Shock qualification facilities of spatial electronic devices using pyrotechnic excitation

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Abstract— **During space flights, pyrotechnic devices are used for various purposes as booster separation, unfolding solar panels or activation of propellant valves. The firing of these pyrotechnic devices generates a severe shock wave, characterised by a high intensity and a wide frequency range, which can damage the surrounding electronic equipments. Test specifications imposed to embarked electronic devices are generally defined as a maximum limit imposed to the Shock Response Spectrum.**

Specific qualifications facilities have been developed in collaboration with Alcatel ETCA. They are based on suspended plate structures supporting the tested electronic device, and submitted to a shock generated by an explosive cord. A trial and error experimental procedure is generally applied to tune the operating parameters in order to satisfy the launcher's specifications.

This paper presents a simulation of the testing procedure in order to predict the Shock Response Spectrum. Such a model facilitates the determination of the adequate operating conditions.

It is based on a finite elements model of the structure, which has been updated using an experimental modal analysis. Different excitation models are tested, such as an equivalent mechanical shock located at a fixed point in the vicinity of the explosive charge, or the propagation along the plate of a wave shock. Vibration measurements on the testing device and air pressure measurements have been experimentally obtained.

Keywords— **Pyroshock, Shock Response Spectrum (SRS)**

I. Introduction

Pyrotechnic devices are widely used in spatial applications (booster separation, unfolding solar panels,...). Therefore, the launchers have to make sure that the aboard equipments will not be damaged by shock waves generated by pyrotechnic explosions. The tested equipments have to respect specifications imposed by the launcher. These specifications are generally expressed in term of Shock Response Spectrum.

At this time, the pyrotechnic shock resistance is generally checked experimentally in reason of the difficulty to approach the problem with computational techniques, especially concerning an accurate model of the excitation.

Several types of shock testing devices have been developed to verify these specifications. We'll focus in this paper on the facilities developed in collaboration with Alcatel Etca (Charleroi). This pyroshock device is made of steel or aluminium plates supported with steel cables at a tubular structure. Different configurations have been tested either in vertical or horizontal orientation. The shock is generated using an explosive cord fired by a detonator.

The simulation of the shock requires an accurate knowledge of the wave shock produced by pyrotechnic explosion and the way it propagates along the plate. A complete simulation is complex because the phenomena depend on the way the wave interacts with the plate, the room geometry governing the wave's reflections. Different excitation models can also be used, such as an equivalent mechanical shock located at a fixed point in the vicinity of the explosive charge, or the propagation along the plate of a wave shock.

II. Test Specifications

A. Shock Response Spectrum : definition

The most widely used technique to quantify mechanical shocks is the Shock Response Spectrum (SRS). Historically, the SRS has been introduced by M.A.Biot [1] to evaluate the effects of earthquakes on building trades. The SRS, viewed as a measure of the damage potential, is useful to compare the severity between different shocks.

The SRS depends on the time history of the absolute response to a shock (commonly in term of acceleration). It is described by the plot of the maximum relative response of a single degree of freedom system in function of its own natural frequency when its foundation is animated by a motion corresponding to the time history absolute acceleration [2]. The maximum relative response is supposed in practice to be related to the stress level in the tested equipment [7], [4]. Figure 2 represents the acceleration time-history for a typical pyrotechnic shock and figure 3 illustrates the SRS associated to this acceleration.

The motion of the system in Fig. 1 is characterized by the following classical diffential equation:

$$m\,\ddot{x} + c\,(\dot{x} - \dot{y}) + k(x - y) = 0\ ,$$

where $x(t)$ is the absolute response and $y(t)$ the foundation excitation. By introducing the relative displacement $\delta(t) = x(t) - y(t)$, this equation can be rewritten as follows:

$$\ddot{\delta} + 2\xi\omega_0\,\dot{\delta} + \omega_0^2\,\delta = -\ddot{y} \tag{1}$$

ω_0 representing the natural pulsation of the system and ξ the corresponding damping ratio defined by:

$$2\,\xi\omega_0 = c/m$$

The solution of previous differential equation 1 is given by the Duhamel integral [2]:

$$\delta(t) = \frac{1}{\omega_0\sqrt{1-\xi^2}} \int_0^t -\ddot{y}(\tau)\, e^{-\xi\omega_0(t-\tau)} \sin\left(\sqrt{1-\xi^2}\,\omega_0\,(t-\tau)\right) d\tau$$

In terms of displacements, the SRS is calculated by considering the absolute maximum of the relative displacement function $\delta(t)$ for each natural frequency. In terms of accelerations, the SRS is modified by multiplying by ω_0^2 the displacement SRS [2], [7].
A damping ratio ξ value of 5% is taken for electronic devices which corresponds to a dynamic amplification factor of 10.

