DYNAMIC TESTS, WHAT'S BEHIND THE CURVES ?

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1. INTRODUCTION

Spacecraft and their components are submitted to several dynamic tests in order to qualify them for the launch or in order to determine their dynamic behaviour. Usual tests are sine sweeps, random tests, acoustic tests, shock tests and micro-vibration tests. The data coming from these tests are often provided to the engineers in a processed form such as acceleration vs. frequency response, Power Spectral Densities (PSDs), Shock Response Spectra (SRS), etc. However, it is of the outmost importance to keep in mind that the raw data coming from dynamic tests are time histories corresponding to the evolution of one quantity (e.g. acceleration, force, strain) with time. The processing of these data may lead to some loss of information that can be detrimental to the interpretation of the results and the understanding of the underlying physical phenomena. It also affects the control of the test itself, which relies on data processing as well. This is illustrated in the following sections by some examples showing that the analysis of the time histories is sometimes necessary to have a complete knowledge of the behaviour of the test specimen.

2. DYNAMIC TEST DATA PROCESSING

The acquisition of data during dynamic tests is made primarily in the time domain. However, the data provided by the test facility to the analysts is most often by default in the frequency domain, after signal processing.

Sensors like accelerometers, strain gauges, load cells and microphones allow to measure the evolution of one quantity with time. It is important to keep in mind that the acquired signal may be affected by a number of measurement errors; for example, sensor or acquisition chain inaccuracy, inadequate location of the sensors, noise, saturation, etc. Those problems are not addressed in this article, except for shocks in Section 6. The effect of digital acquisition system processing is also not discussed in the paper (i.e. sampling rate, anti-aliasing filtering, analogue to digital conversion). The following considers that the measured signals are valid, except for shocks in Section 6. The paper focuses on the information lost due to signal processing from time domain to frequency domain. The typical data processing methods applied for different tests are briefly described below, while examples of the effect of such processing are described in section 3.

Sine tests

Data from sine tests may be processed in different ways. The most commonly used data processing methods to assess the amplitude of the signal are peak (or global), average, RMS and harmonic (also called fundamental or filtered). The main difference is whether only the frequency component at the excitation frequency is considered (harmonic) or components at other frequencies are also considered (see [8] for details). This processing can have a significant impact on the results, especially if the response of the structure is not only at the same frequency as the excitation forcers but includes components at other frequencies (harmonics, high frequencies due to internal shocks, etc). It is of the outmost importance to know what kind of data processing method is used to control the test and what processing is applied to the acquired data delivered to the analysts.

Random and acoustic tests

To allow the control of a random or acoustic test, the power spectral density of the signal is estimated in quasi-real time by the control system on short time samples of signals obtained in the time domain (see details in [11]). From these samples, the corresponding RMS value can be extracted as well. It is important to keep in mind that the size of the time window used by the controller has an impact on both the estimated PSD and the RMS level. A smaller window size will lead to higher variations of these two quantities. The overall PSD and RMS levels provided at the end of the test can also be different if they are computed on the entire time signal (average of a number of time windows), leading to a smoother PSD and a lower RMS level.

Another important feature of random tests is related to the maximum level reached in the time domain compared to the one assessed from the RMS level. The usual assumption is that the maximum level in the time domain hardly exceeds 3 times the RMS level considering that a 3 sigma clipping, in most vibration systems, is usually applied on the random input. However, experience shows that this is an optimistic assumption and it is important to keep that in mind.

Shock tests

During shock tests, short, transient signals with potentially high amplitudes are measured and it is important to ensure that the entire acquisition chain is able to capture them in a reliable way (sampling rate high enough, no saturation, …). The data are often provided in the frequency domain in the form of shock response spectra (SRS) but this processing may mask some problems that could be visible on time histories. Also, the SRS are usually calculated from 100 Hz to 10,000 Hz, masking a low frequency content potentially damaging for the specimen. A lot of work has been done on shock testing and details about the processing of the data and the potential problems are available in [1].

Micro-vibration tests

Micro-vibration tests usually consist in either noise source characterisation or system level test where noise sources excite a sensitive instrument. In both cases, time histories shall be stored and delivered by the test facility in order to perform further investigations. Frequency domain representations of the data (e.g. PSDs, FRFs, peak-hold) indeed provide only a partial view of the data and may not contain all the time history information. In particular, the non-stationary character of some noise sources (e.g. reaction wheel varying speed) cannot be fully represented by pure frequency domain transformations. Waterfall plot (or Short-Term Fourier Transform STFT), which is combining time and frequency representations, is useful to estimate evolution of frequency characteristics with time but its frequency and time resolutions are inversely related to the time window length. On one hand, a good time resolution requires a short window. On the other hand, a good frequency resolution requires a narrow-band filter, i.e. a long window.

In addition, frequency domain data alone do not usually allow to combine rigorously several noise sources together since the statistical distribution of these simultaneous sources cannot be extracted from this representation. Some empirical summation rules are then derived, but most of the time fail to estimate accurately the maximum combined disturbances. It is, therefore, important to keep the time representation since it allows to derive their distribution and therefore understand how they can be combined together.

3. ILLUSTATION OF TIME HISTORY PROCESSING DURING SINE TESTS

The way the sine signals are processed and presented, with one single value per frequency, can lead to very different results, leading to possible incorrect interpretation of the phenomena, e.g. masking unexpected effects. Therefore, the comparison of the signals obtained with different processing - e.g. harmonic, RMS and peak - shall be performed for each sensor, to reveal internal shocks (rattling/chatter) or non-linear behavior, and to understand whether a phenomenon is local or global. Indeed a difference between RMS, harmonic or peak can result from a shock transient that is superimposed to the harmonic signal, resulting in an increased RMS value as described below. Such phenomenon can be further assessed by the analysis of time histories. Analysis of the time signals can also help for the understanding of other kinds of physical phenomena as shown in the following in an example dealing with strain gauges.

Internal shocks – Rattling/Chatter

Internal rattling usually propagate from its origin location (e.g. free play in mechanism, or free play in tank bearings), and can be seen in a large portion of the satellite and even on the pilots (see Fig. 1). When the source is clearly identified, this problem can be solved, for the purpose of the shaker control, by modifying the control parameters, or the filtering applied to the signals.

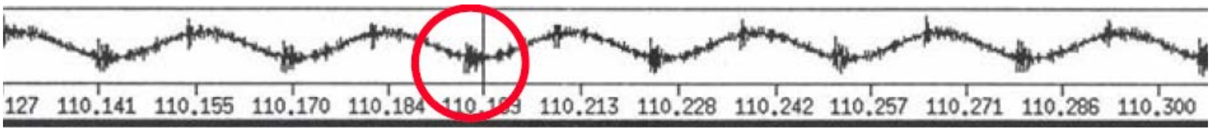


Fig. 1. Example of sine signal affected by rattling.

Hereafter, a practical example is provided on the identification of a source of internal rattling, and on the corrective action taken in subsequent runs to allow the control of the shaker (i.e. higher level sine vibration test).

During this test campaign, considerable differences were observed between the fundamental and RMS signals, at vicinity of the tank interface (see Fig. 2).

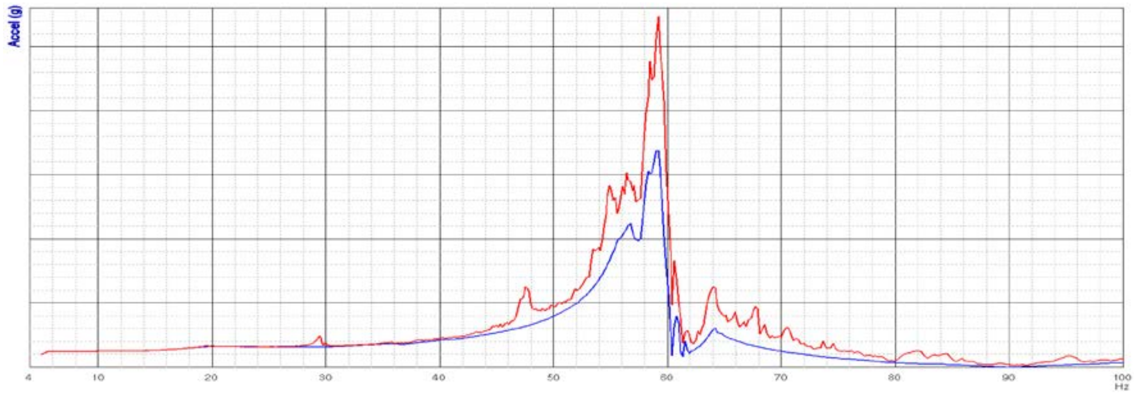


Fig. 2. RMS (red) vs Harmonic (blue) Signal for Tank Interface

These differences were attributed to the tank assemblies due to their propensity to ‘chatter’ at the bearing, strut end/lug and strut pin interfaces (a common phenomenon with this type of arrangement). However due to the considerable difference (a 70% increase in acceleration for the tank), further analysis was required to characterise the frequency content leading to this difference and decide how to pursue with the test, in particular with regards to the shaker control.

Considering the time histories of the test (see Fig. 3), an analysis was carried out (via FFT) and it was concluded that the high frequency content would not be detrimental to the performance of the structure.

