recovered by an equivalent sine sweep (just divide by the Q factor) lasting several minutes instead of a few seconds or less!

This intentionally exaggerated example clearly demonstrates the potential danger of using the SRS without precaution. As said in introduction, replacing a transient by a sine involves risks related to the assumptions used to define the equivalence, in particular the Q factor in addition to the 1-DOF system assumption.

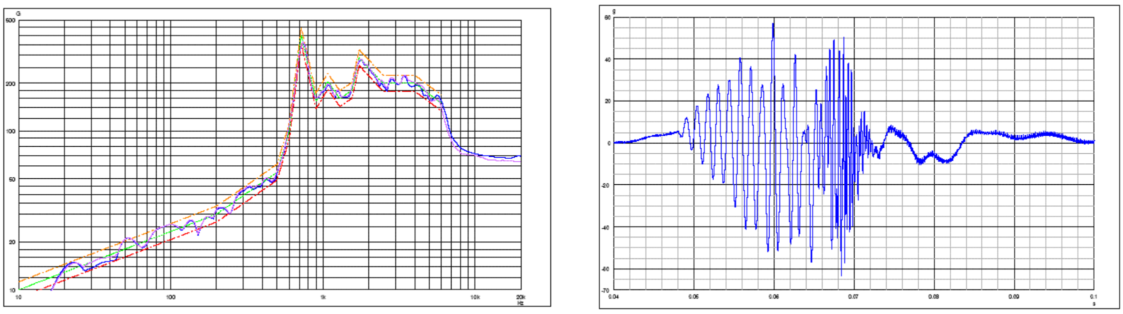
This risk can be tempered by complementing the SRS with additional information about the environment in order to limit the degree of irreversibility, using for example durations (see Girard *et al*. 1998). In the present context, one simple idea is to consider two values of damping since the LV/SC coupled analysis with various load cases provides responses transformed in SRS related to two Q factors (one SRS for each Q factor). These two spectra have now the same amount of information contained in the amplitude and phase of the Fourier transform. It should therefore be possible to derive a *nearly* reversible transformation in order to obtain a more representative transient with respect to the actual environment, in terms of levels and durations (*nearly* only, because the two spectra have probably a certain amount of redundancy).

In this case, the transient test specification will consist of a SRS related to two Q factors derived from envelopes of all the SRS provided by all the transient events taken into account by the LV/SC coupled analyses, possibly weighted by an adequate safety factor derived from the Project safety strategy.

4. Shock synthesis

After the elaboration of the test specification in terms of SRS, the problem is now to perform adequate shock synthesis, i.e., to elaborate a unique time history corresponding to the two spectra.

For a unique given spectrum, this inverse problem can be solved more or less accurately by several techniques (see for example Lalanne 2009). The most widely used is the wavelet technique based on the combination of waveforms such as damped sines, or sines modulated by half-sines. For example, the SRS given in Fig. 4(a) can be synthesized by 37 wavelets as shown, each one with a given frequency, amplitude of the envelope, number of oscillations and delay, providing the time history given in Fig. 4(b).



(a) Specified (tolerances ± 1 dB) and synthesized SRS (b) Synthetized time history

Fig. 4 Example of shock synthesis using wavelets

As seen on the synthesized SRS, each wavelet covers a relatively narrow frequency band. The ±1 dB tolerances require a high number of parameters, generating unavoidable oscillations round the specified SRS. The synthesized time history has a complex shape probably very far from the time history having generated the specified SRS, particularly with regard to the durations.

For two spectra at the same time, as far as we know, this problem has not been tackled. The previous approach is probably inefficient because of too many parameters involved, showing the need of a new method.

An idea for a more efficient shock synthesis is to perform a fast sine sweep. This is not a new idea (see Lalanne 2009) but in our opinion, the capabilities of this approach have not been completely investigated.

With a given spectrum, a simple strategy is to fix the duration for the time history, to derive the corresponding rate for a logarithmic sine sweep for example, and to adjust the amplitude versus time to provide the specified SRS. In this case, the order of magnitude of the sweep rate is the octave per second, instead of the octave per minute for a traditional logarithmic sine sweep, to obtain durations of about a second from 5 to 100 Hz.

Of course, some reserves have to be made with this approach. For example, the SRS of a half-sine cannot obviously be synthesized by a sine sweep of the same duration. A solution may be found only if the synthesized time history can have a reasonable number of oscillations. In the context of LV/SC coupled analysis, as the actual time histories are the responses of the composite including the contributions of its free eigenmodes in the considered frequency range, there should be no problem. In this case, the approach simply comes to reorder the frequency contents of the original environments.