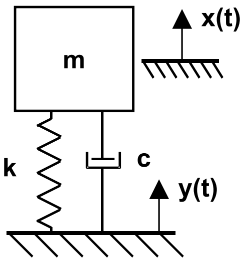

Fig. 1. Single degree of freedom system.

B. *Test specifications*

During the experimental tests, the equipments is submitted to a pyrotechnic shock which has to verify the SRS specifications imposed by the launcher in three orthogonal directions. Acceleration values are specified from a low frequency limit of several hundreds Hz to a high frequency limit of 10 kHz, or even in some case 25 kHz (as it is the case for Ariane 5 specifications)(Fig.4). Generally, a small difference is admitted between observed and required SRS such as in practice [3] :

- ± 6 dB for natural frequencies $\leq$ 3000 Hz,
- $+9$dB$/-6$ dB for natural frequencies $>$ 3000 Hz.

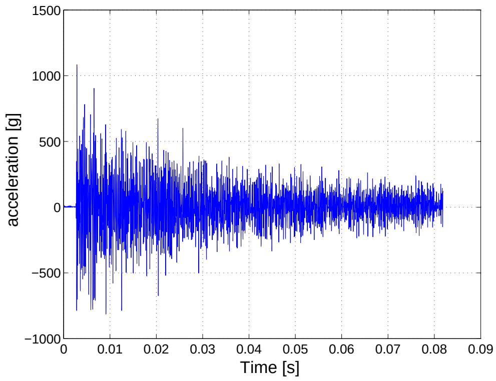

Fig. 2. Acceleration time-history for a pyroshock.

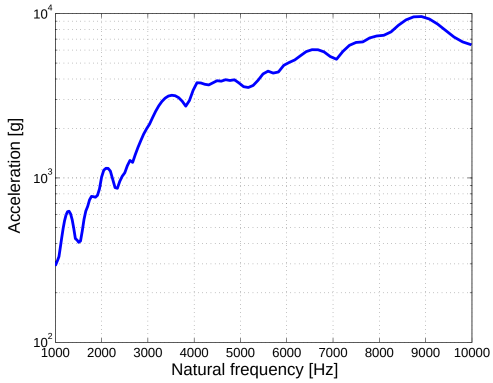

Fig. 3. SRS of a pyroshock.

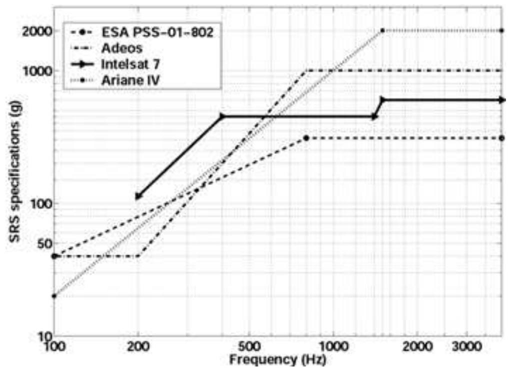

Fig. 4. Examples of SRS specifications

III. The Alcatel Etca test facilities

A pyroshock testing device has been developed in collaboration with Alcatel Etca and is composed by steel or aluminium plates supported to a tubular structure by means of steel cables. Different configurations can be used : simple plate (figure 5), two plates linked by screw bolts (figure 6), either in vertical or horizontal orientation.

The equipment that has to be tested is screwed on a plate and the explosive device that generates the excitation is fixed on the opposite face (Fig.7).

The explosive device is composed by a detonator and a linear explosive cord. A thin rectangular steel or aluminium contact plate is used to avoid to damage the plates of the testing device (Fig.8). A non electrical detonator (NONEL) prevents any perturbation in the measurement

Fig. 5. Simple plate in vertical configuration.

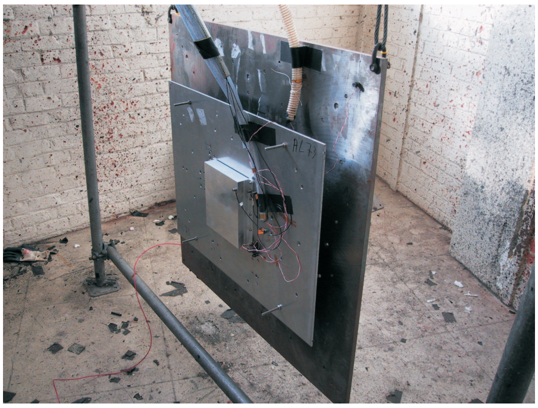

Fig. 6. Double plate in vertical configuration.