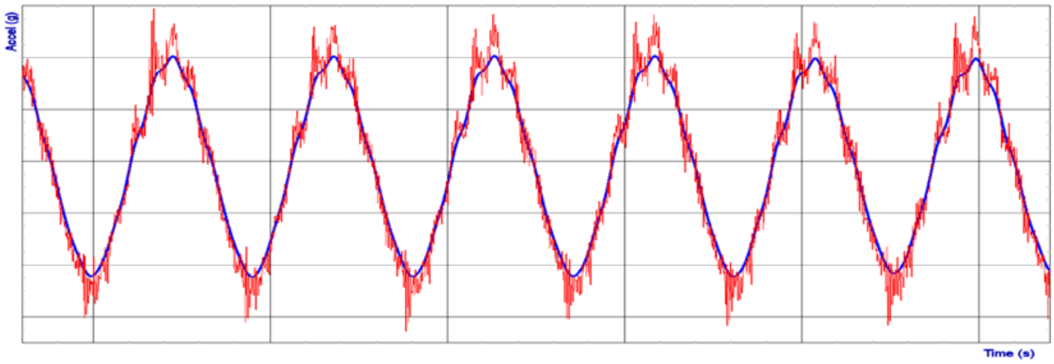


Fig. 3. Unfiltered (red) and filtered (blue) signal

The corrective action consisted in modifying the filter used to compute the RMS signal (with a low pass filter at 300Hz), for controlling the tank response during the test. Another solution could have been to control the specimen considering the fundamental signal, however this would have implied to change the control strategy (preferred approach is to control on RMS, because it is safer than on harmonic).

A detailed post-test visual inspection of the tank assembly was conducted during the refurbishment/inspection of the structure. Upon completion it was concluded that no damage or wear was evident on any of the bearing or strut interfaces, thus confirming that the high frequency content was not detrimental to the test article.

In case of rattling/chatter, it is recommended to follow the following steps:

- Check the time history of the signal.
- Determine the frequency of the perturbation and the source.
- Determine whether the contributions in the acceleration obtained at higher frequencies are critical and relevant or not for the control of the test.
- Determine signal acquisition mode (filtered / unfiltered)

Non-symmetric response of strain gauges

The following example is related to a sine test performed on a satellite. Strain gauges were bonded on the Launch Vehicle Adapter (LVA) in order to assess the axial load and the bending moment at the interface of the spacecraft. Some gauges were unfortunately not working properly but the test could be driven with the help of data collected during previous tests on an identical spacecraft. It appeared that the deformation levels measured by the gauges bonded on the outer side of the LVA were not giving the expected values compared to the previous spacecraft while the acceleration levels were fairly in line. This is illustrated in Fig. 4.

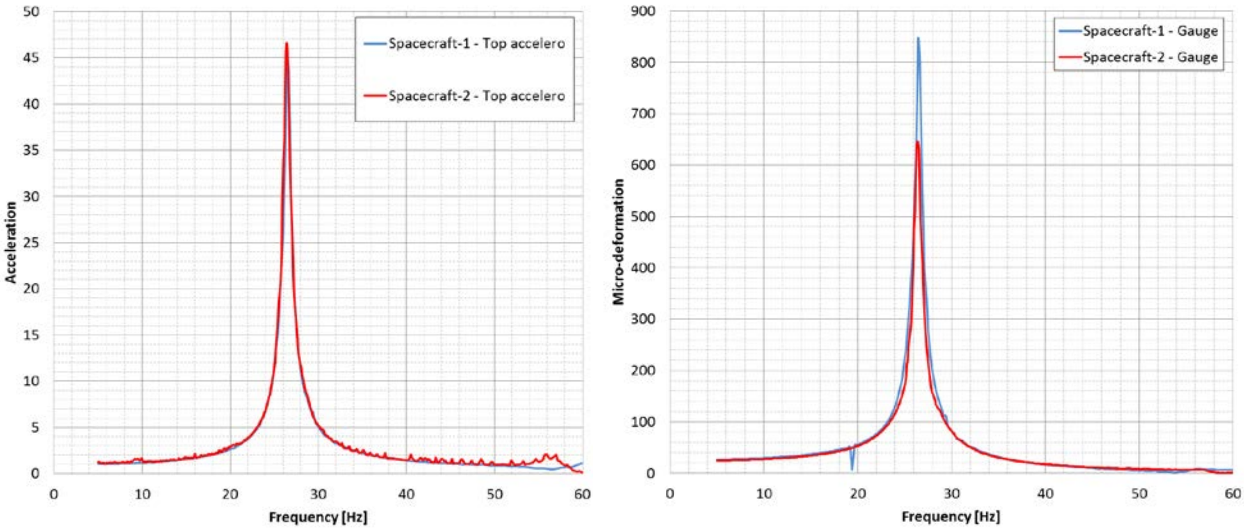


Fig. 4.Sine tests on identical spacecraft. Comparison between response on accelerometers (left) and strain gauges (right) (transfer functions).

This behaviour was difficult to understand and the analysis of the data in the time domain was very helpful. The behaviour of the strain gauges is illustrated in Fig. 5.

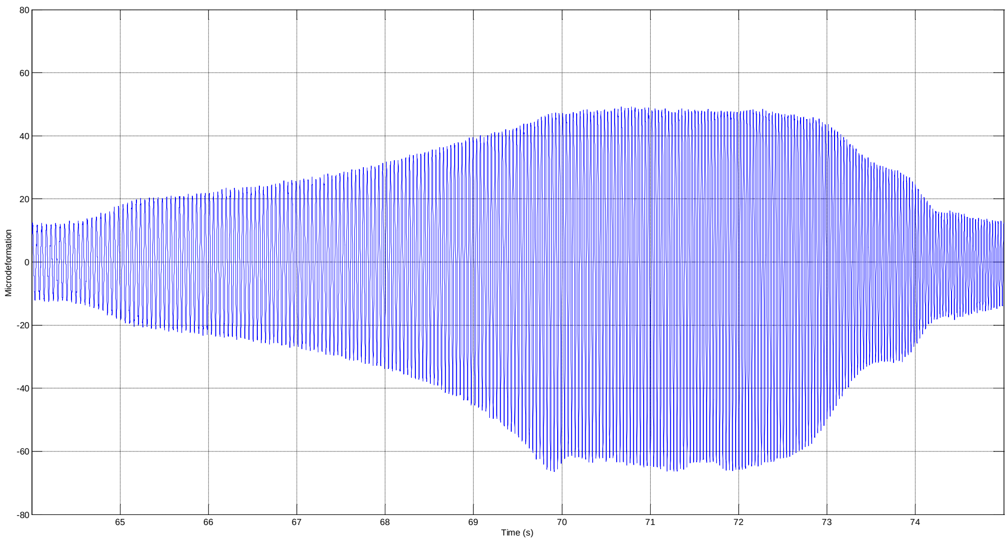


Fig. 5. Time history of strain gauge around the SC main mode.

It is very interesting to note that the signal coming from the strain gauge is not symmetric. Initially, defect in the strain gauge was suspected but it appeared that there was really a physical phenomenon behind this behavior. In fact, the launch vehicle adapter of the spacecraft 2 was slightly conical while the one of spacecraft 1 was purely cylindrical. This was sufficient to induce bending when the LVA was loaded in compression. This is why the signal from the gauge mounted on the LVA was not symmetric. While the LVA was working in compression, the bending contribution generated some tension on the strain gauge, superimposed to the compression. This resulted in a decrease of the measured amplitude. The phenomenon did not appear in tension,. It is interesting to notice also that in the frequency domain data, the amplitude of the signal on the gauges affected by this phenomenon was roughly the mean value between the positive and the negative peaks in the time domain.

As a conclusion, it is recommended to systematically compare the harmonic (fundamental) and peak (global) or RMS signals to detect phenomena like internal shocks and to request and analyse time histories whenever an unexpected phenomenon appears.

4. ILLUSTRATION OF TIME HISTORY PROCESSING DURING RANDOM TESTS

Robust design of structures requires in-depth understanding of the physics governing their responses to dynamic environments where extreme response peaks have been observed; knowledge of these occurrences is of a paramount importance to better understanding the survivability of brittle structures during flight and testing. Recent experimental evidence indicates that dynamic response to stochastic excitation can often go far beyond the 3 sigma RMS level. In fact, 5 sigma is not uncommon in time histories with large numbers of cycles.

Random peak loads and accelerations vs 3 sigma level

During random tests, the results are presented as power spectral densities and RMS levels. In the absence of time history, it is usually assumed that the maximum acceleration level reached in the time domain does not exceed 3 times the RMS level (3 sigma value) and that only a few peaks exceed this value. The following figures contain data extracted from a random test on an instrument. Fig. 6 shows the time history of the acceleration measured by one of the pilot accelerometers, showing the progressively increasing input level during the test. The RMS level computed on the part of the signal corresponding to the full level is 7.6g, leading to a 3 sigma level equal to 22.8g.

