CONCEPTION AND VALIDATION OF A TWO HIGH LEVEL AXES SET-UP FOR PYROSHOCK QUALIFICATION OF SPACE ELECTRONIC EQUIPMENTS

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Abstract

When used for space applications, electronic equipments are submitted to pyrotechnic shocks, for instance during the separation steps of the launcher vehicle stages or when the solar panels of a satellite are deployed. The pyrotechnical charges used for these events generate severe impulsive loads that can cause failures in electronic equipments.

As the prediction of the mechanical behaviour of equipments, in regards of pyroshocks, is very difficult by calculation, the projects must rely on testing to validate the design. Thales Alenia Space ETCA has developed, some years ago, a pyroshock test facility dedicated to the testing of electronic units. The facility uses a resonant test fixture assembly which is excited by a detonating charge (for high acceleration levels) or a mechanical impact (pneumatic jack) for lower levels. The device under test, screwed to the fixture, is submitted to the direct shock wave and to the resonant response of the test fixture, simulating the required shock.

To reach the specified levels, the set-up is checked, by using a dummy test item, and tuned in modifying some significant parameters: quantity of explosive (or pressure of pneumatic jack), type of test fixture (steel or aluminium plate, interfaces between the plates, explosive location,…). When the desired pyroshock is achieved, the nominal tests are performed on the test item.

The choice of an adequate test fixture is the most important parameter in this trial-and-error process. Since the test facility building, more than 3000 firings have been performed. All the recorded results make up a pyroshocks data base. At the beginning of a new test campaign, a computer program scans the data base and looks for the test results closest to the specified spectra.

A new interest is to minimise the number of trial real shocks before to be able to achieve the nominal test. For that, the different set-up used by ETCA are modelled with ANSYS FEA software and used as a new help in the performing of a pyroshock qualification process.

The objective of this paper is to describe the way to reach a high specification (in terms of shock response spectrum) along two axes simultaneously.

At first, the notion of pyroshock is explained in a general way and the mathematical tools used to compare severities of shocks are presented. Then, the pyroshock test facilities of TAS ETCA are described and the main steps of a test campaign are presented to understand the difficulty to achieve a request nominal level.

A new help is now used by ETCA to reduce the time necessary to perform calibration stages. Numerical simulations are realised to know the influence of main parameters of the facilities. For that, an approach by equivalent mechanical shock is presented and is used to perform mechanical transitional analyses. The excitation is modelled by a triangular impulsion. The parameters of amplitude and duration can be optimised to minimise the difference between simulated and experimental results.

First experimental shocks are realised to have a data base of possibilities to reach the imposed specification. Then, the numerical tools described are used to perform parametrical analysises and develop a new configuration of the test facilities. At last, results obtained with the new set-up are presented and show the capability of Thales Alenia Space ETCA pyroshock test facilities to cover a large range of specifications in terms of SRS.

1. Introduction

Nowadays, the space industry uses more and more pyrotechnic devices, such as pyrotechnic valves or Mild Detonating Fuses, to carry out various operations like separation of structural elements (booster separation,…) unlocking mechanisms (unfolding solar panels,…) or activation of on-board operating subsystems. The shock wave generated by the blast of these pyrotechnic devices produces severe vibrations inside the space shuttles. For several years, the effects of these pyrotechnic shocks (so-called pyroshocks) haven't been taken into account because the manufacturers of electronic equipments thought that the duration of the explosion was too short to damage the on-board electronic devices. However, it has shown that many observed breakdowns on the American launchers were caused by the pyroshocks.

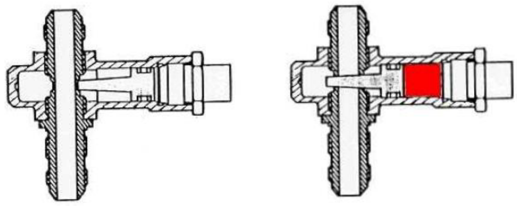


Fig. 1.1: Pyrotechnic valve (before and after activation)

At present time, the pyroshock resistance of the electronic equipments is mainly checked experimentally due to the difficulties to approach the problem with numerical techniques. In fact, it's the modelling of the pyrotechnic excitation which is very difficult to determine. In practice, simplified resonant fixtures, such as plates assemblies, are used to reproduce a vibratory environment equivalent to the real one.

