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Space engineering — Mechanical shock design and verification handbook

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European Foreword

This document (CEN/TR 17603-32-25:2022) has been prepared by Technical Committee CEN/CLC/JTC 5 “Space”, the secretariat of which is held by DIN.

It is highlighted that this technical report does not contain any requirement but only collection of data or descriptions and guidelines about how to organize and perform the work in support of EN 16603-32.

This Technical report (CEN/TR 17603-32-25:2022) originates from ECSS-E-HB-32-25A.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN [and/or CENELEC] shall not be held responsible for identifying any or all such patent rights.

This document has been prepared under a mandate given to CEN by the European Commission and the European Free Trade Association.

This document has been developed to cover specifically space systems and has therefore precedence over any TR covering the same scope but with a wider domain of applicability (e.g.: aerospace).

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Introduction

In recent years, discussions concerning "what to do about shock" in relation to spacecraft have taken more importance. During launch and deployment operations, a spacecraft can be exposed to energetic shock environments. As spacecraft have become more capable, more equipment can be flown, and components are closer together. In addition, more sophisticated and delicate instruments are flown to maximize mission results.

As such, the shock environment has become a source of concern for spacecraft and payload developers. However, not only the definition of the environment, but also the analysis and test verification is complex.

In the same way than for other mechanical environment, it is important to properly address the shock early in the development phase until the final verification of the shock environment, to ensure a successful qualification.

The experience, gained over the past years by Agencies and industries, greatly improves the state of the art in this domain and has helped clear a large number of equipment and spacecraft for launch.

However, one of the problems with respect to mechanical shock design and verification is the fact that relevant information is spread over ESA and industry documents and specialists. To improve this, the current know-how on mechanical shock design and verification is documented in the present handbook in order to make this expertise available to all European spacecraft and payload developers.

The handbook is divided into four parts:

- Part 1 Overview
- Part 2 Shock input derivation to space segment elements and equipment
- Part 3 Shock verification approach
- Part 4 Shock damage risk assessment

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1 Scope

The intended users of the "Mechanical shock design and verification handbook" are engineers involved in design, analysis and verification in relation to shock environment in spacecraft. The current know-how relevant to mechanical shock design and verification is documented in this handbook in order to make this expertise available to all European spacecraft and payload developers.

The handbook provides adequate guidelines for shock design and verification; therefore it includes advisory information, recommendations and good practices, rather than requirements.

The handbook covers the shock in its globally, from the derivation of shock input to equipment and sub-systems inside a satellite structure, until its verification to ensure a successful qualification, and including its consequences on equipment and sub-systems. However the following aspects are not treated herein:

- No internal launcher shock is treated in the frame of this handbook even if some aspects are common to those presented hereafter. They are just considered as a shock source (after propagation in the launcher structure) at launcher/spacecraft interface.
- Shocks due to fall of structure or equipment are not taken into account as they are not in the frame of normal development of a spacecraft.

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3 Terms, definitions and abbreviated terms

3.1 Terms and definitions from other documents

For the purpose of the present document, the terms and definitions from ECSS-S-ST-00-01 and ECSS-E-ST-32 apply.

3.2 Terms and definitions specific to the present document

3.2.1 shock

local transient mechanical loading of short duration, high frequency and high amplitude, with substantial initial rise time

NOTE For additional details, see 4.1.1.

3.2.2 shock response spectrum (SRS)

calculated function based on an input transient, allowing characterizing the shock effect on a dynamical standardized system in order to estimate its severity or its damaging potential

NOTE For additional details, see 4.1.4.2.

3.2.3 similarity

degree to which different specimens show the same behaviour when exposed to the same shock condition.

NOTE See para 12.6.2, for an example of process for verification by similarity. Verification by similarity is part of the verification by analysis.

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3.3 Abbreviated terms

For the purpose of this document, the following abbreviations apply:

Abbreviation	Meaning
CoG	centre of gravity
CDF	cumulative distribution function
CLF	coupling loss factors
DLAT	destructive lot acceptance testing
DLF	damping loss factors
ESEA	experimental statistical energy analysis
FEA	finite element analysis
FEM	finite element model
FFT	fast fourier transform
FRF	frequency response function
HDRM	hold-down and release mechanism
HF	high frequency
HSRSF	highest shock response spectrum frequency
IEPE	integrated electronics piezolectric
I/F	interface
IP	in plane
ISM	iso-static mount
LFA	lowest frequency analysis
LMPR	local modal phase reconstruction
LV	launch vehicle
MAC	modal assurance criteria
MAF	maximal analysed frequency
MEE	maximum expected environment
MF	medium frequency
NRL	naval research laboratories
NTL	normal tolerance limit
OOP	out of plane
PCB	printed circuit board
PDF	probability distribution function
PIND	particle impact noise detection
PLF	payload fairing
ppm	parts per million (10^{-6})
PSD	power spectral density
PV	pyrovalve

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Abbreviation	Meaning
QL	qualification level
R&D	research and development
RRS	random response spectrum
S/C	spacecraft
SDRA	shock damage risk analysis
SEA	statistical energy analysis
Shogun	shock generator unit
SASSA	shock attenuator system for spacecraft and adaptor
SRS	shock response spectrum
STFT	short time fourier transform
TFA	time frequency analysis
TFT	time frequency transform
TWT	travelling wave tube
VEB	vehicle equipment bay
VSEA	virtual statistical energy analysis
WT	wavelet transform

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General

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4 Background – Shock environment description

4.1 Shock definition and main characteristics

4.1.1 Shock definition

A shock is a local **transient mechanical loading** characterised by its **short duration** (order of magnitude from 50 µs to 20 ms), its high frequency (>1 kHz up to 1 MHz in case of pyroshock) and **high amplitude** with substantial initial rise time (approaching 10 µs).

It is usually very difficult to precisely measure or characterise the loading itself. Therefore a shock is classically observed through acceleration measurements which constitute the system response to the shock loading. These measurements are characterised in terms of time history by:

- Highly oscillatory response with large positive and negative peak amplitudes with the same order of magnitude;
- An envelope by a decreasing form of exponential function.

In terms of frequency, typical acceleration response to a shock loading are characterised by:

- Forced response at frequencies contained in the external shock loading (usually at high frequency);
- System natural frequencies (usually at lower frequency).

As an example, Figure 4-1 presents the typical acceleration profile resulting from a pyroshock.

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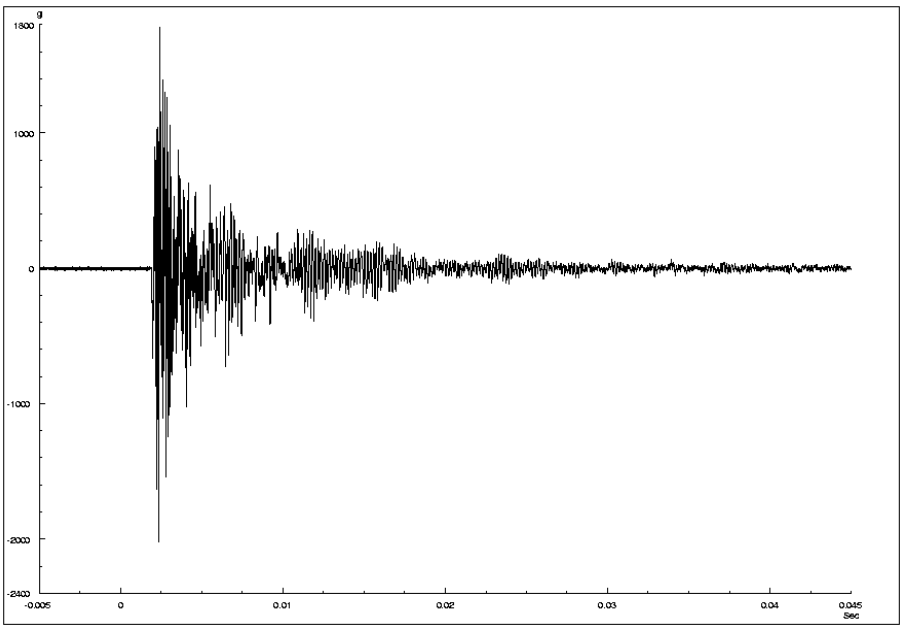


Figure 4-1: Example of shock acceleration measurements resulting from a pyroshock

4.1.2 Physical aspects of shocks

A shock **propagates** throughout the considered system as tension-compression, flexural or shear **waves** with **complex phenomena of reflection, dissipation and diffraction** at boundary conditions or mechanical discontinuities (bolted and riveted joints for instance). The flexural waves are dispersive whereas tension-compression and shear waves are not dispersive.

High frequency waves quickly vanish both in time and space, reducing the sharpness of the wave front, because of damping in materials and attenuation in joints: therefore it is more observable at the beginning of the shock measurement time history and at the vicinity of the shock source. Waves reflect on boundary conditions and internal interfaces, initiating a modal response of the system: this produces longer wavelength responses which can be found wherever in the structure even far from the shock source.