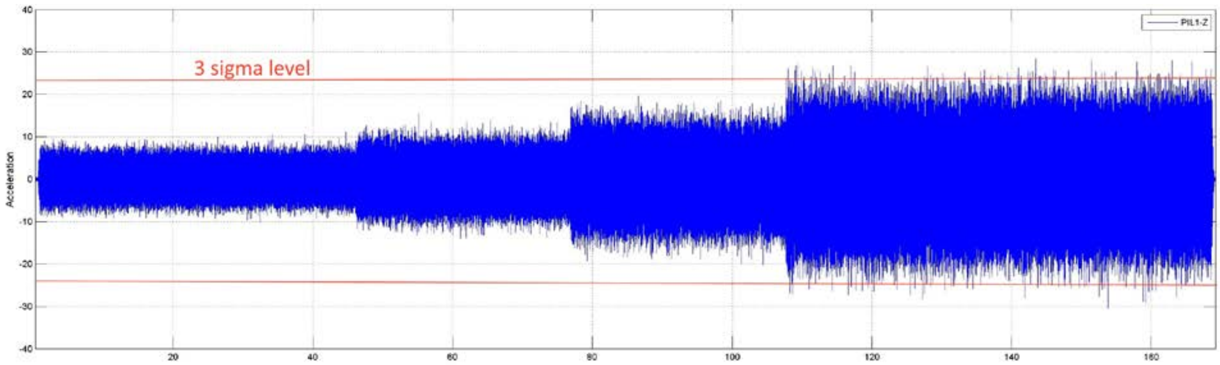


Fig. 6. Time history vs. 3 sigma level measured on a pilot accelerometer

This figure shows that for the pilot accelerometer, the occurrence of maximum acceleration above 3 sigma level remains limited. However, the maximum time response reached for this case is 30.4g, which is 33% more than the 3 sigma level. Fig. 7 provides the time history for an accelerometer located on the instrument.

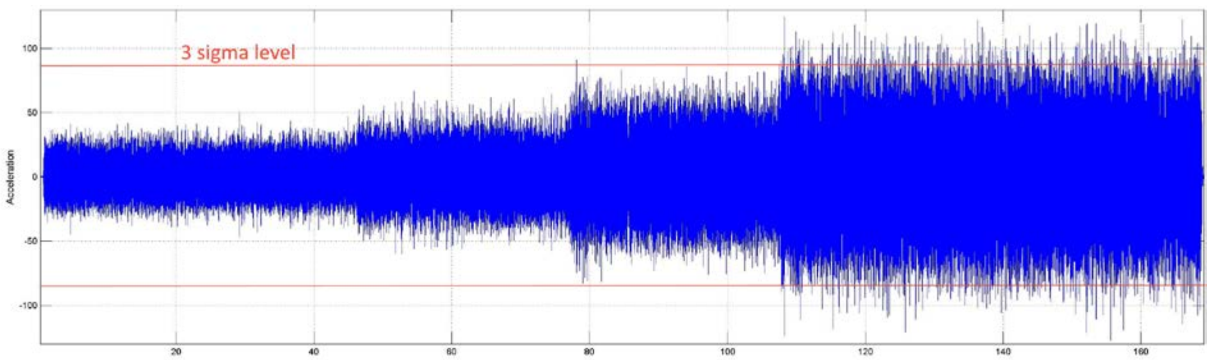


Fig. 7. Time history vs. 3 sigma level measured as a response of the instrument

For this sensor, the RMS level reached 28.7g, leading to a 3 sigma level equal to 86g. It is interesting to notice that the occurrence of the number of peaks above the 3 sigma level is much higher than for the pilot accelerometer. The maximum acceleration reached during the test is 127g. This is 47% more than the 3 sigma level.

Extreme peaks, exceeding 3 sigma value, during random vibrations are not an exception but rather systematic. It has been observed on all cases where time signals are recorded. It does not only affect accelerations, but also loads, as demonstrated in [4] and [5]. Those references show, in addition, a weak dependence of the extreme peaks from random vibration test data (number of sigmas reached) on structural damping.

The analytical investigations show that this is exactly what is predicted under the common assumptions of Gaussian (normal) distributions. In particular, the theory predicts over 50% probability that a 5-sigma extreme will occur within a stationary Gaussian time history with 100,000 cycles. However, test and flight data show that these extreme peaks may occur with higher frequency.

3 Sigma clipping

The example below is an illustration of a random test along X axis of an equipment using the usual 3 sigma clipping option provided by the shaker control (see [10]). The clipping is clearly visible on the current and voltage applied on the shaker coil as illustrated on the lowest plots U(80kN) and I(80kN) of Fig. 8. The first remark is that the clipping process does not consist in removing values above +/- 3 sigma. It modifies the overall distribution of the signal, therefore, departs from the usual bell shape of a Gaussian signal (shown in red) and is more flattened around the mean.

Now, looking at the distributions of the response signals (estimated by histograms), one can see that they are usually close to a Gaussian distribution (even though the shaker control is not fully normal), and that they are not clipped at 3 sigma. The clipping effect is slightly visible on the sensors along the excitation direction. For instance, TP1:-X, which is the closest from the interface of the test article shows tails thinner than a pure Gaussian distribution, though the extrema still exceeds the 3 sigma value. The sensor TP2:-X shows peaks well in excess of 4 sigma. The cross-axes sensors (e.g. Y or Z directions) distributions exhibit thick tails due to some superimposed noise to their Gaussian distribution.

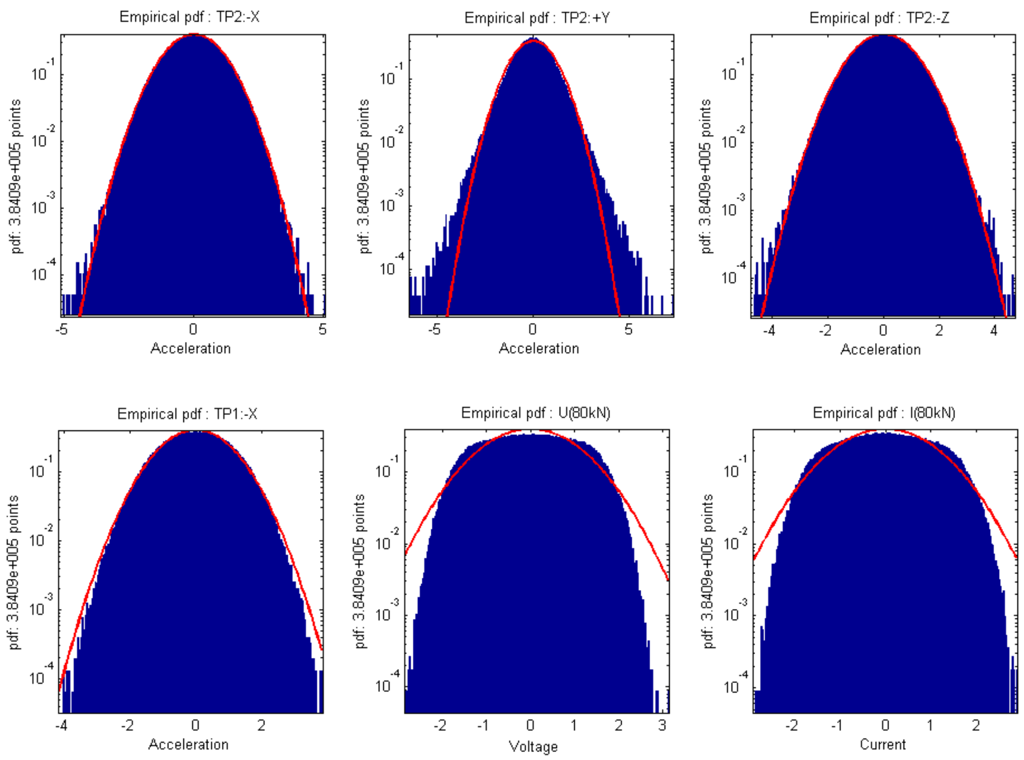


Fig. 8. Distribution of responses, shaker tension and current during a random test using 3 sigma clipping. Red curves are normal distributions

Since brittle failure is usually considered to occur on the first instance of an overstress, and ESA and NASA's Handbooks and Standards recommend designing structures to 3 sigma ([6] & [7]), this raises the question of why brittle failures are not very common occurrences. The reason is that the non-conservatism of the 3 sigma standard is being balanced in some way with over-conservatism in other aspects of the design - arbitrary safety factors, conservative estimates of parameter values and input excitations, etc. Even if such a procedure results (somewhat by accident) in a safe design, it is unlikely to lead to one that is efficient in the minimization of cost and weight. Furthermore, the true safety margins also depend on the methods used for numerical predictions. More refined numerical procedures may reduce these safety margins, even if there is no change in design philosophy. This could result in loss of reliability in the future if design procedures are not modified. These new design challenges need to be addressed by maintaining a procedure that is both cost-effective and safe and is based on use of accurate estimates of both physical parameters and statistical quantities of brittle structures under dynamic environments. Establishing such a procedure requires future experimental and analytical study.

Stationarity of the signal - short time window RMS vs global RMS

It is also important to notice that the overall RMS level computed at the end of the test may be quite different from the instantaneous RMS level computed in real time by the control system during the test and used for example to trigger the system aborts. Fig. 9 shows the RMS vs. time computed with different time windows (0.5, 1 and 2 seconds).