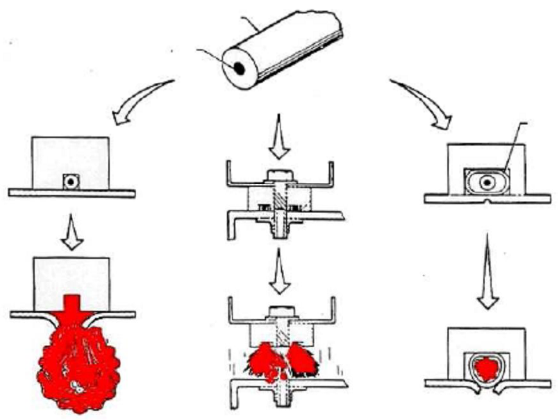


Fig. 1.2: Mild Detonating Fuses (MDT)

A new test campaign always begins by the choice of an adequate test facility. A trial-an-error process is applied on the test assembly, loaded with a dummy of the equipment to test, with the objective to reach the imposed specification.

When the wanted vibratory environment is achieved, the nominal test is performed on the real equipment. Obviously, such a procedure is rather expensive. Consequently it's useful to dispose of a mathematical model of the test facility to predict the vibrations levels generated by pyroshocks.

2. Shock Response Spectrum (SRS)

A shock is a solicitation with a short duration which leads to transitory dynamic constrains in the structures. The severity of a shock can be estimated only in function of the characteristics of the system submitted to this wave.

A simple and useful way to compare several shocks has been proposed by A. BIOT (1932) [1] in a study of earthquakes on buildings. Then, his work has been generalised to the analysis of all mechanical shocks. This mathematical tool consists in replacing the real structure by an array of independent single degree of freedom systems and to calculate the maximum response of each resonator when its foundation is animated by a motion corresponding to the shock time history.

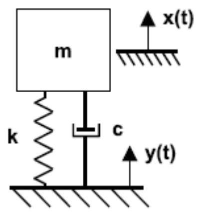


Fig. 2.1: Single DOF system

Each single DOF system is composed of a mass m_i, a stiffness k_i and a damping coefficient c_i chosen to have a relative damping:

$$\xi = \frac{c_i}{2.\sqrt{k_i.m_i}} \qquad (1)$$

the same for each single DOF system. When the support is submitted to the shock, each mass m_i gives an output motion function of its natural frequency:

$$f_{0i} = \frac{1}{2\pi}.\sqrt{\frac{k_i}{m_i}} \qquad (2)$$

The analysis consists to search the maximum constraint observed for each DOF system. A shock A is considered more severe than a shock B if it induced, in each single DOF a more important constraint.

So, to extrapolate (questionable), if a shock is more severe when it's applied to a single DOF group, it will more severe when it will be applied to every real structure. With this method, it's possible to calculate the SRS of all acceleration:

- Each single DOF is excited by the shock to perform (modelled by $\ddot{y}$)
- Calculation of the acceleration $\ddot{x}$
- The operation is performed for all the frequencies f_i

The SRS is finally obtained in reporting, for each single DOF system, the maximum acceleration calculated.

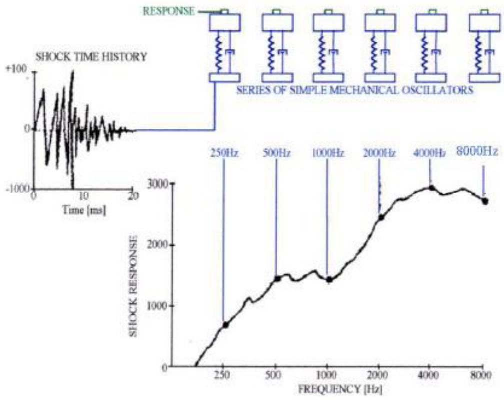


Fig. 2.2: Principle of SRS Calculation

Mathematically, if *y(t)* is the excitation, *x(t)* the output answer, *δ(t)*, the relative displacement of the mass:

$$\delta(t) = x(t) - y(t) \qquad (3)$$

The equation of the motion for each single DOF system is:

$$m\ddot{x} + c(\dot{x} - \dot{y}) + k(x - y) = 0 \qquad (4)$$

$$m\ddot{\delta} + c\dot{\delta} + k\delta = -m\ddot{y} \qquad (5)$$

$$\ddot{\delta} + 2\xi\omega_0\dot{\delta} + \omega_0^2\delta = -\ddot{y} \qquad (6)$$

with $2\xi\omega_0 = \frac{c}{m}$ and $\omega_0 = \sqrt{\frac{k}{m}}$ (7)

The solution of this differential equation is given by the Duhamel's integral:

$$\delta(t) = \frac{1}{\omega\sqrt{1-\xi^2}}\int_0^t [-\ddot{y}(\tau)]e^{-\xi\omega_0(t-\tau)}\sin(\sqrt{(1-\xi^2)}\omega_0(t-\tau))d\tau \qquad (8)$$

The displacement response spectrum S_d is the absolute maximum of the relative displacement *δ(t)* for each natural frequency $f = \omega/2\pi$:

$$S_d = |\delta(t)| \qquad (9)$$

For pyroshocks, the pseudo-acceleration spectrum S_{pa} is generally used [4]. The pseudo-acceleration is obtained in multiplying the displacement response spectrum S_d by ω².

$$S_{pa} = \omega^2 S_d \qquad (10)$$

The pseudo-acceleration S_{pa} has the units of acceleration but it doesn't represent the absolute acceleration of the mass *m*, except for a zero damping coefficient. The mathematical relationship between the pseudo-acceleration spectrum S_{pa} and the absolute acceleration spectrum S_a is given by the equation (3):

$$S_a = [\ddot{x} = \ddot{y} + \ddot{\delta} = -2\xi\omega\dot{\delta} - \omega^2\delta]_{\max} \qquad (11)$$

The pseudo-acceleration spectrum can be schematically represented by two asymptotes when it's plotted in a log-log scale [5]. This asymptotic behaviour is defined by the following parameters [2]:

- The cuttof frequency f_c
- The slope α in dB/octave at lower frequencies
- The maximum response *A* at higher frequencies

So, the more common and useful way to represent a SRS is to trace it in a bi-logarithmic graph giving the pseudo-acceleration in function of the frequency (generally traced for $\xi = 0.05$.).

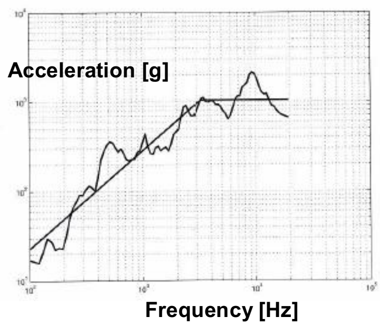


Fig. 2.3: Example of SRS and comparison with its simplified asymptotic behaviour

3. Test Specifications

Equipment specifications are commonly expressed in terms of SRS specified from a low frequency limit of a few hundreds of Hz to a high frequency limit of 10 kHz and sometimes more. The acceleration levels are generally defined in the three orthogonal directions. Shock levels are often more difficult to achieve for in-plane directions.

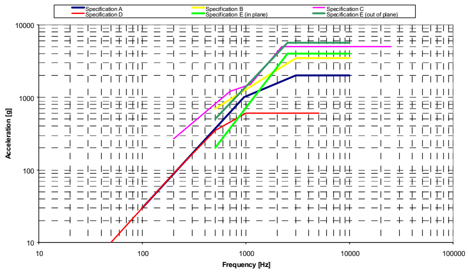


Fig. 3.1: Examples of specifications

Sometimes, tolerances are admitted on the imposed spectrum. For example: -6 dB for frequencies under 1000 Hz and higher than 6000 Hz.