While waiting for an extension to two spectra, a campaign on the Intespace bi-shaker devoted to system level (two 160 kN) was undertaken to show its capability to perform a fast sine sweep test.

5. Shaker tests results

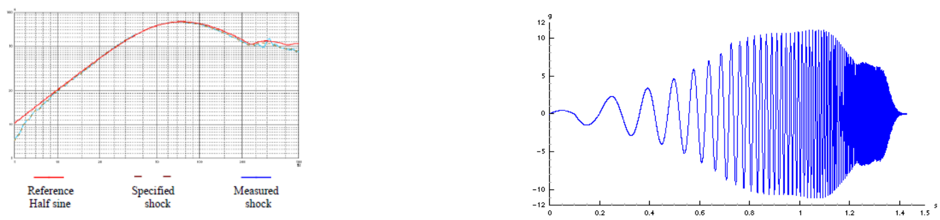
A first real test was first carried out on the Intespace bi-shaker aiming at synthetizing a time history equivalent to a half sine in terms of its SRS. The specification and limitations were the following ones:

- Half sine: 50 g-11 ms
- SRS computed with a factor Q = 10 between 5 Hz and 500 Hz
- Tolerated time history duration: roughly 1 second excluding pre and post-shocks
- Shaker limitations:
    - Maximum acceleration: A_{max}=11 g
    - Maximum velocity: $\dot{u}_{max} = 0.9\ ^{m}/_{s}$
    - Maximum displacement: u_{max}=22 mm

Fig. 5 Intespace 320 kN bi-shaker in empty vertical configuration

The shaker was in empty vertical configuration (see Fig. 5), the goal of this test being to validate the methodology with one spectrum, the feasibility and the procedure for such a test. Even if the time history generated corresponds to a fast-swept sine, it should be considered as a transient signal; thus, the piloting system was used in transient mode.

Fig. 6(b) displays the synthetized time history, including pre-shock (first oscillation) and post-shock (decaying sinusoïd). The duration of this waveform was around 1.2 second excluding pre-shock and post-shock. The reason for the introduction of pre and post-shocks lies in the necessity to maintain the resulting velocity and displacement within the capabilities of the shaker, as mentioned previously.

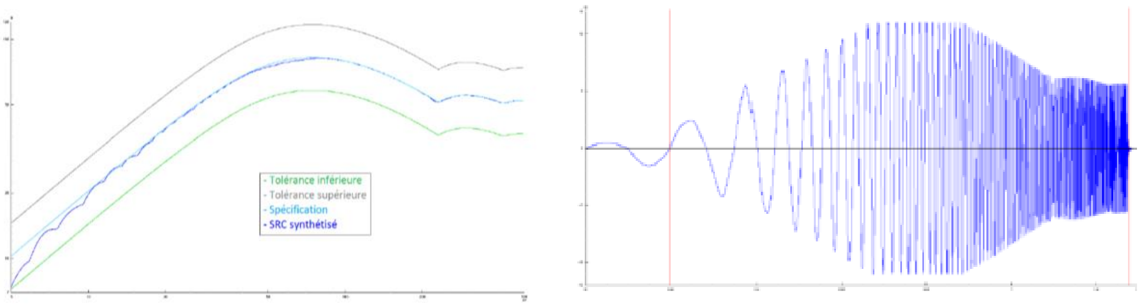


(a) Computed SRS (b) Synthetized time history

Fig. 6 Half sine: Synthetized time history and associated SRS without specimen

Fig. 6(a) displays the SRSs associated to the generated time history, to the measurement on the shaker and to the reference, which are quite close. In this case, the optimization process (improvement of characteristics of the transient waveform) was not included in the routine generating the time history; this can thus explain the slight fall-down at the end of the frequency band. Nevertheless, the results remained within reasonable tolerances and were quite encouraging.

The introduction of the optimization iterative loop yielded the synthetized time history displayed in Fig. 7(b); the associated SRS are displayed in Fig. 7(a). Note that, for that purpose, the condition on the waveform duration was relaxed to 2 seconds. The tolerances seen on Fig. 7(a) have been set to +/-3 dB.



(a) Computed SRS (b) Improved synthetized time history

Fig. 7 Half sine (50g – 11 ms): Improved synthetized time history

This improved waveform well respects the tolerances and fits better the specified SRS, in particular at high frequencies. Note that the time history duration is now 1.55 second, excluding pre and post-shocks, which does not extend the waveform quite significantly and remains reasonable. This SRS computed from the synthetized waveform remains within +/- 1 dB tolerances with a good margin except at very low frequencies where the rebounds observed deviate slightly from these tolerances. The existence of these rebounds decreases with increasing frequency or shock duration, and can be explained by the relatively small number of oscillations at these frequencies.