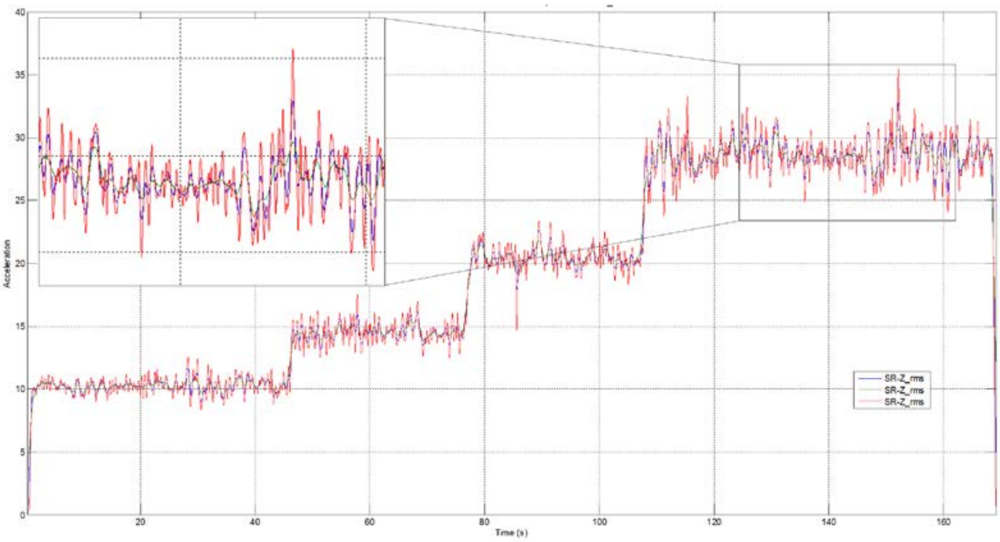


Fig. 9. RMS vs. time computed with 0.5s, 1s and 2s time windows

The "instantaneous" RMS is quite dependent on the size of the window and its maximum value may be quite different compared to the overall RMS obtained at the end of the test. This is interesting to keep in mind, especially if abort limits are set based on the maximum RMS, or PSD level of some sensors.

Identification of non-linear behaviour and failure

Fig. 10 shows an example of a strain gauge data taken from a flight hardware random vibration qualification test, at -6dB level. The top plot is the raw data with sigma (extreme peak/rms) estimated to be close to 7 and the middle plot is the same data low-pass filtered at 800 Hz. The sigma for the filtered data is close to 6.4. The important point about these plots are 1) indeed the higher sigma occurs during vibration testing, and 2) the extreme peak is associated with the fundamental modes of the structure and is not related to shock-like events that may produce higher sigma. Table 1 summarises the force, accelerometers, and strain gauge measurement from the test.

The sigma, skewness, and kurtosis estimated from the test data show its non-Gaussian nature and the time history indeed shows that the signal is not symmetric, indicating a non-linear behaviour.

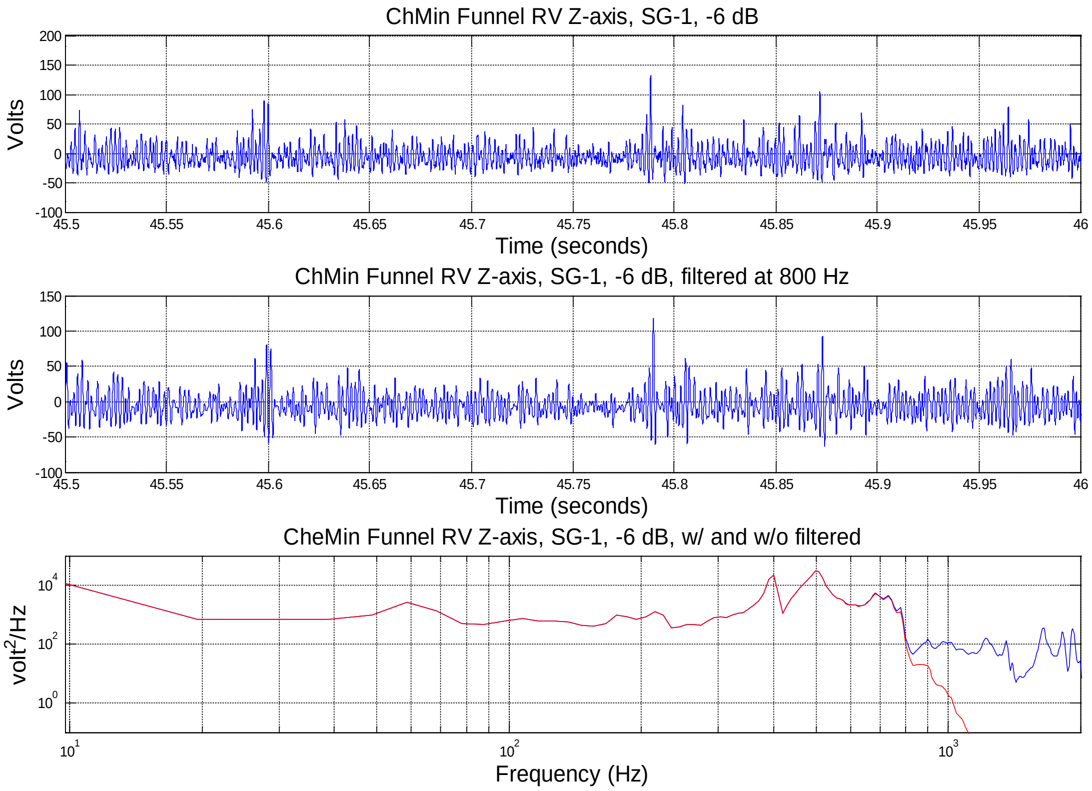


Fig. 10. Random vibration signatures from hardware that underwent qualification testing. Raw strain gauge data - sigma ~7 (top), low-pass filter @ 800 Hz strain gage data - sigma ~6.4 (middle), corresponding PSD (bottom)

	Unfiltered									
	Force	A3Z	A6Z	P010L	P010R	Bipod	SG-1	SG-5	SG-6	SG-11
rms	35.85	53.7	21.42	11.13	13.67	20.93	171.53	38.58	30.79	39.19
Sigma	4.61	5.56	4.9	5.75	5.19	6.8	4.45	7.24	8.44	6.21
Skewness	-0.02	-0.1	0	0	0.01	0.23	0.36	0.56	0.75	0.43
Kurtoisis	2.95	2.96	3.01	3.06	3.03	3.22	2.08	3.56	3.87	3.35
	Filtered									
rms	34.83	53.37	19.97	9.69	10.42	18.45	171.21	37.89	29.96	38.46
Sigma	4.64	5.05	4.72	5.82	4.92	4.6	4.02	6.35	7.07	6.09
Skewness	-0.01	0.01	0	-0.05	0.02	-0.01	0.34	0.37	0.43	0.3
Kurtoisis	2.96	2.94	3.01	3.06	3	2.86	2.01	3.31	3.38	3.26

Table 1. Summary of the sigma, skewness, and kurtosis estimated from force gauges, accelerometers, and strain gauges taken from a flight hardware undergoing random vibration test with a test duration of 60 seconds (-6dB).

Fig. 11 below shows time histories of the full level (0 dB) for the same hardware, leading to a failure. The time histories are taken from a strain gauge data sampled at 20 KHz (top plot) and low-pass filtered at 800 Hz (middle), and corresponding PSDs provided in arbitrary units. The failure registered by this sensor is clear from these time histories. A few observations can be made from this case. The PSD alone, in general, does not provide adequate information about the failure unless the structural failure had already advanced. It is of paramount importance to review the time history data in real-time, where the kind of abnormal signatures, such as the one shown in Fig. 11, can be recognized. Also it is important to estimate the Gaussian distribution curves in real-time to assess if the random data deviates from normal distribution (i.e. the skewness and Kurtosis change from 0 and 3, respectively). Any departure from Gaussian distribution (indicated by changes in skewness and Kurtosis) would indicate potential chatter, one-sided, and shift from zero in the time history data. All or some of these features may point to potential structural failure. A careful examination of the test data by assessing PSDs, time-histories, and Gaussian distributions will provide very useful information for test conductor to prevent major failure in flight hardware.

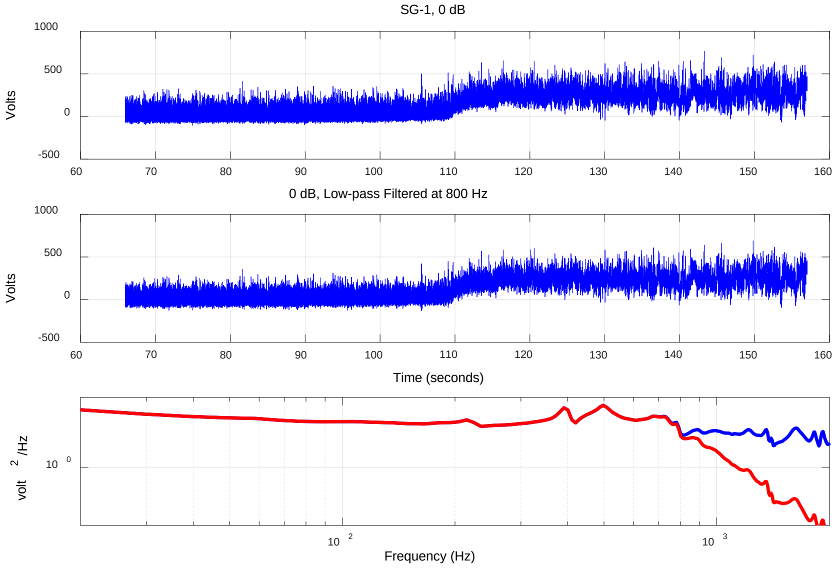


Fig. 11. Strain gauge data from a random test with failure, raw data (top), data low-pass filtered at 800 Hz (middle) and associated PSDs (bottom)

Another example shown in Fig. 12 illustrates the impact of a component failure inside an electronic box during a random vibration test. The component was found completely detached from its Printed Circuit Board (PCB) after the vibration test. At first sight, the PSD of the closest sensor from the failed component does not show any specific anomaly with a main equipment mode at around 1500 Hz.