Such a shock environment is completely different from standard vibration. On one side a shock has an excitation duration which is significantly shorter than the response time of the equipment, and then the system responds freely. On the other side a vibration environment has an excitation duration which is long compared the response time of the equipment.

4.1.3 Main shock effects

The shock environment is an important matter of interest as it can induce **major failure** resulting in the total or partial loss of a space mission [RD-01][RD-07].

A non-exhaustive list of problems that can be caused by shocks at equipment level is given hereafter:

- Impact on electronics: material electronic card malfunction due to failure or degradation of electronic components such as for example relay, quartz, transformer, and self.
- Structural impact on materials: cracks and fractures in brittle materials (ceramics, crystals, epoxies or glass envelopes), local plastic deformation, or accelerated fatigue of materials for repeated shocks;

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- Impacts on mechanisms: the components used in the mechanisms, which are reputed sensitive are the bearings, gears, worm gears; their degradation mode is an excessive marking. The life duration impacts on the selection and the severity of the damage criteria. In this way, the residual marking is practically forbidden for long life duration mechanisms. In the opposite, for the mechanisms which are activated only a few times during their life, the residual marking size allowed are limited by their functionalities.
- Impacts on valves: the valve degradation modes are a limited leakage in quantity and time, a significant or permanent leakage and a structural degradation, which involves a malfunction of the valve mechanism.

4.1.4 Shock response spectra (SRS)

4.1.4.1 Overview

Time history constitutes the primary (and the most natural) accessible data since almost all physical signals are obtained by receivers recording variations with time. It contains obviously all the pertinent information and it is essential to save any time history in order not to lose any information.

However, a shock measurement in the form of a time-history is not directly useful for engineering purposes, e.g. comparing shocks severities and frequency contents, or understanding its effect on components. A reduction to a different form is widely used to deal with shocks: the Shock Response Spectrum (SRS).

4.1.4.2 Shock response spectra definition

The shock response spectrum (SRS) is a calculated function based on an input transient. It allows characterizing the shock effect on a **dynamical standardized system** in order to estimate its **severity or its damaging potential**. Thus it allows to compare shocks with each other or to establish equivalence criterion between a measured transient environment and a laboratory simulation of that transient environment.

The method consists in applying a time history as a base excitation to **an array of single-degree-of-freedom (SDOF) systems** and then calculating for each of them the **temporal maximum of their response**. The SRS can be defined for any input or response parameters of interest (displacement, velocity, or acceleration). For aerospace structures, it is common to define the input transient in terms of an **acceleration**. See Figure 4-2 and Figure 4-3.

The natural frequency of each SDOF is an independent variable. Thus, the calculation is performed for a number of independent SDOF systems, each with a unique quality factor Q=10, assuming conventionally the same damping (5 %) for each SDOF.

The choice of damping should be carried out according the structure subjected to the shock under consideration. When this is not known, or studies are being carried out with a view to comparison with already calculated spectra, a Q factor Q=10 is conventionally chosen.

Any arbitrary set of unique natural frequencies can be used for the shock response spectrum calculation. A typical scheme, however, is based on a proportional bandwidth, such as 1/24 octave. This means that each successive natural frequency is $2^{1/24}$ times the previous natural frequency. The SRS resolution is determined by this bandwidth and is independent of the transient duration. There are several SRS values that can be of interest for different applications, namely, the maximum absolute response of the SDOF versus frequency that occurs:

- during the application of the transient, called the **primary** SRS,
- after the transient is over, called the **residual** SRS,
- in the positive direction, called the **positive** SRS or SRS+,

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- in the negative direction, called the **negative** SRS or SRS-,
- at any time in either direction, called the **maximax** SRS (most usually used).

A typical maximax SRS is shown hereafter. The SRS acceleration is also called the maximum or peak absolute response.

NOTE 1 Primary and maximax SRS can differ when time signal has a non-negligible zero shift (also called DC-offset). See Paragraph 14 of the Part 3.

NOTE 2 SRS are often presented on a log-log graph. It is important to take care with this representation because of the real gap between two curves are visually minimized at high frequencies. A lin-lin representation allows sometimes to clearly visualise gaps.

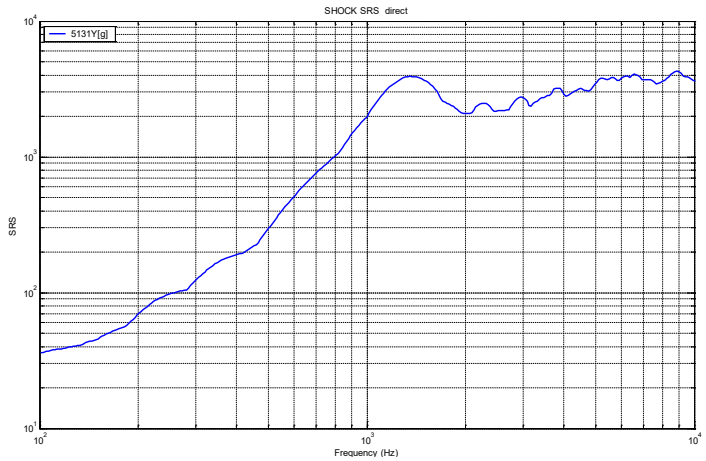


Figure 4-2: SRS example

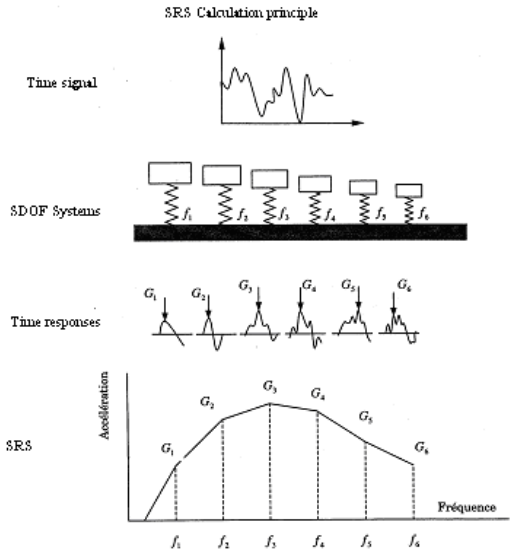


Figure 4-3: Shock response spectra principle

4.1.4.3 SRS properties

SRS main properties are given hereafter:

- If the velocity change is zero between the beginning and the end of the transient, the shock response spectra should have an initial slope of 12 dB/octave or a slope which changes in a smooth manner between 6 dB/octave and 12 dB/octave. SRS should be globally increasing (i.e. without taking into account local maxima) in low frequency range up to a maximum value. If the curve is decreasing or flat at the beginning, it could indicate a problem of zero offset or a truncation error. One of the dangers of these errors is they can propagate when specification are derived from incorrect measured SRS [RD-09]. See Figure 4-4.

NOTE The slope N of a line on a log-log graph is defined as

$$N = \frac{\log_{10} \frac{A_2}{A_1}}{\log_{10} \frac{f_2}{f_1}}$$

Therefore:

N=1 corresponds to a 6dB/octave line.