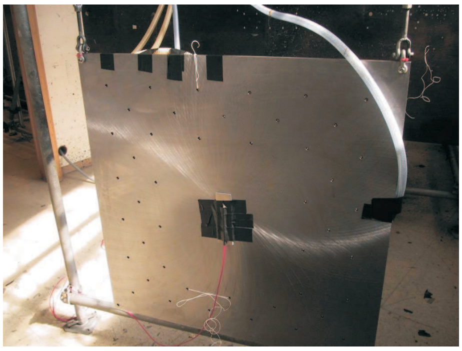

Fig. 7. Explosive disposition.

line or in the operation of the tested electronic equipment .

The explosive cord contains 10 grams of penthrite per meter; its length depends on the main excitation level which has to be reached.

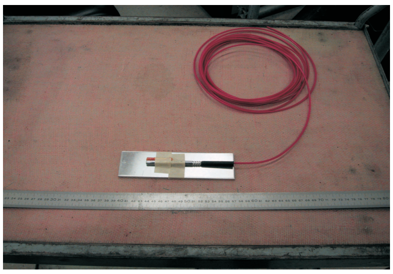

Fig. 8. Explosive device

The main parameters which influence the experimental SRS are the following ones:

- the configuration of the test facility (number of plates and their orientation in space);
- the plates material, area and thickness;
- The power of the explosive charge (in practice the length of the explosive cord);
- the relative localisation of the explosive device and the tested equipment.

These parameters have to be tuned in order to respect the launcher's requirements. A test campaign begins with a trial and error process on a dummy of the electronic equipment: the test parameters are then modified until the SRS of the measured accelerations at the basis of the equipment corresponds to the SRS specifications. This procedure can however be very costly as it can require a lot of tries. A model of the test facility could therefore be very helpful to tune these parameters during the experimental procedures.

IV. Finite elements model

The modelization procedure first requires an accurate model of the structure as well as an appropriate description of the excitation generated by the detonation.

The basic configuration corresponding to a double plates device is composed of a square steel plate (1m x 1m x 0.015m) and a rectangular aluminum plate (0.8m x 0.590m x 0.006m), linked by screw bolts (Fig.9). The dummy of the equipment is screwed on the aluminium plate(Fig. 6).

Solid 8 nodes elements with three DOF nodes have been used to model the plate elements. The screw bolts have been described by beam elements leading to equivalent geometric and dynamic properties. The cables supporting the base plate have been modeled by two non-linear elements, only acting in traction.

It's recommended to define an element size which is inferior to the smallest flexion wavelength. In an infinite uniform plate the wavelength λ of the flexion waves is given by[5]:

$$\begin{aligned} \lambda &= \sqrt{\frac{2\pi}{f}} \left(\frac{D}{M_s}\right)^{1/4} \\ D &= \frac{E\,h^3}{12\,(1-\nu^2)} \end{aligned}$$

where M_s is the surface mass, E the Young modulus, ν the Poisson coefficient, h the plate thickness and f the frequency of the flexion wave.

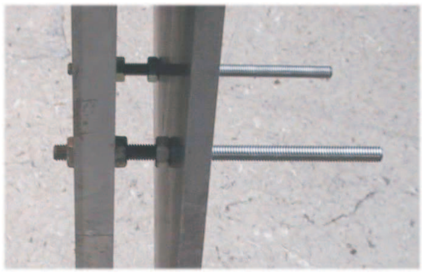

Fig. 9. Screw bolts disposition.

A 34x34 elements grid has been defined in order to respect a number of four elements per wavelength, corresponding to a frequency of the flexion wave of 10 kHz (Table I). The final model is represented in figure 10.

TABLE I
NUMERICAL VALUES

	steel plate	aluminium plate
E	$2.1e^{11}$ N/m^2	$2.7e^{10}$ N/m^2
ρ	7850 Kg/m^3	2715 Kg/m^3
ν	0.3	0.346
h	0.015 m	0.006 m
f	10000 Hz	10000 Hz
λ	0.121 m	0.0605 m

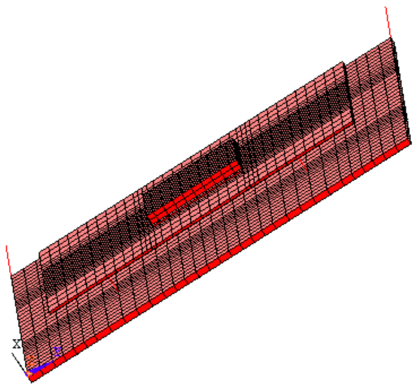

Fig. 10. Finite elements model of the double plates with equipment.