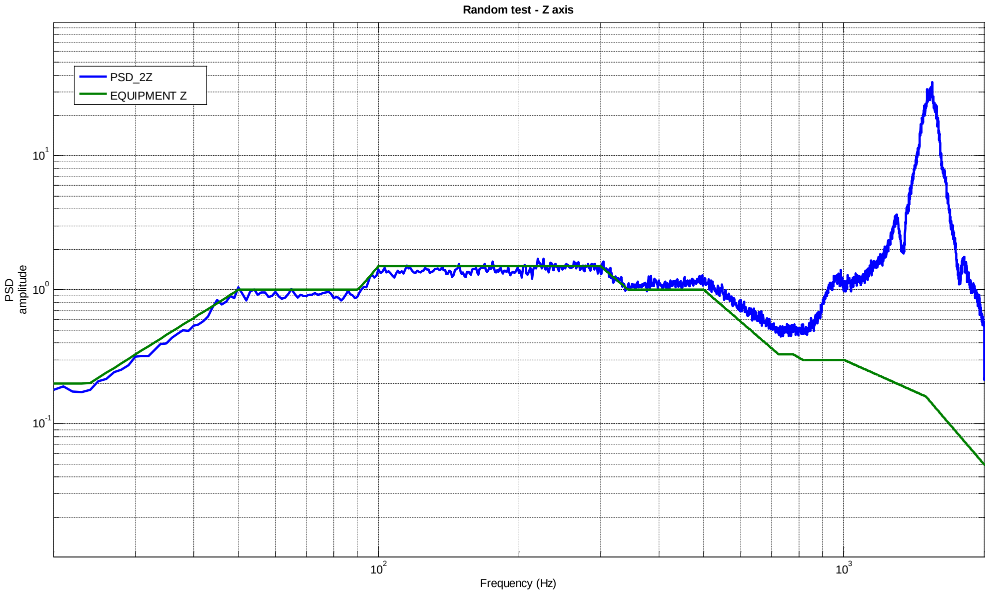


Fig. 12. PSD of sensor 2Z – dominated by one main mode

The comparison of the initial and final low level sine runs shows spectral shape changes at high frequency. However, the main frequencies of the equipment are still within the usual pass/fail criteria (e.g. +/- 5%) as shown on Fig. 13. The amplitudes of two high frequency modes above 1750 Hz have changed and a mode just below 2000 Hz is appearing after the full level random test. These facts alone may not provide a clear indication of the failure of the equipment.

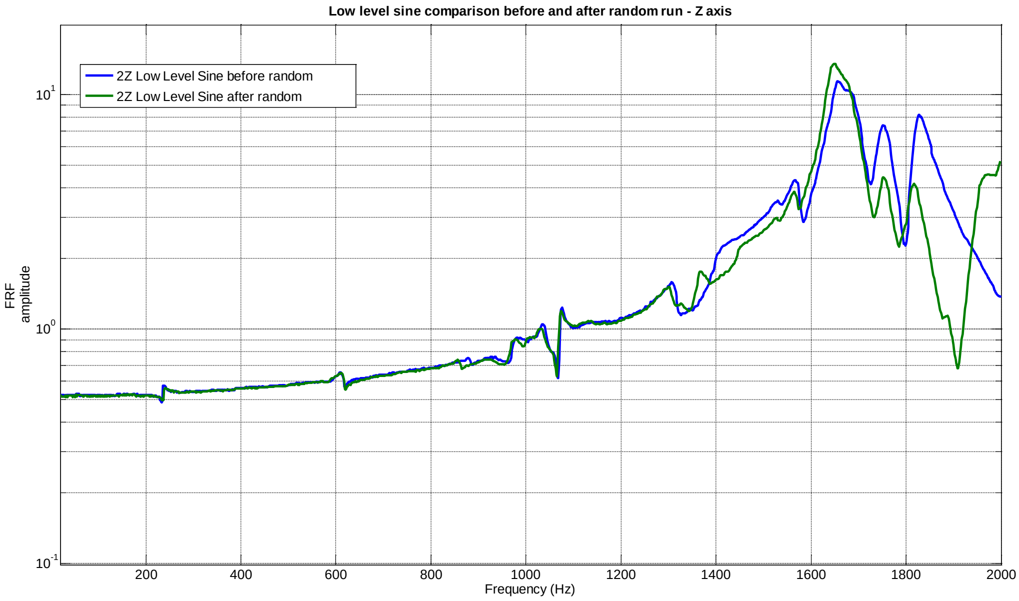


Fig. 13. Low level sine runs before and after random vibration test

A closer look at the corresponding time history (see Fig. 14) is revealing some asymmetry in the signal (positive peaks exceeding 400 g whereas negative peaks are in the range 300g). However, the overall time history DC offset is close to 0, which means that it is not linked to a wrong calibration of the sensor but to a physical phenomena. When looking at the distribution of the original signal illustrated in Fig. 15, on the left plot, the asymmetry is obvious in the positive sigma direction. It is confirmed by the skewness of the distribution, which is close to 0.3 (compared to a nominal value of 0). The asymmetry may be explained by the rattling of the component impacting the box frame structure and generating high frequency components. When the above signal is filtered above 2000 Hz (see Fig. 15. right), the resulting distribution almost recover a bell shape, confirming that the electronic component chattering on the equipment structure was creating mainly high frequency noise. The low frequency behaviour is not really impacted as confirmed by the last low level sine search where the changes after random are mainly visible above 1700 Hz as shown on Fig. 13.

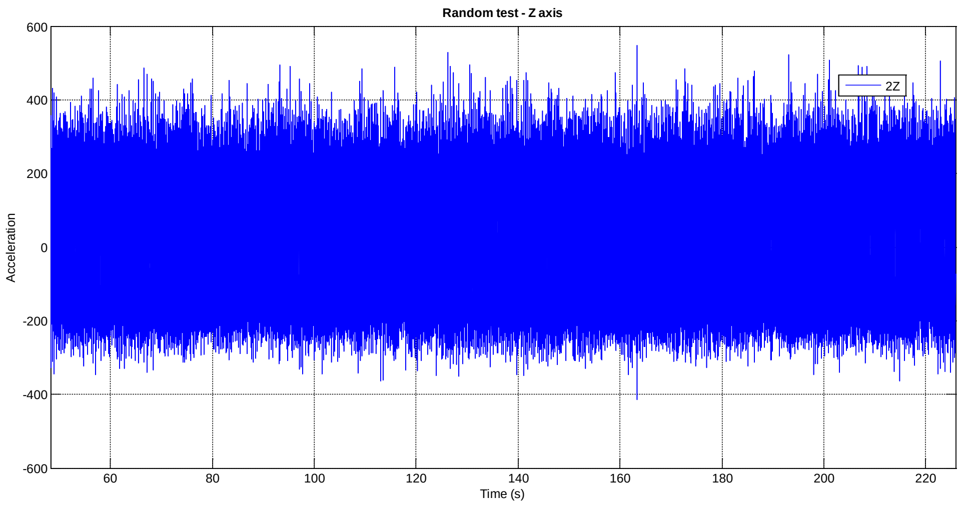


Fig. 14. Time history sensor 2Z

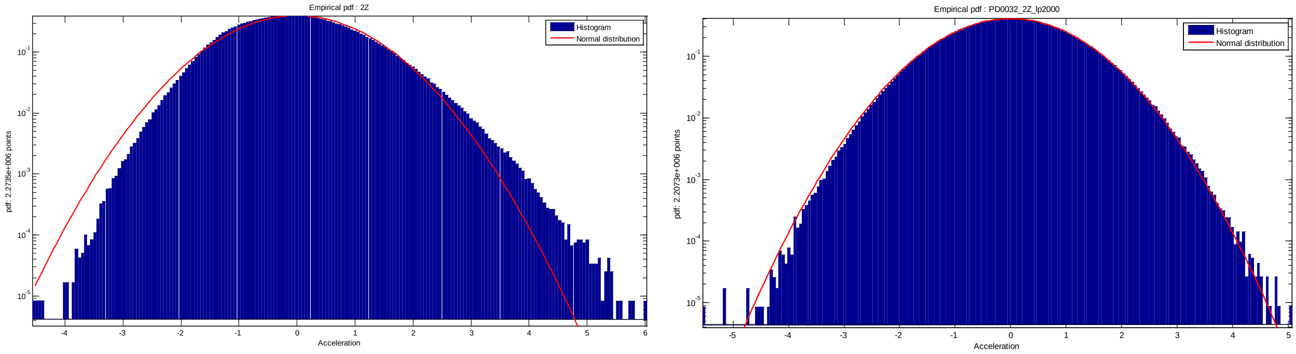


Fig. 15. Distribution of time history and comparison with normal distribution (red) – original signal (left) – filtered signal (right)

Another way to identify failures during random vibration test, based on time histories, is described in [9].