N=2 corresponds to a 12dB/octave line

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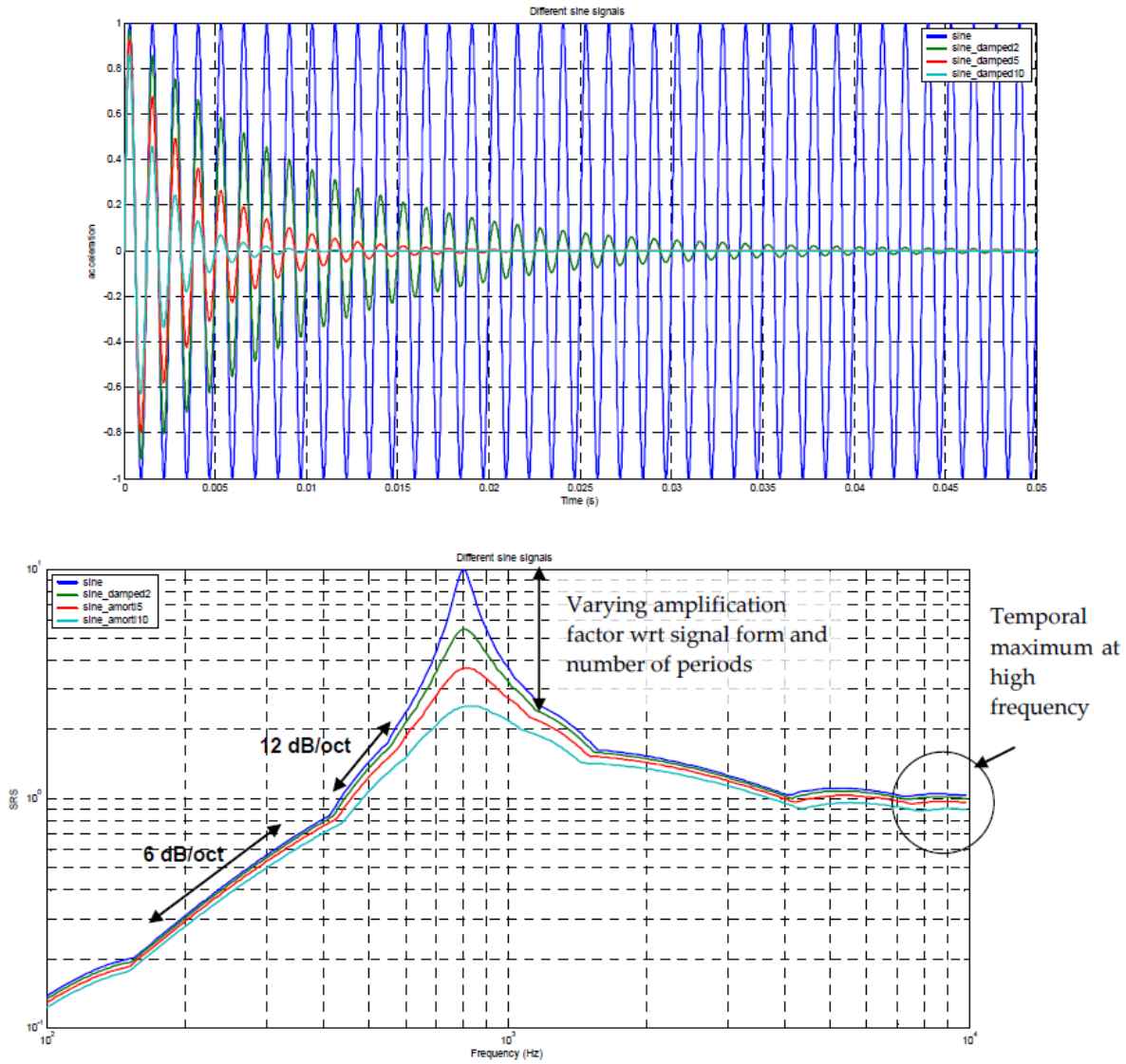


Figure 4-4: Example of SRS calculations, as function of transient signal characteristics

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- The value of the SRS approaches the absolute maximum value of the transient acceleration as the natural frequency of the SDOF exceeds the lesser of the highest frequency in the Fourier spectrum of the transient, or the upper frequency limit of the data acquisition system. The time history at the base of the considered SDOF acts indeed as a quasi-static excitation at this frequency. The SDOF's response follows consequently the time history oscillations. (see Figure 4-4)
- The amplification factor of a component in a signal depends on the signal form (see Figure 4-5). Considering a Q-factor of 10 for SRS calculation, it is comprised between 1,6 , corresponding to a half-sine time signal, up to 10, corresponding to a perfect sine signal with a sufficient number of periods. SRS of real signals have generally an amplification comprised between 3 and 4. In other words, a shock spectrum response (Q=10) performed on a shock signal has an amplitude about **3 to 4 times** higher than the maximum of the time history due to the transient (non-harmonic) nature of the signal. **This order of magnitude is useful to determine accelerometers calibration during a test campaign.**

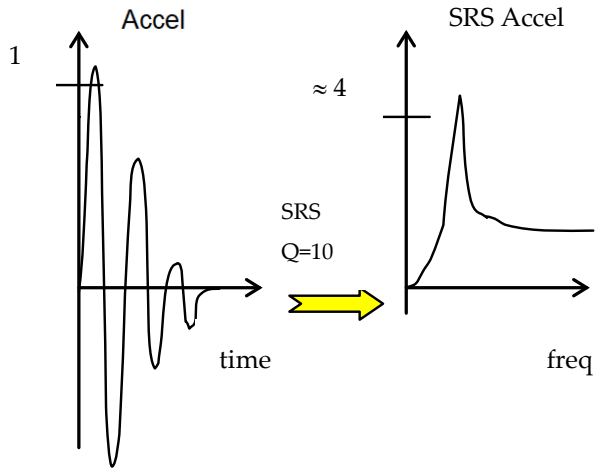


Figure 4-5: SRS peak amplitude derived from typical transient shock signal

- The SRS is **not linear with regard to the addition** of time signals. That is to say that the SRS of time signals sum is not equal to the sum of the individual time signals SRS.
- The SRS **is, in return, linear with regard to a scalar multiplication**. That is to say that the SRS of a time signal multiplied by a scalar α is equal to α times the SRS of the time signal.
- The SRS calculation is **not a bijective calculation**. Some information is definitively lost (like the phase or the effective duration information). It is thus essential to save any time history in order not to lose any information. Both the transient time history and resulting spectrum are critical to the environmental definition and test verification.

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4.1.4.4 Recommendations on SRS calculation

It is recommended to adhere to the following general guidelines:

a. The sampling rate for the input time history should be 8 times greater than the highest shock response spectrum calculation frequency and at least superior to 5 times.

b. The recommended frequency range for a SRS of a near-field time source is 100 Hz-100 kHz.

c. The recommended frequency range for a SRS of a medium or far-field time source is 100 Hz - 10 kHz.

d. The minimum sampling rate should be 12 points per octave, with an optimum number of 24 points per octave. Note that the higher the used Q-factor is the higher the frequency sampling should be.

e. For measurements on structures that experience no net velocity change due to the transient event, **the signal should be forced to yield a net velocity change of zero from the beginning to the end of the transient** event before the SRS computation. This condition is achieved by calculating the mean value of the acceleration signal, and subtracting this mean value from all data values.

4.1.4.5 SRS limitations

The notion of severity is relative to the considered dynamical system. Thus, real systems do never correspond to the standardized system: they do not have the same natural frequencies, and the real damping can be very different from 5 % (Q = 10).

Damage can be caused by amplification on an eigenmode. A source time signal with a frequency component near this eigenfrequency can be very severe, whereas another time signal with a high but different frequency component can be less severe for the considered unit. The difficulty comes generally from a very approximate knowledge of the mid and high frequency eigenmodes of real systems.

The SRS tool allows to compare shocks transients with each other, to consider envelopes and then specify shocks levels. This is today the universal tool for describing shocks, specify them or pronouncing qualification. However, it is not a perfect tool:

- The SRS **does not have a unique relationship with the transient signal** from which it is computed; i.e., it is possible for different transients to have the same SRS. These shocks have consequently the same effect on any of the SDOF with a Q-factor of 10 but can have a different effect on the considered system. In particular, it is often possible to at least coarsely approximate the maximax SRS for a complex, multi-cycle transient environment by an appropriately shaped single pulse transient in the laboratory. Of course, the required single pulse used for the simulation can have a much higher maximum level and a different effective duration than the actual environment, raising serious questions about the real severity of the simulation.
- The SRS does not allow to describe completely the frequency content of a signal. Some frequencies can be hidden by others peaks. Changing the Q-factor is the method to reveal these hidden peaks.
- The SRS is based on the response of a 1-DOF system which is not representative of real multi-DOF systems. This limitation is all the more important that the studied system has eigenmodes at close frequencies.

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5 Shock events

5.1 Shock occurrence

Spacecraft can sustain various types of shock during their development and mission.

From the launch to its mission end, a spacecraft can for instance sustain the following shocks:

- Launcher induced shocks such as fairing or stage separation. They propagate in the launcher structure, reach the launcher-spacecraft interface and then propagate in the spacecraft structure. These shocks are usually comprised in the launcher specification.
- Spacecraft release shock. They are directly generated at the launcher-spacecraft interface by the separation system (clampband release or other system). These shocks are also usually comprised in the launcher specification.
- Appendage release shocks or subsystem actuating shocks. Some appendages which are clamped for launch are released when in function (solar arrays, antenna reflectors, instruments). In the same way some subsystems can be actuated by devices producing shocks, such as pyrovalves or mechanisms. These shocks occur generally during stationing or at the beginning of mission, but can occur even later after an interplanetary travel for instance.

These shocks can sometimes be generated by low shock devices, which significantly reduces their criticality.

During spacecraft development, some shocks can also occur: they are usually qualification or acceptance shock tests at system (spacecraft release shock) or subsystem level (equipment qualification on shock machine or test bench); they can also be characterisation tests (SHOck Generator UNit or Shogun to evaluate propagation w.r.t. launcher induced shocks).

5.2 Shock environmental categories

Shock environment is usually divided into three categories, basically near-field, medium-field and far-field. The distinction between these categories is based on the magnitude and the spectral content of the environment. There is however neither formal separation nor precise limit value, especially in terms of distance from the source: such a classification depends on the type and strength of the considered device and the detailed configuration of the structure (that drives the shock propagation path). However these categories can have a strong influence on the hardware design or selection.