However, in the context of low frequency transient testing from LV/SC coupled analysis, this phenomenon should be attenuated and moreover, the very beginning of the frequency band of interest is not the area to particularly focus on.

The comparison between Fig. 4(a) (synthesis by wavelet technique) and Fig. 7(a) (new approach) confirms the efficiency of this new method for shock synthesis. Moreover, the elaboration of such a fast-swept sine is quite easier and faster than the wavelet technique, and does not require the experience of the operator.

This time history was not simulated on the bi-shaker but there is no doubt on its reproducibility. A second study case was tackled for a specimen to test in order to synthetize a time history equivalent to another half sine in terms of SRS. One of the main goals of this test lies in the study of the influence of the specimen on the excitation, the former test having been performed in empty configuration.

The specification and limitations were here:

- Specimen mass: 3500 kg

- Half sine: 10 g-16 ms
- SRS computed with Q = 10 between 5 Hz and 500 Hz
- Tolerated time history duration: roughly 1 second excluding pre and post-shocks
- Shaker limitations:
  - Maximum velocity: $\dot{u}_{max} = 0.9\ {}^{m}/_{s}$
  - Maximum displacement: u_{max}=22 mm
  - No limitation on the acceleration as the half sine amplitude is not too high

The specimen was simulated by a dummy composed of an adapter (1400 kg) on which a plate (2400 kg) was fixed, and the Intespace bi-shaker was used in vertical configuration, as shown in Fig. 8. A pilot sensor was installed on the plate.