5. ILLUSTRATION OF TIME HISTORY PROCESSING DURING ACOUSTIC TESTS

The previous Section 4 was dealing with random testing for which it was shown that levels higher than expected can occur. It is worth to underline that the same kind of behaviour can be expected during acoustic tests.

Acoustic test signal distribution

Acoustic test results are most of the time provided in terms of overall Sound Pressure Level (SPL) values and PSD for pressure, accelerations, forces or strains. Very often, acoustic response time histories are not available, though they can reveal interesting information about the nature and extrema of the measured signals. As an example, distributions in Fig. 16 show that the generated signals are Gaussian (i.e. very close to the Gaussian distribution in red), and that the maximum levels largely exceed the usual 3 sigma considered in the dimensioning of the units for all type of signals (pressure, acceleration or strain). In this specific case, the maximum levels are in the order of 4.5 sigma for a one minute acoustic test. There is clearly no clipping process during acoustic excitation as it can be applied during a random vibration test on a shaker.

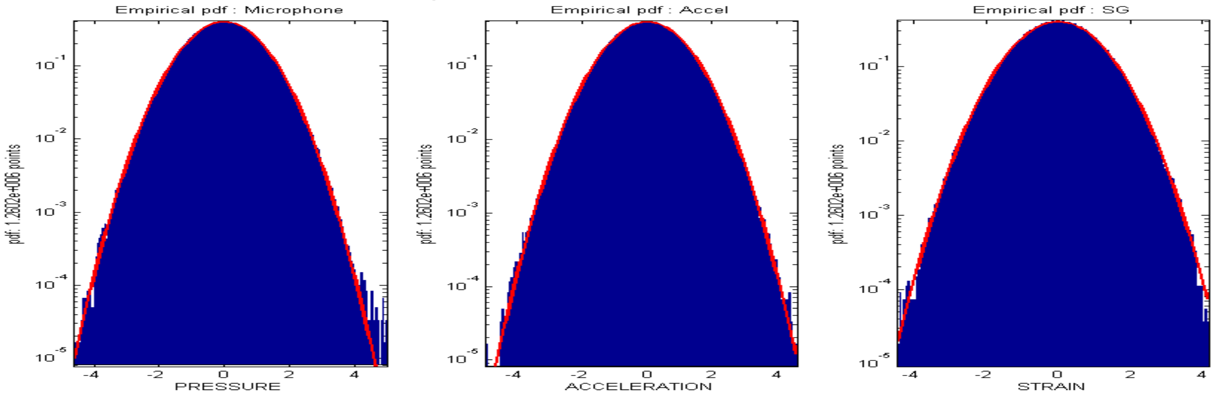


Fig. 16. Pressure, acceleration and strain time history distribution during acoustic test

It is also interesting to look at the theoretical mean time to exceed *n* sigma computed from the wideband peak distribution (blue) of the corresponding strain gauge PSD. It shows values in agreement with the measurement (red) as shown in Fig. 17. This is a demonstration that the acoustic test to which spacecraft are submitted to may generate loads and acceleration higher than the usual 3 sigma values applied in the dimensioning of the structures. They usually exceed 4.5 sigma over 1 minute test and may reach 5 sigma over two minutes.

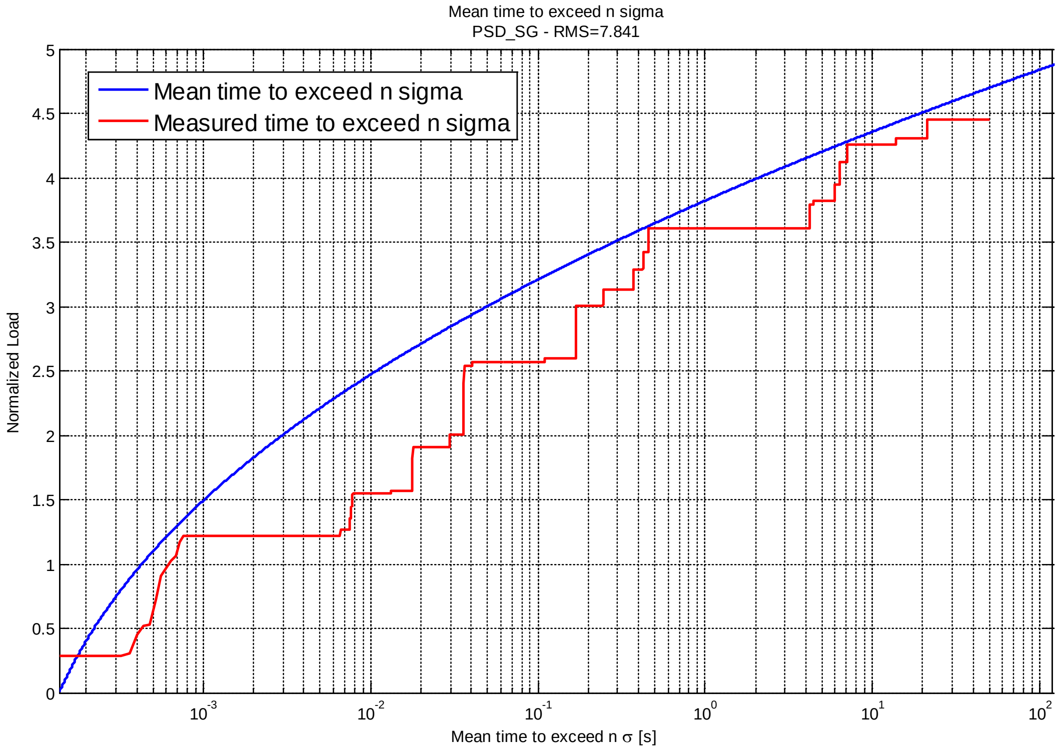
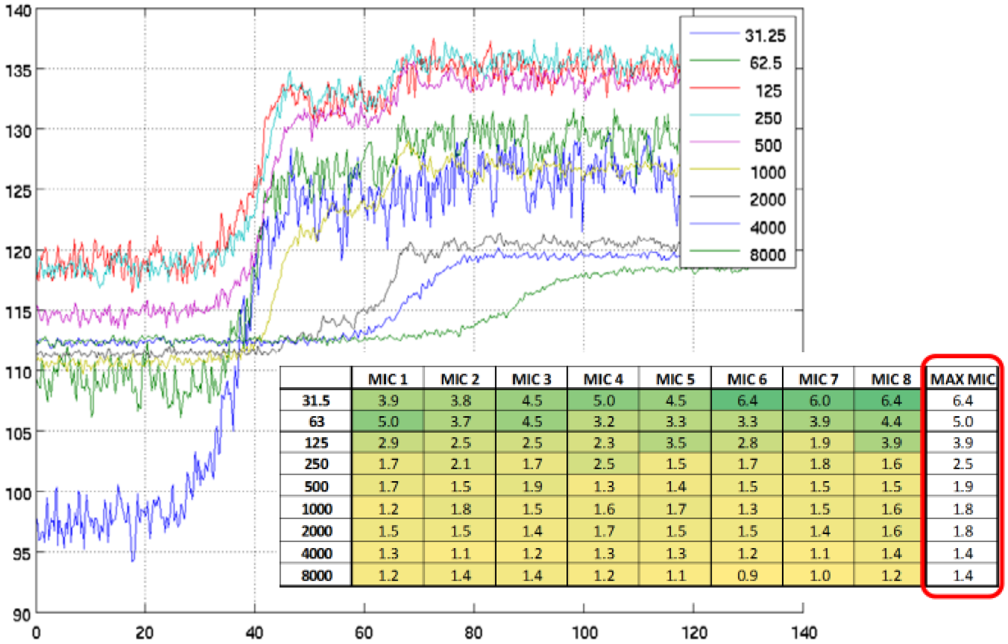


Fig. 17. Mean time to exceed n sigma associated to Strain Gauge (SG) PSD, theoretical (blue) and measured (red)

Sound Pressure Level (SPL) Variation Over Time

During acoustic tests, the applied sound levels are usually fairly approaching the specified levels (with defined test tolerances), but the averaging method for SPL computation masks some inherent fluctuations during the test (similarly to what is shown in for random in Fig. 9). These natural fluctuations shall be kept in mind.