These categories are generally described as follows:

- The **near-field** environment is dominated by **direct wave propagation** from the source with very high peak accelerations (that can exceed 5000 g) and a very high frequency content (well above 10 kHz for pyrotechnic sources). Depending of the source such a near-field environment is located from several to a dozen centimetres from the source.

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- The **mid-field** environment is characterised by a **combination of the propagating waves and the structural resonances**, issued from recombination of reflecting waves on the boundary conditions. The maximum acceleration peak is weaker than in near-field (down to a fifth of the near-field peak values) and the frequency content still presents high frequency components (up to 10 kHz). Depending on the source, mid-field environment is located from a dozen to several dozen centimetres from the source.
- The **far-field** environment is dominated by the **structural resonances** issued from recombination of reflecting waves on the boundary conditions. The resulting peak accelerations are really weaker (up to a fifth of the near-field peak values) as compared to those in near- or medium-field and most of the frequency content is below 10 kHz. The far-field environment is located outside the mid-field environment.

As illustrated in Figure 5-1, the severity (characterised here by its Shock Response Spectrum, see 4.1.4) of a far-field environment is not necessarily decreasing when the distance from the source to the response point of interest is increasing. This is especially true in the frequency range dominated by high structural resonances (typically below 2 kHz).

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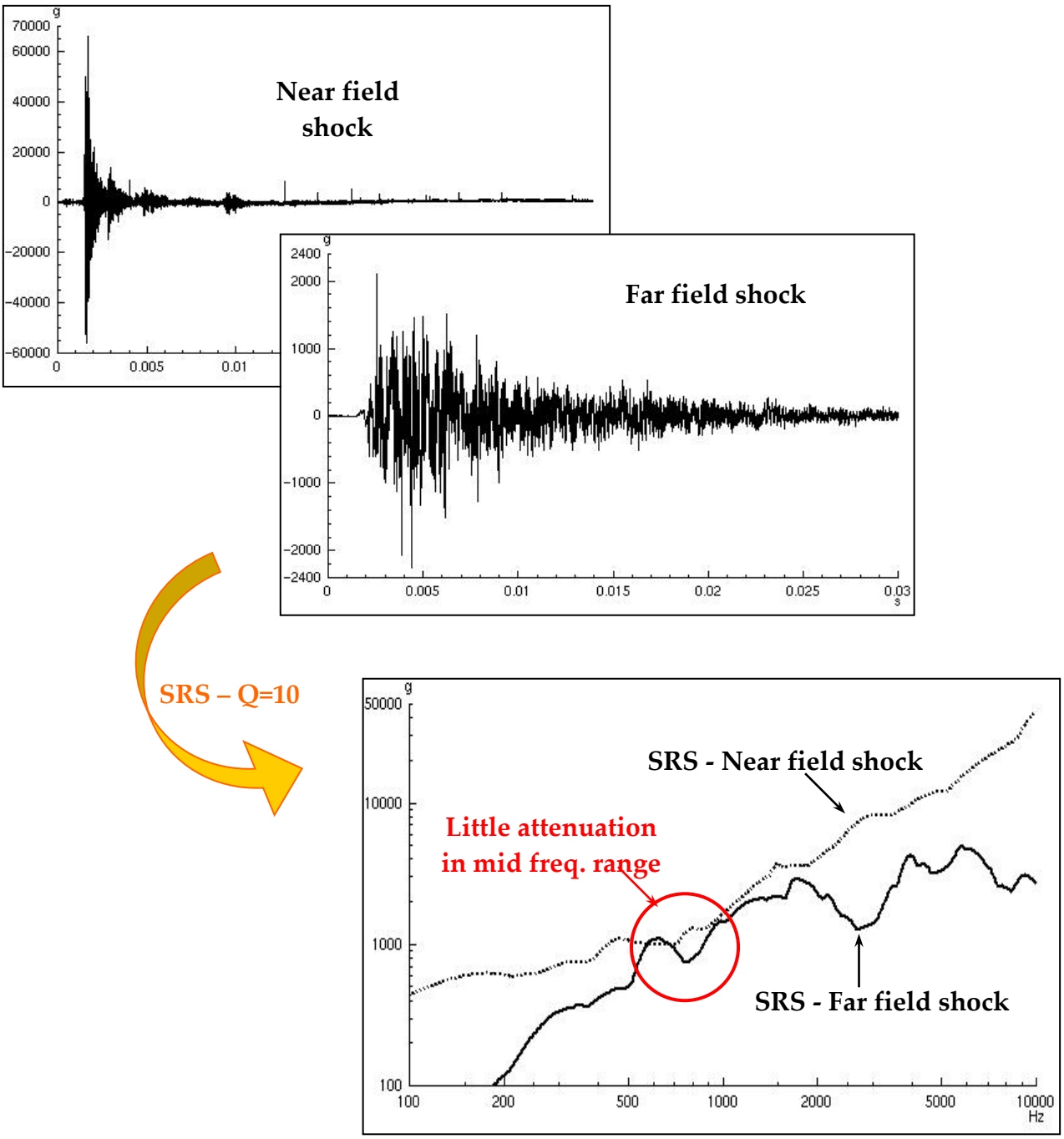


Figure 5-1: Comparison of shock severity of two signals, one close to the shock source (near field) and the other several meters from the source (far field)

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6 Introduction to shock design and verification process

6.1 Presentation of the global process

The process of shock design and verification is illustrated in Figure 6-1.

The structure of this Handbook is built with respect to this process.

The first part is the current one, presenting the basis of shock design and verification.

The second part is dealing with the derivation of spacecraft shock environment to units and subsystems. The main inputs are information on shock sources such as shock specification from the launcher and spacecraft internal shocks environments and the spacecraft architecture. The objective is to determine the shock environment for each unit of the spacecraft and use it to derive a specification using a given margin policy. The main methods to do it are similarity and heritage methods and numerical FEM calculations. Additional inputs are required depending on the method: a test database for the first one and a Finite Element Model or SEA model for the second. Additional outputs can be attenuation rules related to the studied structure or Maximum Expected Flight Environment (MEFE) when using statistical methods.

The third part focuses on the shock verification approach. The objective of the verification is to prove that the specimen (at unit or system level) can sustain the required shock environment. This can be done either by analysis or by testing. In case of testing, specific inputs are needed: a shock test facility adequate with the specification and the unit hardware depending on the testing philosophy (e.g. PFM and QM). The test results should be used to feed shock databases as these are inputs for derivation of spacecraft shock environment to units or for unit qualification by analysis. In this part, methods and tools to have a proper assessment of shock data and thus evaluate the shock test are also given. In the ideal case, the capability of the spacecraft to withstand or, if appropriate, to operate in the induced shock environments is demonstrated after this operation. And the shock qualification is achieved.

However, in some cases, the shock qualification cannot be directly achieved (shock environment not completely validated by system level and unit level testing). In general, this problem is discovered too late to perform a delta qualification at unit level. This can lead to a Shock and Damage Risk Analysis (SDRA) which is the topic of the **fourth part**. This part focuses on shock consequences on equipment and needs many engineering or functional data on the concerned unit. Equipment sensitivity and failure modes are particularly focused on. The main output is a risk analysis which concludes on the ability to flight of the concerned unit.