V. Model validation

A model validation has been realized by comparing the modal properties of the test facility deduced from the model and those experimentally identified from measured frequency response functions.

The frequency response functions have been measured in the perpendicular direction of the plates, the excitation being generated using an impact hammer. The analysed frequency band ranges from 0 to 1000 Hz with frequency resolution of 0.625 Hz. A typical experimental FRF is presented in figure 11

The resonant frequencies f_k, damping factors ξ_k and modal vectors $\{\phi_k\}$ have been identified and compared to the ones deduced from the finite elements model. Two comparison criteria have been used, in particular the relative difference between resonant frequencies and the modal assurance criterion -MAC-.

The relative difference between resonant frequencies is calculated as follows [6]:

$$\xi_k = \frac{\left|f_k^E - f_k^M\right|}{f_k^M} \tag{2}$$

where the superscripts ^{E} and ^{M} are used for respectively experimental and model data.
If $\{\phi^E\}$ and $\{\phi^M\}$ are respectively the experimental and model deduced modal vectors, the MAC is given by [6]:

$$MAC_k = \frac{\left(\{\phi_k^E\}^T\{\phi_k^M\}\right)^2}{\left(\{\phi_k^E\}^T\{\phi_k^E\}\right)\left(\{\phi_k^M\}^T\{\phi_k^M\}\right)} \tag{3}$$

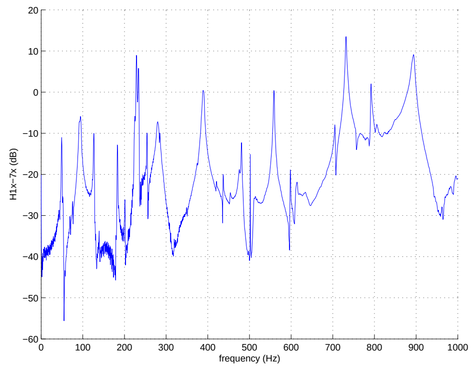

Fig. 11. measured frequency response function

TABLE II
CORRELATION BETWEEN EXPERIMENTAL AND SIMULATED MODES

MAC (%)	f^E (Hz)	f^M (Hz)	Frequency difference (%)
78.84	49.41	49.96	1.1
97.89	93.21	89.42	4.06
82.69	104.37	94.39	9.55
79.97	126.99	127.62	0.5
88.88	182.15	173.92	4.5
60.57	234.13	235.15	0.43
96.84	252.09	258.17	2.41
72.39	282.09	290.64	3.03
65.14	389.54	413.875	6.24
74.37	475	488.916	2.93
73.59	559.33	580.717	3.82
87.25	600.86	649.02	8.01
76.43	616	669.255	8.64
63.98	704.47	677.804	3.78
71.08	734.57	741.752	0.97
71.38	894.59	905.03	1.16

Table II summaries the first 16 experimental and analytical modes, correlated with a MAC value greater then 0.6 et a frequency relative difference smaller than 10%.
The updating process leads to the validation of the finite elements model up to 1000 Hz, assuming that it can be extrapolated at higher frequencies.

VI. Computer modeling of the excitation

Two differents approaches have been tested to describe the excitation :
- The real distributed excitation is replaced by an equivalent mechanical shock located at a fixed point in the vicinity of the explosive charge.
- The effects of the explosion is modeled by a moving pressure wave.

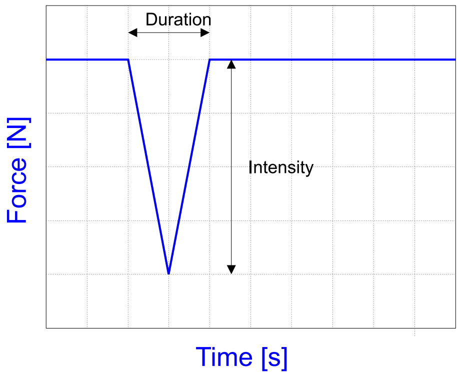

Fig. 12. Equivalent shock.

In this paper, we will only describe the first approach base on an equivalent mechanical shock.