Fig. 18 shows an example coming from an acoustic qualification test performed recently on a spacecraft. The time histories recorded on the microphones were used to identify the SPL peak value over time by applying a processing similar to the one applied by the launcher to derive the acoustic environment from flight data (SPL evolution in 0.5s sliding windows). These data are compared to the sound pressure levels averaged over the duration of the test provided by the test facility and the table in Fig. 18 shows the differences obtained for the acoustic pressure in the various octave bands. It is interesting to notice that the evaluation of the SPL over the 0.5s time windows leads to maximum peak acoustic levels around 2dB higher than the ones computed over the total duration of the test in the octave bands above 250 Hz. The difference is even greater in the lower octave bands with up to 6dB. This variation of SPL over time is significant and shall be characterised. In some cases, this may help to consolidate the qualification of a specimen if the levels reached during the test are slightly below the specifications, especially if the acoustic excitation has a transient nature on the launcher.



	MIC 1	MIC 2	MIC 3	MIC 4	MIC 5	MIC 6	MIC 7	MIC 8	MAX MIC
31.5	3.9	3.8	4.5	5.0	4.5	6.4	6.0	6.4	6.4
63	5.0	3.7	4.5	3.2	3.3	3.3	3.9	4.4	5.0
125	2.9	2.5	2.5	2.3	3.5	2.8	1.9	3.9	3.9
250	1.7	2.1	1.7	2.5	1.5	1.7	1.8	1.6	2.5
500	1.7	1.5	1.9	1.3	1.4	1.5	1.5	1.5	1.9
1000	1.2	1.8	1.5	1.6	1.7	1.3	1.5	1.6	1.8
2000	1.5	1.5	1.4	1.7	1.5	1.5	1.4	1.6	1.8
4000	1.3	1.1	1.2	1.3	1.3	1.2	1.1	1.4	1.4
8000	1.2	1.4	1.4	1.2	1.1	0.9	1.0	1.2	1.4

Fig. 18. Spacecraft acoustic test – SPL processing in 0.5s sliding window over time. The table shows the maximum variation over time with regard the average SPL per octave band and per microphone

6. IMPORTANCE OF TIME HISTORY PROCESSING FROM SHOCK TESTS

Specificity of shock environment is related to the difficulty of ensuring the validity of measured signals. Precautions to be taken in relation to test monitoring, selection of suitable acquisition system and sensors, and validation of recording of shock response data are discussed in details in the ECSS Shock Handbook [1]. The aim of this paragraph is to underline the importance to ascertain the validity of recording of shock response data (in particular for near-field testing), based on pyroshock validity criteria, before it can be utilized (for data analysis such as SRS, or for performance of shock FE analysis).

The first criteria is the inspection of the time histories. This paper does not address all the validation steps (validity frequency range, positive versus negative SRS, and velocity validation), which are presented and illustrated in details in the ECSS Shock Handbook [1], as well as in other standards, and often referred as the Piersol Criteria [2] & [3].

Recent experiences indicate that typical far-field measurements (general instrumentation on a satellite far from shock sources, or standard shock testing of a unit by a mechanical impact) are generally reliable. This is the result of improvements on acquisition systems and accelerometers as well as by improved procedures applied by the testing organizations. On the other hand, near-field measurements still require a dedicated attention. In relation to near-field measurements, the probability of occurrence of a faulty measurement remains high, which can take various forms (wild points, saturation, offsets, etc. …). In that case, the time history visual inspection shall not be omitted as it will reveal which measurements shall be discarded. In several cases, the measurement can be seen satisfying the Piersol criteria in terms of positive versus negative SRS including the velocity validation, but detailed inspection of the time history would reveal that the data is to be considered invalid.

This is the case in the following examples:
Example 1 – Pyroshock test generating intense environment, first showing a transient signal which satisfies the shape factor (duration decaying function) and the Piersol criteria in terms of positive versus negative SRS. But zooming-in, the measurement appears to be a collection of wild points, as a result of a combination of failure cases (saturation, aliasing, connector, etc).

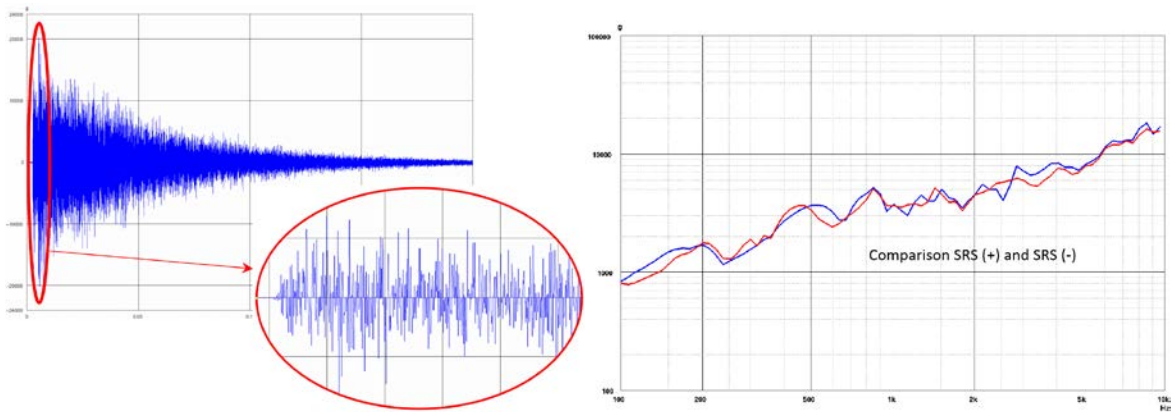


Fig. 19. Temporal data consisting in a collection of wild points (left), whereas the criteria on SRS(+) and SRS(-) is met (right)

<u>Example 2</u> – System level shock test with signal processing consisting firstly in applying a high pass filter (> 100Hz). This kind of processing is sometimes performed prior to the delivery of the database to the customer, but can cause a spurious signal to be wrongly considered valid by the customer. Hence it is recommended that the traceability of the applied processing shall be provided together with the database to the customer. In this example, the problem was highlighted by comparison with neighbouring sensors, indicating that the suspicious measurement was clearly out of family.

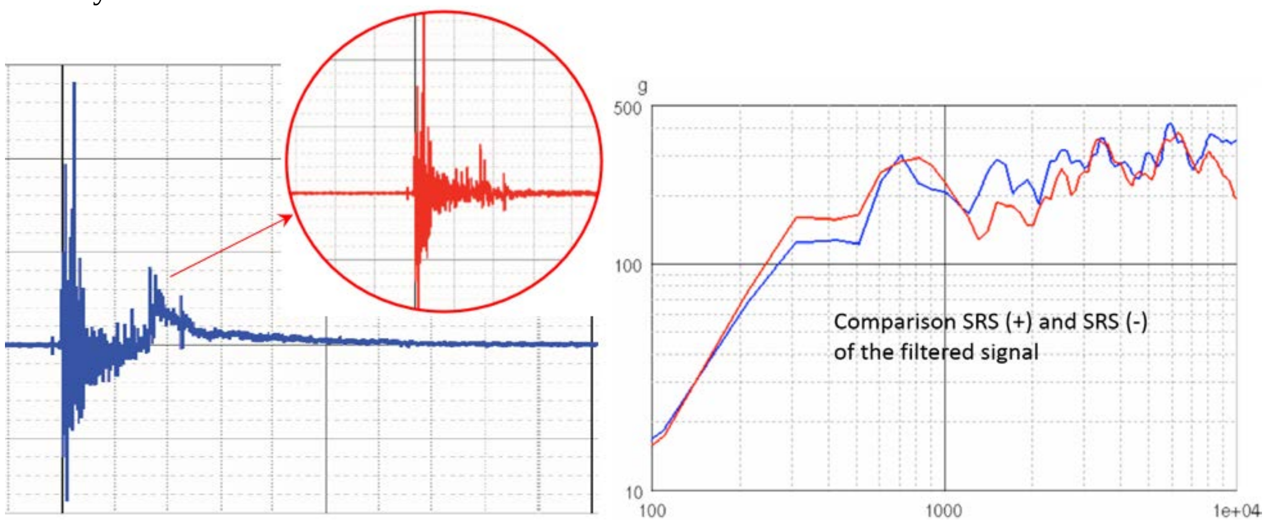


Fig. 20. Temporal data containing spurious signal, and filtered before delivery to custormer (left), whereas the criteria on SRS(+) and SRS(-) is met on the filtered signal (right)

As a conclusion it is important to ascertain the validity of recording of shock response data, based on pyroshock validity criteria, without neglecting detailed inspection of the temporal data. Traceability of processing applied by the testing facility together with the characteristics of all constituents of the acquisition chain shall be communicated to the customer.

7. IMPORTANCE OF TIME HISTORY PROCESSING FROM MICRO-VIBRATION TESTS

Microvibration response distribution

The probability of the payload performance to be impacted by on-board microvibration is higher when one or several structural modes are excited by equipment operational noise sources. Fig. 21 shows acceleration measured from an optical bench during a reaction wheel ramp down excitation. Criticalities in terms of disturbance are well localised in time, and they correspond to specific reaction wheel speeds which excite particular structural modes and lead to peak accelerations. The waterfall plot below shows that one wheel harmonic is exciting one or several structural modes around 90 Hz resulting in the highest peak disturbance over the entire wheel speed range. This is to be compared with the excitation around 210 seconds, which shows a large number of excited harmonics but none amplified by a structural mode. As explained in section 2, the waterfall alone cannot provide the exact distribution of the signal around these particular wheel speed configurations.