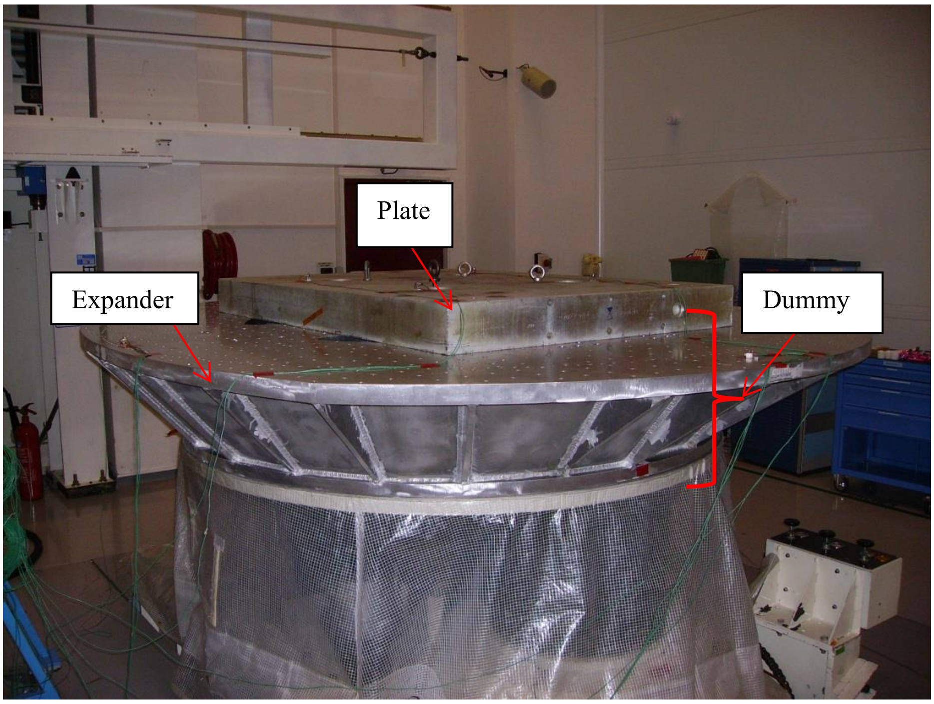


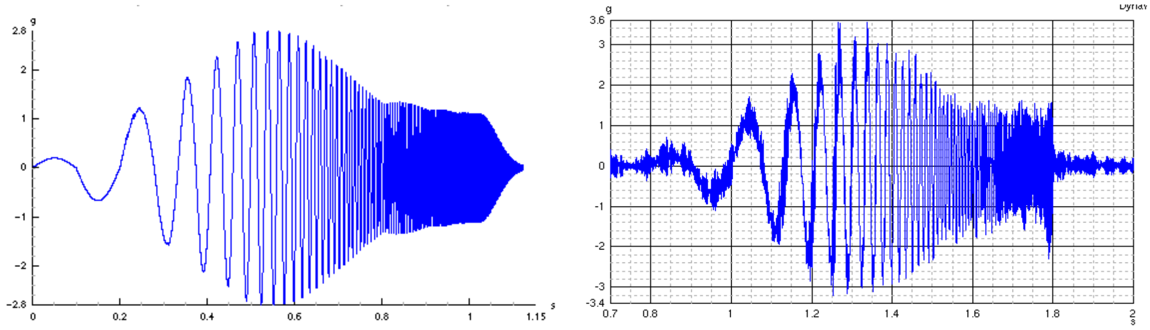
Fig. 8 Test configuration with a dummy

A first "classic" swept sine test between 5 Hz and 500 Hz showed, as expected, the presence of the modes of the expander starting at 250 Hz.

Then, shocks of increasing level were performed starting from -20 dB, with a correction between each shock in order to use the transfer function of the previous shock. At 0 dB, a few additional iterations enabled to limit the gaps below 1 dB.

Fig. 9 displays the specified time history (9(a)) and the time waveform measured on the pilot sensor (9(b)):

The corresponding SRS are displayed in Fig. 10 where the reference SRS (half sine) is plotted in green and the measured SRS (pilot sensor) in blue; red curves are the tolerances at +/-1 dB to the reference SRS:



(a) Specified time history (b) measured waveform on pilot sensor

Fig. 9 Specification and measurement for test on dummy

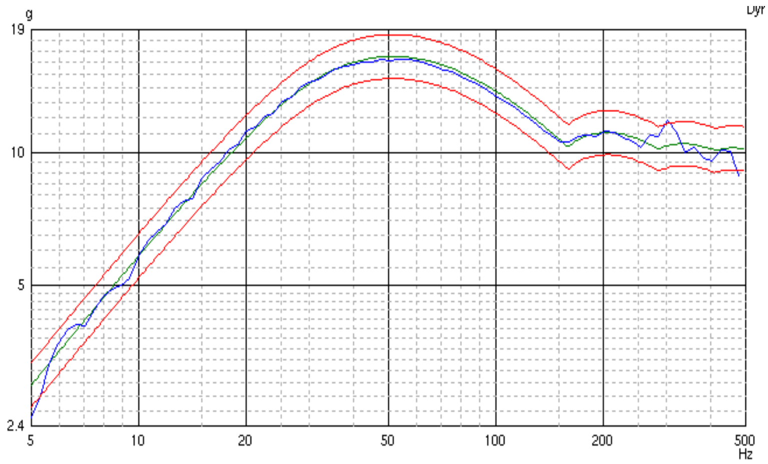


Fig. 10 SRS from test on dummy

The measured time history (Fig. 9(b)) is relatively noisy; this might be due to the dummy which includes a plate of coarse flatness and surface conditions likely to generate slips and/or micro-shocks at high levels. In the context of coupled load analysis at spacecraft level for qualification, such an excitation should be of better quality due to a more linear behaviour of the specimen.

The SRS is well reproduced until 250 Hz where it turns perturbated because of the expander modes, but the gap between the measured SRS and the reference remains clearly within 1 dB tolerances.

As a conclusion for these test campaigns, the objective was just to show the capability of a shaker to perform a fast sine sweep of one or a few seconds corresponding to a given SRS in the usual low frequency range of a spacecraft. In this context, the results are satisfactory, even if the selected SRS were not representative of coupled load analysis results which depend directly on the spacecraft dynamic properties. The next step is now to consider realistic SRS coming from coupled analyses with a given spacecraft.

6. Conclusions

Examining the real dynamic environment of a spacecraft structure shows the interest to replace the usual high-level sine sweep test by a low level one completed by a transient test to cover the real transients.

The transient test specification could be derived from coupled load analysis results providing a SRS related to two Q factors.

As the current methods for shock synthesis are probably inefficient with this kind of data, a new strategy with more potential was investigated: a fast sine sweep considered as a transient.

The feasibility of elaborating this kind of time history related to a given SRS, then performing the corresponding test on shaker, was demonstrated on a simple case, half-sine SRS on a dummy specimen.

The next step is to consider a real spacecraft with its coupled load analysis results providing a SRS related to two Q factors, to derive the corresponding fast sine sweep, and to reproduce it on shaker. The key point is the elaboration of the time history. First investigations are in progress and have shown encouraging results.

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