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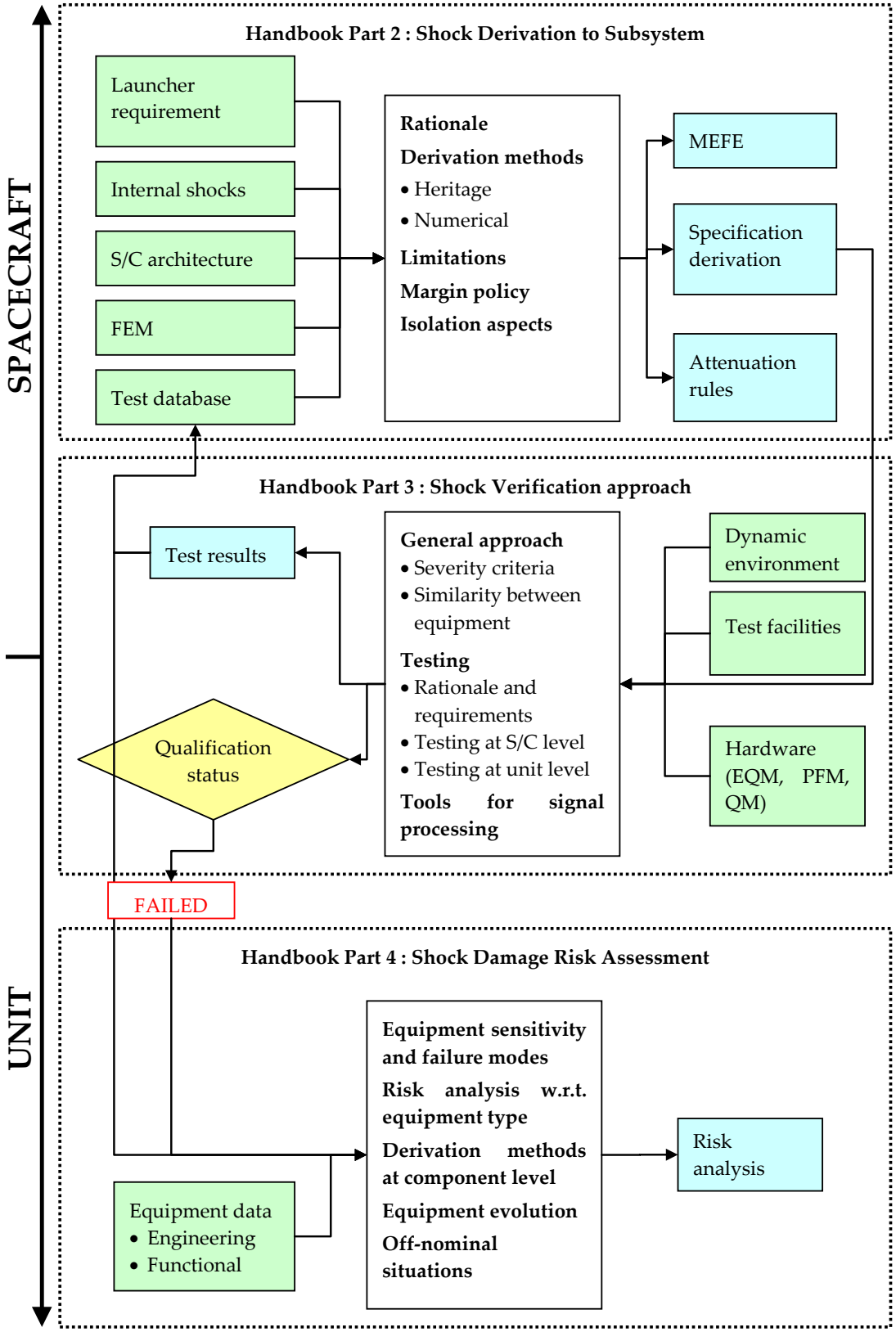


Figure 6-1: Overall logic of shock handbook w.r.t. shock design and verification process

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6.2 Means to conduct an evaluation of shock environment and criticality

To follow this global process of shock design and verification, several means are available and can be explained and detailed in the further parts of the handbook: e.g. numerical analyses and extrapolation methods.

The objective of this paragraph 6.2 is to present what is recommended in term of tasks to be performed with respect to the workflow of a standard programme. Table 6-1 thus shows the hypotheses, objectives, recommended method and requirements of this shock evaluation at 3 main stages of a programme: Early phase (SRR level), Intermediate phase (PDR/CDR level) and Final verification phase (QR level).

Table 6-1: Shock evaluation methods w.r.t. project status

	Early phase (SRR level)	Intermediate phase (PDR/CDR level)	Final verification phase (QR level)
Hypothesis	• Overall configuration defined but structural details not fixed. • Shock events known but sources and inputs only roughly defined.	• S/C structure already defined but layout subject to changes. • Shock events, sources and inputs known.	• System and subsystems shock tests already performed. • Qualification status not achieved.
Objective	To derive preliminary conservative specification within each zone of the spacecraft, and better understand/anticipate the shock severity within each zone	To derive consolidated and conservative specification within each zone of the spacecraft.	To have a critical review of test results and specifications (doubt on representativeness of test configuration,…) in order to consolidate the qualification status.
Method	Identify dimensioning shock environment and apply relevant similarity-heritage-extrapolation methods.	Combination of similarity-heritage-extrapolation methods and numerical analyses (several restitution points within each zone).	Verification of analysis robustness followed by detailed numerical analyses (restitution points at sensors location).

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Part 2
Shock input derivation to space segment elements and equipment

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7 Shocks in spacecraft

7.1 Overview

This chapter lists the different shock events and associated devices. Its aim is to remind that the use of certain devices should always make shock a matter of concern.

7.2 Potential shock sources for spacecraft

The different shock events are separated in two different categories: shocks during service life and shocks related to testing as described in Figure 7-1.

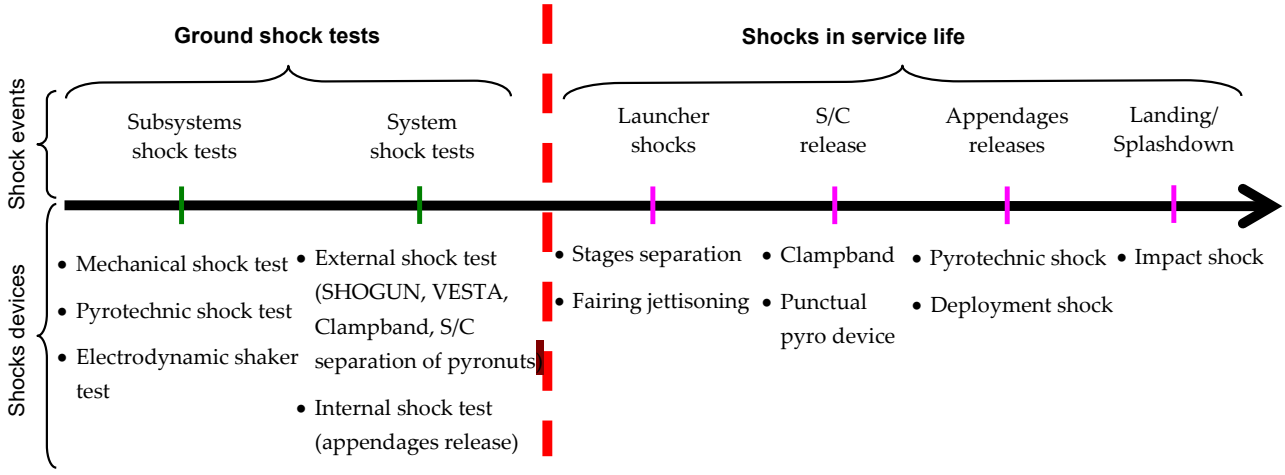


Figure 7-1: Shocks in a spacecraft project

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7.3 Shocks devices description

Shock devices used for these different shock events are quickly presented in Table 7-1 for ground shock tests and in Table 7-2 for shocks in service life, for which indication of shock origin (external/internal with respect to spacecraft) is given.

Table 7-1: List of potential shock sources for ground shock tests

Ground shock tests	
Subsystem shock test	Mechanical and pyrotechnic shock machine used for equipment testing: several kinds of shock machines have been developed to qualify equipment to shocks. They can be either mechanical (usually by the mean of a hammer hitting a dedicated shock table) or pyrotechnic. See Part 3 of this handbook for further information. Electrodynamic means (shaker): shakers can be used to qualify equipment to shock with short excitation pulses. They are however relatively limited in terms of level and frequency band capacities.
Specific shock tests at system level (i.e. not on-ground tests of flight devices)	SHOGUN: this device is intended to represent Ariane 5 launcher shocks, especially fairing separation. It is composed of a pyrotechnic linear cord charge inside a weakened aluminium structure. The shock wave is generated by the expansion of the tube causing a controlled rupture of the lower flange screw section. VESTA: this device is intended to represent VEGA launcher shocks, especially fairing separation. It is represented by a full scale mock-up of the VEGA upper composite and the shock is generated by the release of the HSS belt achieved through the activation of bolt cutters. Pyrotechnic Ariane 5 ASAP kit: such a device is intended to be representative of an ASAP 5 microsatellite separation system shock. See 7.4.4 for further information.

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Table 7-2: List of potential shock sources for shocks in service life

Shocks in service life		
Shock	**Description**	**Origin (w.r.t. S/C)**
Launcher induced shock before spacecraft release	This category gathers all shock sources inside the launcher, such as stages separations or fairing jettisoning. Different systems exist: for instance separation by pyrojets, symmetric or asymmetric tight barrier.	External
Spacecraft release from launcher	Clampband release: the clampband is a structural piece usually used to link the spacecraft to the launcher interface. This clampband is preloaded and is released by different means, usually using pyrotechnics. Other separation systems (see 7.4.4 for further information): Rockot Mechanical Lock Systems: used for spacecraft attached to the launch vehicle through discrete points. PSLV spacecraft separation system: separation system based on ball locks. ASAP 5 microsatellite separation system: this device is used on Ariane 5 structure for microsatellites ASAP5. Classical pyronut separation systems	External
Appendages release (during stationing or mission)	Bolt-cutter: a pyrotechnic device actuates a cutter which cuts a pre-loaded bolt that maintains a subsystem in its clamped configuration. Wire-cutter: a pyrotechnic device actuates a cutter which cuts a pre-loaded wire that maintains a subsystem in its clamped configuration. Pin-puller: a pyrotechnic device generates gases which drive the pin through pressure effect from its initial clamping position to its end position, releasing a mechanism. Explosive bolts (including for separation system): bolts loaded by a pyrotechnic device that explode to release the subsystem they were maintaining. "Low shock" devices with a mechanical pre-load which is released by other means than a pyrotechnic system: these devices can be used as pin pullers, separation nuts or bolts, release mechanisms, actuators, switches, powered hinges and valves. See below.	Internal
Other shock sources during mission	Mechanical stop in mechanisms: Such shocks can occur in mechanisms such as stepper, or at the end of an appendage deployment due to stop end. Pyrotechnic valves: a pyrotechnic device produces gases under high pressure, which has the effect of suddenly deforming a membrane equipped with a rigid weight. The latter projects a punch, which shears a tight end fitting, thus freeing the fluid passage.	Internal

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Low shock devices are used for internal appendages release, in order to protect very sensitive equipment or instruments which are implemented in direct vicinity of the release device (shock source). This allows facilitating or even making possible the spacecraft or sub-system architecture, e.g. on optical instruments where systems are installed close to the secondary mirror for opening a protection cap.