A. Equivalent mechanical shock.

A.1 *Unidimensional equivalent shock*

The equivalent mechanical shock corresponds to the mechanical shock which would lead to an equivalent vibration behaviour of the plate. In pratice it corresponds to the localised force that applied on the finite elements model, at the node coinciding with the center of the detonator, gives a Shock Response Spectra close to the one calculated from the experimental accelerations measured on the plate. Different impact profiles could be used [8]. We have choosen to use a triangular symmetrical profile equivalent to those observed in mechanical impact.

During the pyrotechnic shock the maximum of the energy being injected perpendicularly to the plate [7], an equivalent shock in the orthogonal direction at the plate has been defined.

The equivalent shock is completely characterised by the duration and the intensity of the impact, as showed in the figure 12. The intensity F_{Max} and the duration Δt of the impact are deduced in order to minimize the difference between shock response spectra of the measured and simulated accelerations, using the following criterion:

$$\min_{F_{Max},\Delta t} \sum_{f} \sum_{j=1}^{N} \left| SRC_j^{Measured} - SRC_j^{Simulated} \right| \qquad (4)$$

SRC$_j^{Measured}$ and SRC$_j^{Simulated}$ representing respectively the shock response spectrum of the measured acceleration at node j and the corresponding simulated one. N is the number of measured responses and f represents the frequency.

This approach gives accurate mathematical results when it is used in the case of specific geometry and operating conditions. An example of agreement between experimental and simulated SRS's is presented in the figure 13 in the case of a simple plate for which impact duration and impact intensity correspond respectively to

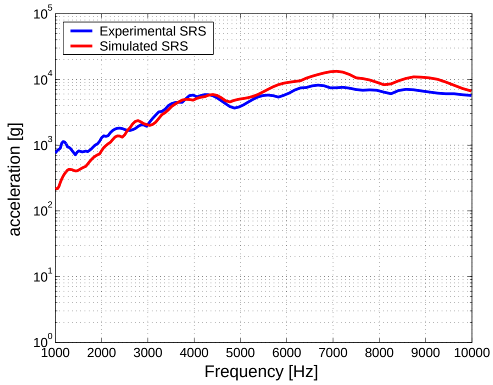

Fig. 13. Comparaison between the experimental and simulated SRS for a simple plate

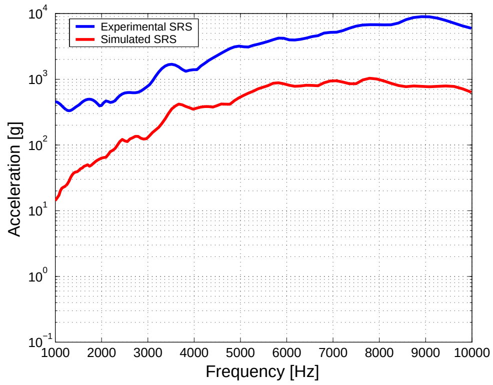

Fig. 14. Comparaison between experimental and simulated SRS in the plane of the plate.

80 μs and 54756 N. However it presents the drawback that the optimized duration and intensity corresponding to a pyroshock cannot always be extrapoled from a configuration to another. Moreover, this perpendicular shock don't inject enough energy in the plane of the plate; therefore the acceleration levels in this directions are not perfectly reproduced (Fig.14).

A.2 *Three-dimensional equivalent shock*

In order to ameliorate the plane predictions the real excitation has been replaced by equivalent excitation defined by three mechanical shocks acting in the three directions. The mechanical shocks have the same triangular profil that the unidimensional equivalent shock. A constant impact duration is imposed to the 3 shocks, the three-dimensional equivalent shock being therefore characterized by the impact duration and the impact intensities in the 3 directions which are also identified by a similar optimisation process. For a given configuration, the 3-dimensional mechanical shock allows an accurate prediction of the experimental SRS in the 3 directions (Fig. 15 and 16). Nevertheless, the 3-dimensional equivalent shock presents the same drawback as the unidimensional shock: the impact duration and impact intensities can not be extrapolated when the structure is changed.

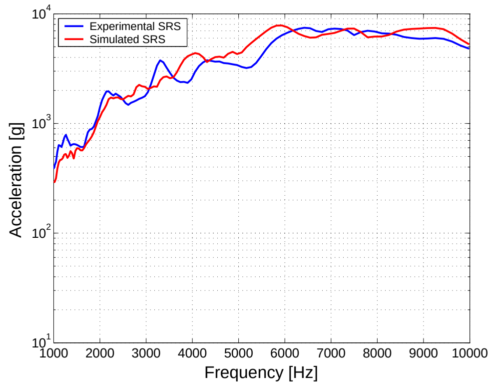

Fig. 15. Comparaison between experimental and simulated SRS in the perpendicular direction at the plate.