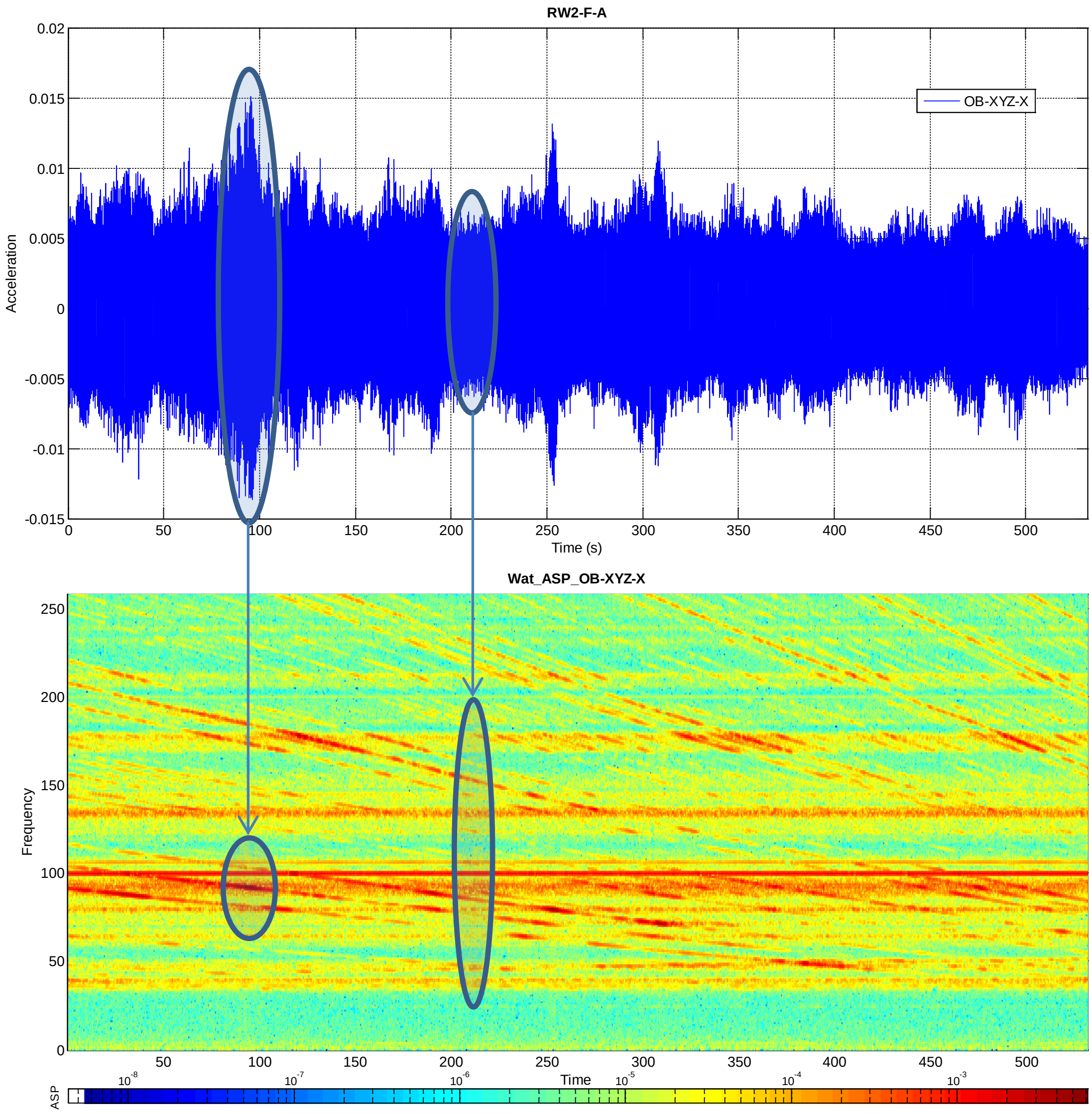


Fig. 21. Microvibration response of optical bench under reaction wheel excitation – Time history and corresponding waterfall plot

The signal distribution over a 2s rectangular window centred around the above peak acceleration time is shown in Fig. 22, together with the corresponding FFT. The distribution around the peak response (top) is clearly bimodal and is close to a pure sine wave distribution (superimposed with some noise). The FFT of the same window shown on the left of Fig. 22 confirms the predominance of one main frequency around 90 Hz. As a consequence, the maximum disturbance cannot be estimated using a Gaussian assumption but shall consider the harmonic nature of the disturbance. When several harmonic sources are running simultaneously (e.g. several reaction wheels), summation rules corresponding to those specific distributions shall be considered to estimate the resulting disturbance at payload level. On the contrary, the distribution around the flat response (bottom) is very close to a Gaussian distribution resulting from a broader frequency content with several non-negligible peaks (see bottom FFT).

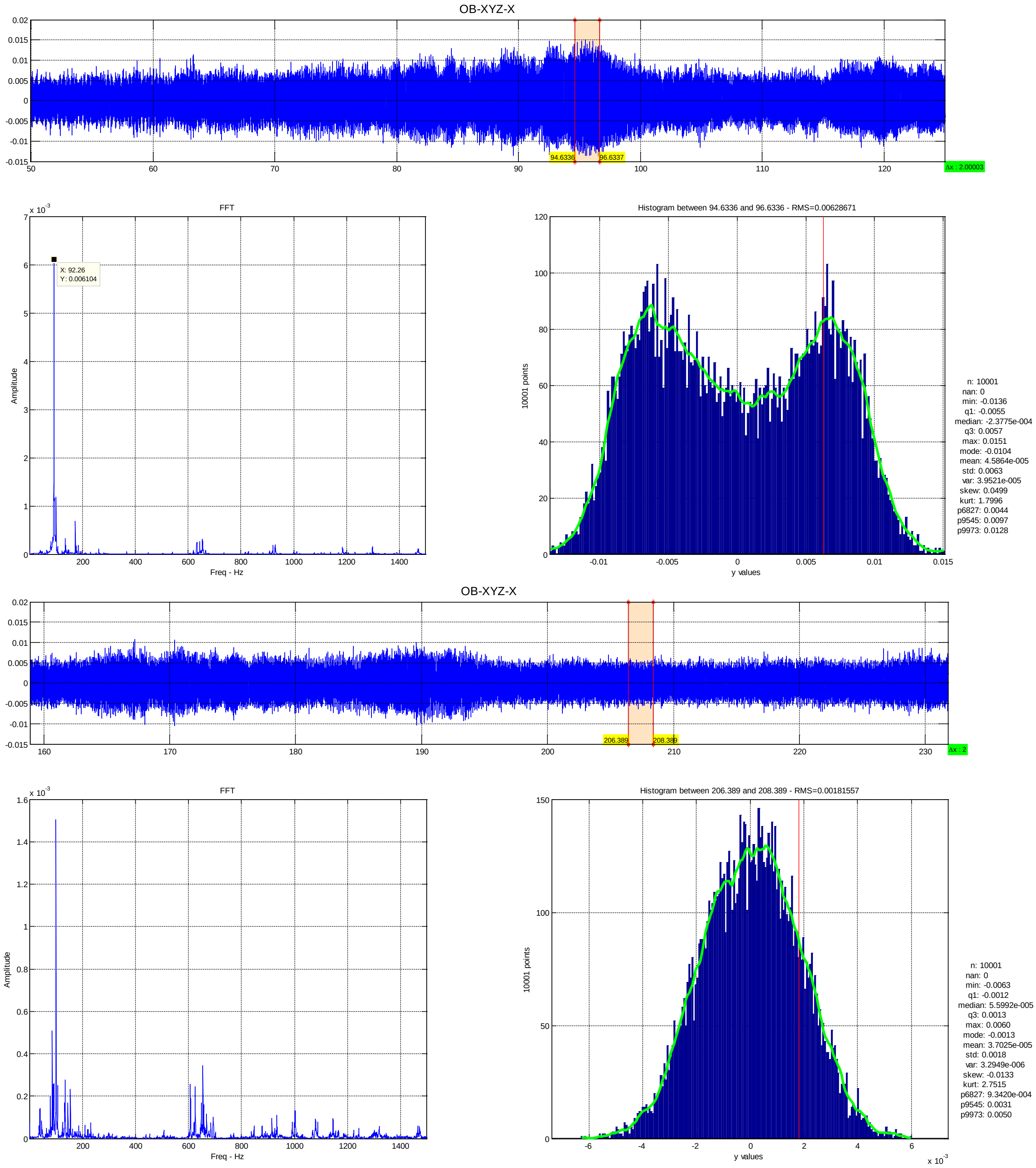


Fig. 22. Signal distribution over a 2 s window around the peak response (top) and around flat response (bottom)

8. CONCLUSIONS

The examples described in this paper show that signal processing applied to time histories can hide a number of important information. It is therefore strongly recommended to make sure that the time histories of all measured data are recorded and made available to assess them and be aware of the post processing that has been applied. This is important to assess the levels that are actually applied to the test article (extreme response peaks) and compare them with allowable values and also to understand the physical phenomena at hand (e.g. chattering, combination of noise sources). Time histories and their analysis can also help for the early detection of unexpected behavior and failure. Processing of measured signals is also a key parameter for the control of the test.

It would be useful during test to provide access to diagnostic tools to support investigations as presented in this paper.

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