The implementation of such devices is very complex, as most of the time a lot of electrical energy is needed to actuate them the routing of adequate cables can, in some cases, be complex, and therefore it is very important to take this into account as early as possible in the design process.

It is also noticeable that "low-shock" can be an abusive term where it consists only in replacing the pyrotechnic actuator (thus reducing a primary shock) without changing the released mechanical element. For instance, when a low-shock device is used to release a highly preloaded tie-rod, high shock loads can still be generated by the relaxation of the stored energy into the tie-rod.

A specific list of current low shock technologies is shown hereafter to sum up the currently available shock devices technologies ([RD-010][RD-011]):

- Electro-mechanical spool: a spring is loaded by a sectioned spool, overwrapped by a retaining wire, the latter held in-place by a linkwire. Current passing through the linkwire causes it to fail, thereby releasing the retainer wire and allowing separation of the spool halves.
- Paraffin actuator: High Output Paraffin (HOP) actuator uses constrained volumetric expansion of highly refined polymer at a given transition temperature to produce large hydrostatic pressure that is translated to actuator through a hermetic seal.
- Shape Memory Alloy (SMA): such system uses the shape memory effect which is based on a transformation which is reversible upon heating. Thus SMAs can undergo deformation which is retained until they are heated above a transition temperature at which point a reverse transformation occurs and the original non-deformed shape is restored.
- Pyrosoft: the Pyrosoft is a low shock device. The release of the screw is initiated by the melting of a thermite composition. Those thermite allow the debasing of a threaded ring which releases the piston and the threaded segment. The duration of the process, at least 0,5 second allows a progressive release of the screw in two phases; first the release of the tension and in a second part the liberation of the screw.
- Thermal knife: this kind of device is based on thermal degradation of a pre-tensioned cable (for instance Kevlar/Aramid). An electrically heated knife gradually melts through the cable causing degraded fibres to fail reducing cable cross section until the cable to fail under the residual tension.

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7.4 Detailed information on specific shock events

7.4.1 Overview

This paragraph 7.4 describes the different shock events and their main characteristics (notably in terms of frequency content with an SRS representation). A distinction is made between external shocks originating from payload fairing jettison, launcher stage separation or spacecraft release and internal shocks occurring in the spacecraft, typically for appendage release.

7.4.2 Launcher induced shocks

Launcher induced shocks gather all shocks occurring in the launcher structure that propagate through the launcher structure and the payload adaptor up to the spacecraft interface. Such shocks are mainly due to stage separation and fairing jettisoning. Clampband release is not considered, in this handbook, as a launcher induced shock and is specifically addressed in the paragraph 7.4.3.

The severity of the launcher induced shock seen by the spacecraft, mainly depends on:

- The type of separation devices used for the stage separation or fairing jettisoning, with a lower severity for bi-rupture (symmetric) separation or punctual separation systems compared to mono-rupture or pyrojet separation systems.
- The overall architecture of the launcher, and especially distance and loadpath characteristics between the shock sources and the spacecraft interface.

There is therefore no absolute rule valid for all launchers, each of them having its own specificities:

- **ARIANE 5**: Owing to continuous improvements of the launch vehicle, the severity of the launcher induced shocks has been significantly reduced, through the introduction of a bi-rupture separation system for the upper stage separation (replacing mono-rupture separation system), and of a quasi-symmetric separation device for the fairing (so-called HSS3+, with recurring production target in mid 2015).

  NOTE With the introduction of the HSS3+, the fairing separation shock level is equivalent to the upper stage separation shock and below 0.2 x f. The dimensioning shock event for the spacecraft becomes the clamp-band release.

  NOTE The handbook currently presents the shock environment of the earlier and current launch vehicle definition (excluding HSS3+) and associated verification method (i.e. Shogun test method, see Para. 7.4.2.1, and Part 3).

- **VEGA:** Dimensioning shock is induced by the fairing separation especially for frequencies up to about 3kHz. For higher frequencies, the upper stage separation is dimensioning.

In general these specificities are presented and continuously updated in user manuals. For other launcher, user manuals should be consulted.

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The launch induced shocks have specific characteristics depending on the type of separation.

- Frequency content of the excitation: There can be important **low frequency components** in launcher induced shock, typically from 300 Hz to 1kHz. These components are due to modal response of some elements of the launcher that are well transmitted to the spacecraft-launcher interface. An important parameter driving these low frequency components is the stiffness and the diameter of the interface where the separation occurs.

  Figure 7-2 here below presents the envelope spectrum for stage and fairing separations (HSS1) and for clampband release. The existence of specific modal responses between 400 and 700 Hz is here indicated through the particular shape of the stage/fairing spectrum at these frequencies. Thus level is higher in this band in comparison with a continuously increasing slope (of 12 dB or 9dB per octave) up to the elbow point at 1000 Hz. This is not seen for clampband release for which response is driven by interface ring mode around 1000 Hz, depending from the spacecraft ring diameter.

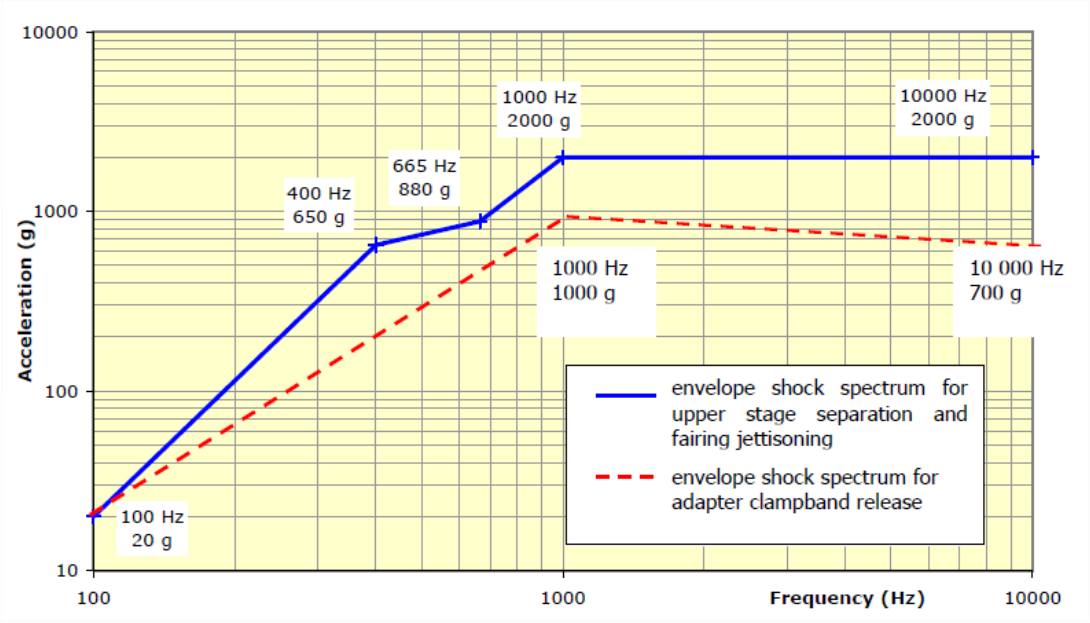


Figure 7-2: Envelope shock spectrum for the upper stage separation and fairing jettisoning and envelope shock spectrum for clampband release at spacecraft interface – From Ariane 5 User's Manual Issue 5

- Due to dissipation and diffraction effects, the further the separation occurs from the spacecraft-launcher interface, the greater is the attenuation of the high frequency levels. This notion of distance is based on both the physical distance and the complexity of the propagation path (number of structural joints). This is usually not true for low or medium frequency levels. An example of the dependency of high frequencies shock levels with respect to the distance is shown in Figure 7-3, with the comparison of shock levels along the primary loadpath and for increasing distances with respect to the shock source. As such, the excitation of lower frequency modes are well transmitted to the spacecraft-launcher interface and beyond, whereas the high frequencies shock levels are more quickly attenuated.