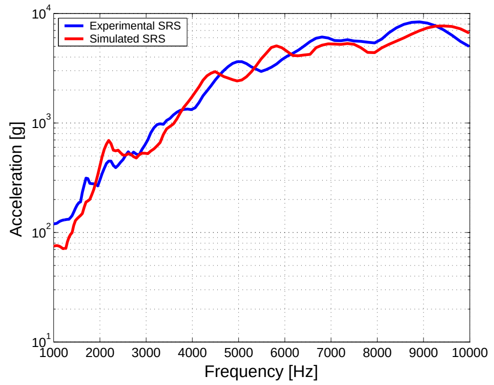

Fig. 16. Comparaison between experimental and simulated SRS in the plane of the plate.

This procedure gives however a mathematical solution which helps to predict the qualitative influence of several operating parameters and to orientate the experimental procedure of the pyroshock testing.

The model allows to estimate the influence of several parameters, as for example the thickness of the plate or the localization of the excitation, on the plate's vibration behaviour. The evolution of the acceleration levels with the thickness is given for a simple plate device in figure 18. The excitation is applied at node 1 and the response is calculated at node 8 (Fig. 17). The used excitation is the equivalent mechanical shock identified for a pyroshock with an explosive cord of 4cm. When the thickness is doubled the vibration level decreases of about 10 dB.
The vibration level is slightly influenced by the localization of the explosive charge, with a maximum difference about 4 dB (Fig.19).

VII. Conclusions

This paper presents a test facilities developed with Alcatel ETCA to satisfy the SRS specifications imposed by the launchers. A finite elements models of these facilities has been developped and validated experimentally using experimental modal analysis.

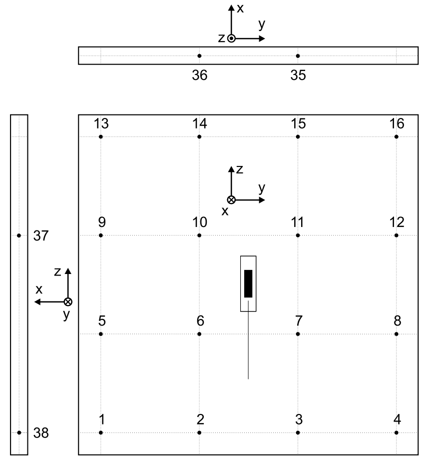

Fig. 17. Localization of plate's nodes

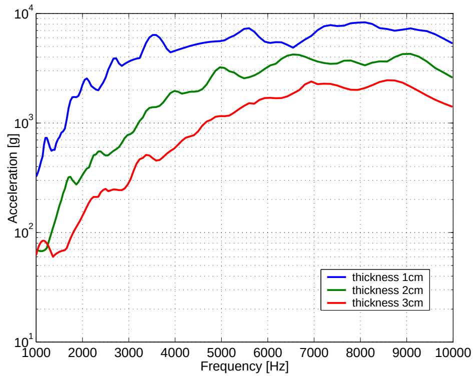

Fig. 18. Influence of the thickness on vibration level

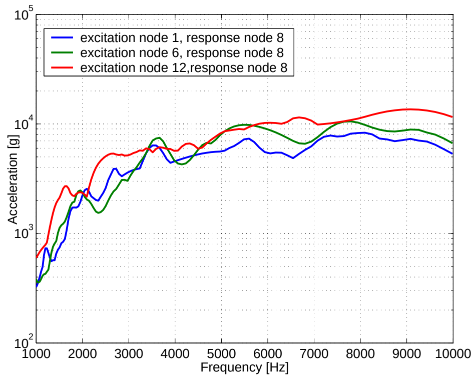

Fig. 19. Influence of explosive charge's localization on vibration level

An approach based on equivalent mechanical shocks has been used to describe the pyrotechnic explosions. This procedure allows to reproduce in a satisfactory way the experimental SRS's in the three orthogonal directions for a given configuration. A drawback of this procedure is that the equivalent mechanical shock identified for a given configuration of the test facility can n't always be extrapoled to another. It allows however to decribe the qualitative influence of several operating parameters and can orientate the experimental procedure of the pyroshock testing.

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