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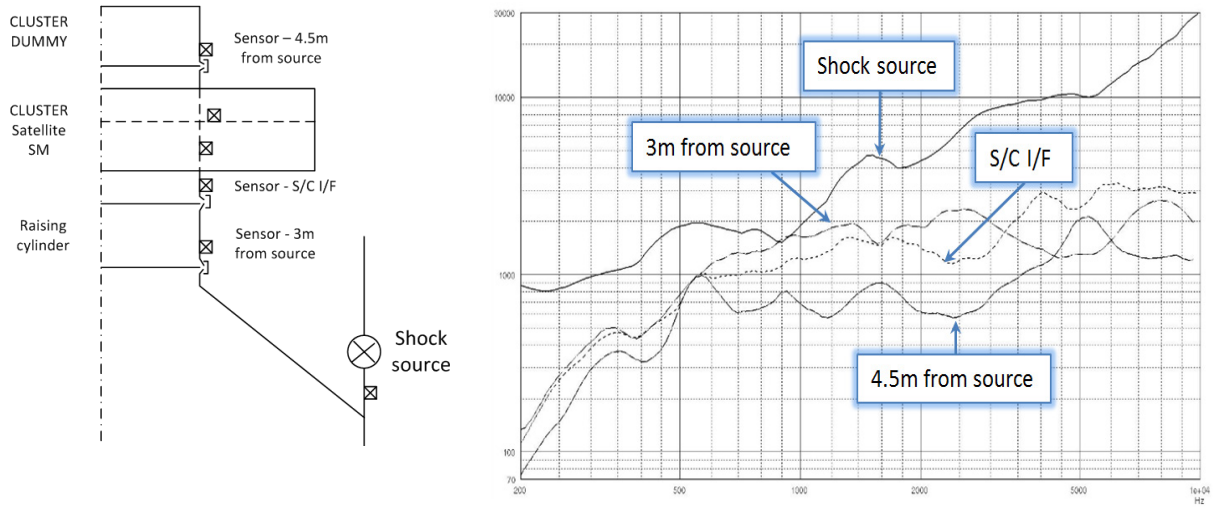


Figure 7-3: Comparison of shock levels with increasing distances from the shock source (system level shock test performed on CLUSTER satellite)

- Severity: A mono-rupture separation creates more levels at low and medium frequencies up to 6000Hz than a bi-rupture separation. An example of such an impact of the separation type is shown in Figure 7-4.

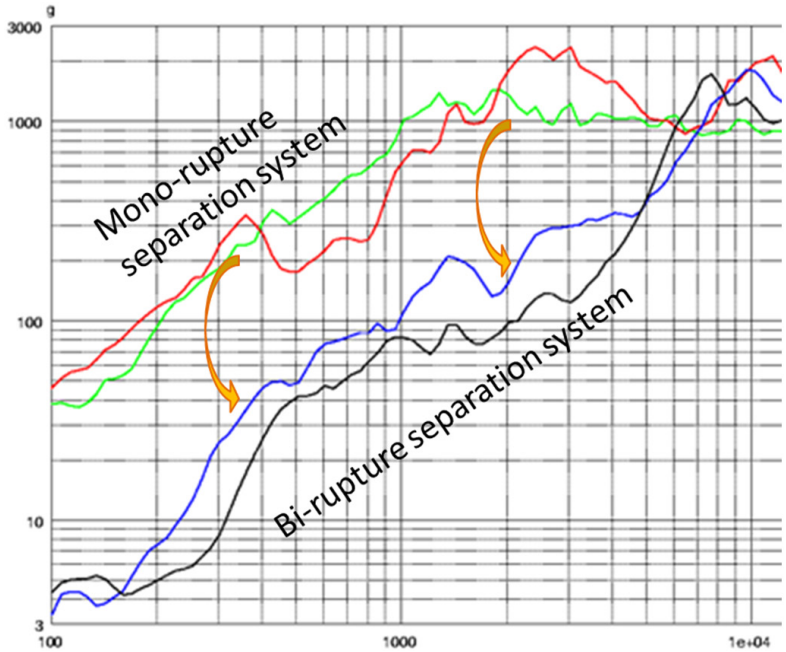


Figure 7-4: Comparison of shock levels at spacecraft interface for a mono-rupture and a bi-rupture separation system

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- The best way to have a representative characterisation of such a launcher induced environment is to conduct a test at system level with launcher structures and a payload dummy, with a flight representative separation system being fired. In this case a particular attention should be paid to boundary conditions.
- As the pyrotechnic separation device is very well controlled, if the mechanical characteristic on the propagation path toward the spacecraft are identical, a good repeatability is achieved.
- The launcher induced shock specification is derived from flight measurement and statistics made on a spacecraft family using a given launcher position and a given adaptor. An illustration of consistency between launcher induced specification and the shock flight measurement for two spacecraft within the same family (same platform in same launcher position with same adaptor) on Ariane 5 is presented on Figure 7-5. It shows the good repeatability of launcher induced shock and the adequacy of the specification at spacecraft interface.

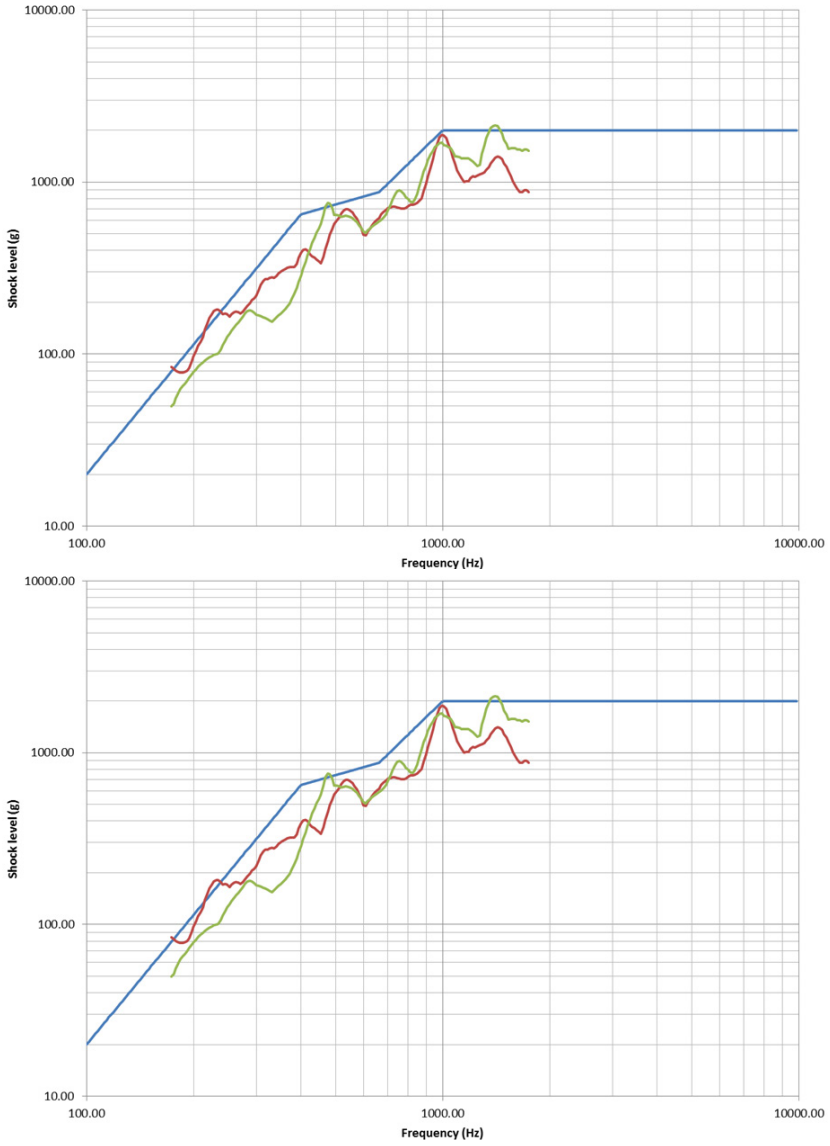


Figure 7-5: Consistency between flight shock measurement and launcher induced specification for Ariane 5 at spacecraft interface in launcher Axial direction.

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7.4.2.1 Example of spacecraft/LV shock compatibility test – SHOGUN

Shogun stands for SHock Generator UNit: it is a **characterisation mean** designed for dealing with the specificity of shocks generated by the Ariane 5 launcher. It is a pyrotechnic device based on the expansion of a pyrotechnic tube that breaks a weakened section (Figure 7-6). In this way the principle is similar to the of a launcher stage separation, which it is intended to represent.

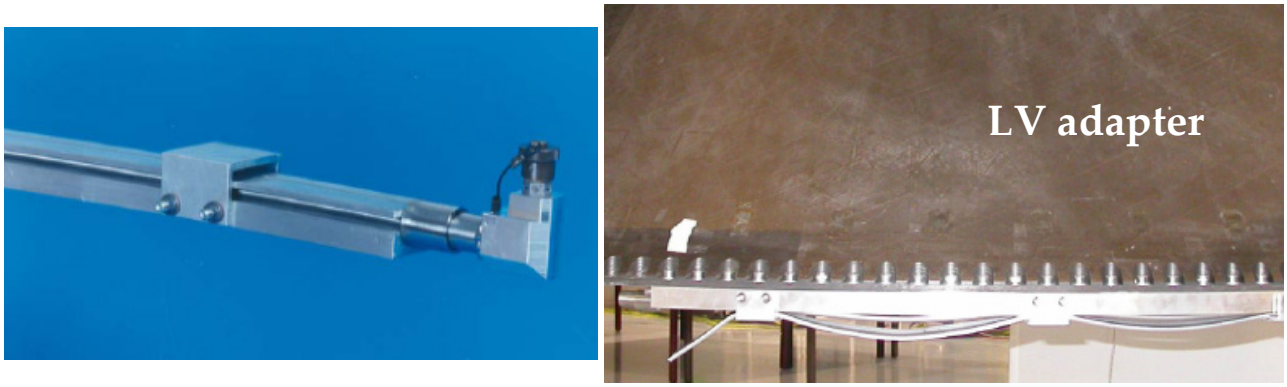


Figure 7-6: Views of a Shogun device (Dassault / Courtesy)

The main characteristics of such a shock are given hereafter:

- Even if the shock source is achieved by adopting the same principle of a launcher stage separation, this shock occurs with different boundary conditions (LV adapter is free at its base) in comparison to those of a real launcher induced shock. Thus the Shogun low frequency content can be quite different from the one of a launcher induced shock. This can be seen in Figure 7-7.

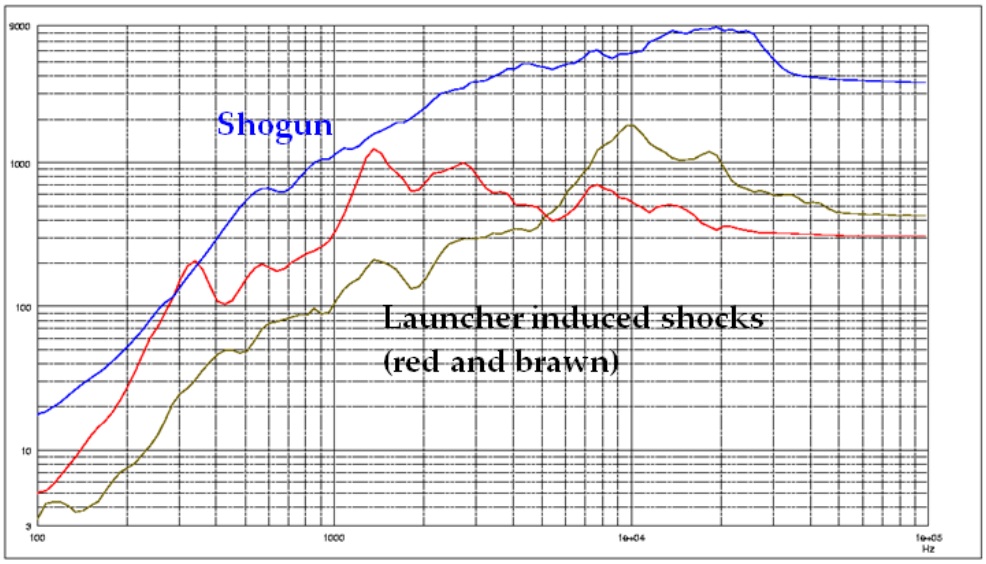


Figure 7-7: Comparison between Shogun and launcher induced shocks levels at the spacecraft interface

- A Shogun test occurs immediately at the base of the payload adapter, which is far closer to the spacecraft interface than for a real launcher shock. As a consequence high frequency levels are less attenuated than for a real launcher shock event. This can also be seen in Figure 7-7.

Therefore the use of such a test is limited to the characterisation of the transfer function between spacecraft launcher interface and an equipment inside the spacecraft. As a matter of fact the Shogun

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test is considered representative of the shock propagation inside the structure for launcher induced shocks type of source.

Details on the associated extrapolation method to derive qualifying environment at unit levels, can be found in paragraph 13.3.2.2.2.

7.4.2.2 Example of spacecraft/LV shock compatibility test – VESTA

VESTA is the acronym for VEga Shock Test Apparatus. It is a test method designed and developed in order to support the qualification of spacecraft to be flown on the VEGA launcher. It aims at reproducing the shock generated during the VEGA fairing jettisoning phase.

The test method (see Figure 7-8) is built from several stage/component full scale mock-ups used during the VEGA development and consists in a flight representative model of the VEGA upper composite. VESTA simulates the release of the fairing belt at the base of the payload adapter using the same hardware available during a typical VEGA flight (fairing belt and bolt cutters), then the shock generated is fully representative with respect to the one experienced in flight.



Figure 7-8: VESTA test method including the AGILE STM

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The main characteristics of the shock generated by VESTA are given hereafter:

- The shock level at the spacecraft base is driven by the tension applied in the HSS belt. The SRS is mainly dominated by the response of the adapter ring mode at about 800 Hz
- The shock levels can be tuned by adjusting the tension of the HSS belt (from typically 20kN up to the HSS tension foreseen at the time of the Fairing separation).

Several tests have already been performed in order to characterize and validate this test tool. Some results in terms of shock at spacecraft interface are shown in Figure 7-9.

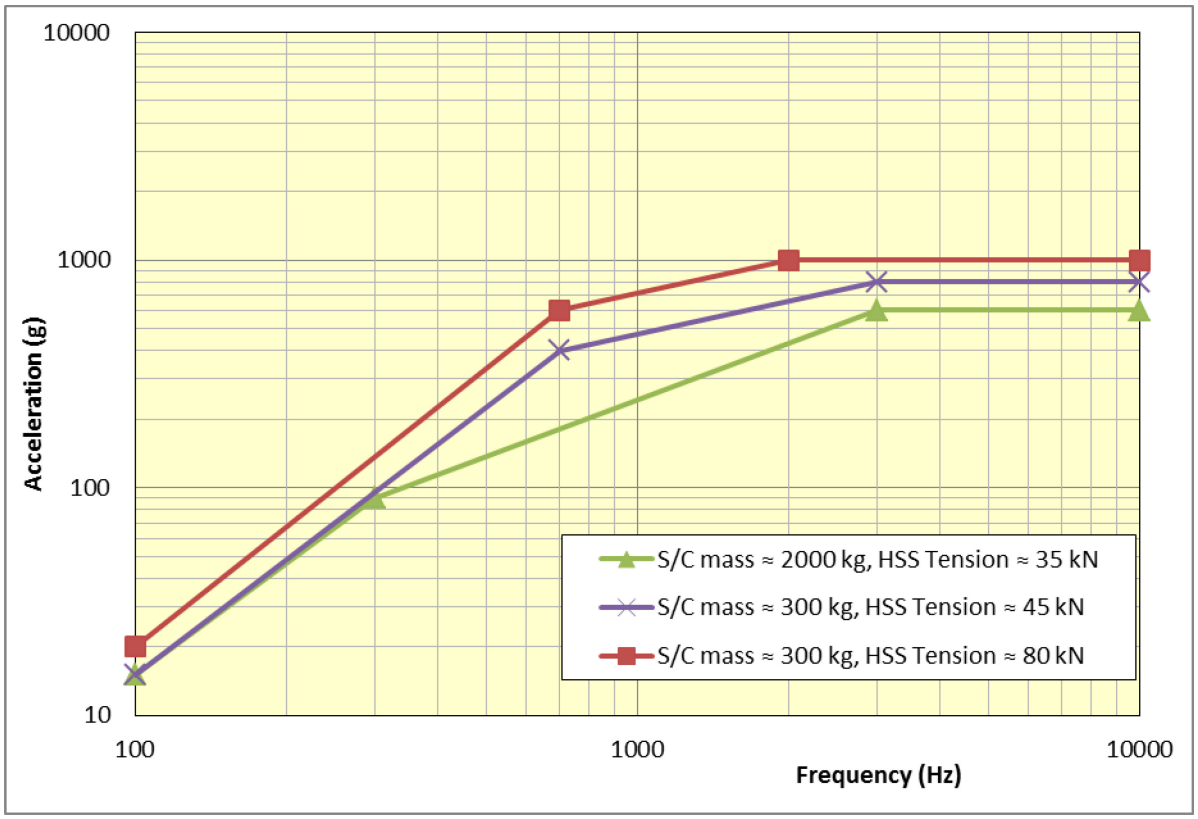


Figure 7-9: Results from VESTA test method for different configurations (shock at S/C interface, on the LV side)

Details on the associated extrapolation method to derive qualifying environment at unit levels, can be found in paragraph 13.3.2.2.2.

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