4. Thales Alenia Space ETCA Pyroshock tests facility

4.1. Generalities

The facility, developed by ETCA, some years ago, is a resonant fixture which can be excited by an explosive charge or a mechanical impact (hammer, pneumatic jack,…). On this fixture, one, two or three plates are mounted and are used to fix the equipment under test. The fixation means between the plates, the material, dimensions and thickness of the plates (aluminium, steel,…), the quantity of explosive charge (or pressure in pneumatic jack) and its location are parameters which allow to get SRS different from one experimental shock to the other and to reach the imposed specifications. Two main configurations are used:

- Horizontal configuration
- Vertical configuration

Fig. 4.1: Double plate in horizontal configuration

Fig. 4.2: Double plate in vertical configuration

In the case of a pyroshock, the excitation is generated by an explosive device composed of a non-electrical detonator (used for safety issues and to not generate electromagnetic interferences) and a detonating charge assembled on a small steel plate.

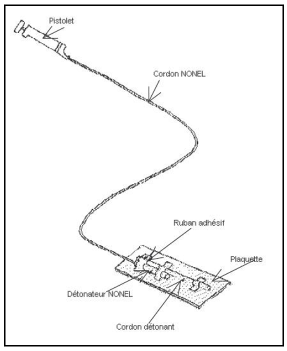


Fig. 4.3: Pyrotechnic device

4.2. Pyroshock tests performing

4.2.1. Logic way

The different steps followed by TAS ETCA to perform a pyroshock tests campaign are : Prospection, technical analysis of the request, calibration stage (the longer part), nominal shock and closing.

4.2.2. Main steps description

Analysis of a request

- Reception of the customer's request
- Appreciation between the test facilities and the request
- Discussion between TAS ETCA and its customer
- Evaluation of the quantity of work
- Technical and financial offer

Calibration stage

- Performing of a shock on a dummy of the unit to test, based on the empirical knowledge of the test facilities (with some numeric supports)
- Analysis of the results

- Choice of the next configuration and innovation if necessary

Return in iterative process at first point of this stage

- Calibration tests report written for the customer with the best results and description of the choices

Discussion with the customer to lead to the nominal shock performing

5. Finite Element Models

5.1. Definition

The computations of the pyrochock response require a dynamic model of the test facility and a mathematical description of the excitation sources. This one is very difficult to know because it can't be measured directly. Moreover, a lot of complex physical phenomena can appear during the pyroshock as for example the interaction between the shock wave, generated by the explosion, and the geometry of the room which controls the numerous reflection waves.
Double plates configurations can be easily modelled with FE software (ANSYS 10.0 in our case). 2-D elements are used to represent the plates, and the steel cables supporting the base plate are modelled by non-linear elements acting only in tension.

5.2. Model validation

Models validations can be realised 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 $H_{ij}(\omega)$ can be measured in the direction perpendicular to the plate, with help of an impact hammer, and in the frequency range [0 – 1000 Hz]. Modal characteristics can be identified and then, resonant frequencies, damping factors and modal vectors. It allows to update the finite element model from experimental results by minimizing the relative difference between experimental and model data resonant frequencies.

6. Equivalent Mechanical Shock (EMS)

6.1. Definition

Many works have been realised between TAS ETCA and the Faculty of Engineering of Mons (Belgium) about the modelling of the excitation. The latest researches have been performed by D. Wattiaux [9] as part of his Doctor thesis. In this work, the notion of Equivalent Mechanical Shock (EMS) has been introduced. It corresponds to the mechanical force which has to be applied to the FE Model to obtain acceleration levels. In our case, the force is applied to the center of the explosive charge. Although the pyroshock is a three-dimensional excitation source, it has been considered an EMS only in the direction perpendicular to the plate because the energy is mainly injected in this direction. For a given impact duration τ, the shape of the excitation does not influence the SRS calculations as far as the integral $\int_0^{\tau} F dt$, which represents the energy injected in the system, is constant. In this paper, we consider only triangular symmetrical profiles equivalent to those observed during a hammer impact. So, the EMS is defined by two parameters:

- The intensity F_{max} of the impact
- The duration τ of the impact

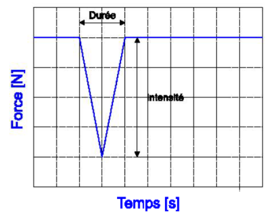
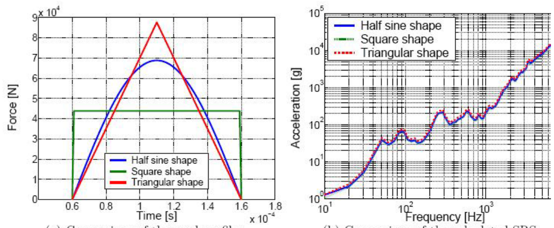


Fig. 6.1: Definition of the EMS



(a) Comparison of the used profiles (b) Comparison of the calculated SRS

Fig. 6.2: Influence of the used profiles

deduced by an optimisation process which minimises the difference between experimental and simulated SRS:

$$\varepsilon = \min_{F_{Max},\tau} \sum_{f=100Hz}^{10kHz} \sum_{j=1}^{N_{SRS}} \left| SRS_j^{Measured} - SRS_j^{Simulated}(F_{\max},\tau) \right|^2 \quad (12)$$

where $SRS_j^{Measured}$ and $SRS_j^{Simulated}$ represent respectively the shock response spectrum of the measured and simulated accelerations at node j. N_{SRS} is the number of measurement points on the plate and f the frequency.

6.2. Model Validation

Some statistical indicators can be used to compare experimental and simulated SRS:

1) $\Delta_i(f)$: The difference at frequency f

between experimental and simulated SRS for node number *i*

2) $\mu(\Delta_i)$ and $\sigma(\Delta_i)$: The mean and the standard deviation of the first indicator along the frequency range
3) μ_G and σ_G: The mean and the standard deviation of the frequency difference between experimental and simulated SRS considered on the whole set of measured nodes.

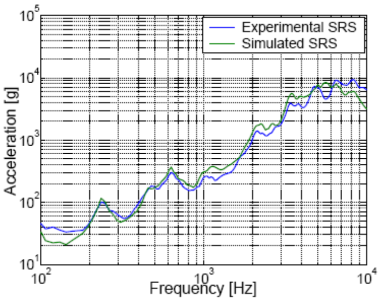


Fig. 6.3: Comparison between simulated and experimental SRS - Double plate configuration (perpendicular direction)

For the example of Figure 6.3, $\mu(\Delta_i)$ and $\sigma(\Delta_i)$ are respectively equal to 2.19 and 1.24.
Although the SRS is the most frequently used tool to quantify a vibratory environment, the comparison between experimental and simulated SRS is a not sufficient criterion to validate the EMS model because different acceleration profiles can lead to the same SRS. Consequently, it's essential to make sure that the model allows to reproduce also the experimental acceleration fields. The next figure shows a comparison between experimental and simulated acceleration fields for the example of Figure 6.3.

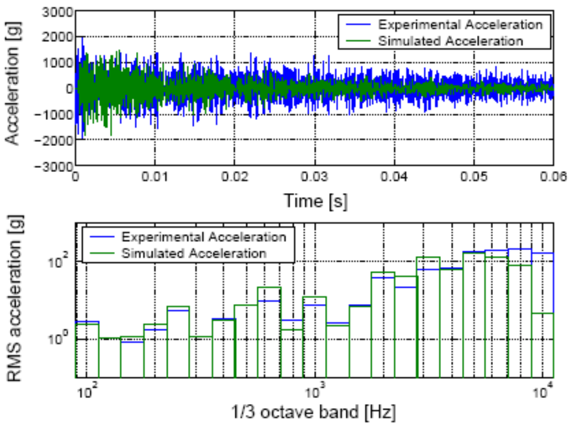


Fig. 6.4: Comparison between experimental and simulated acceleration fields

The mode superposition has been used to predict the transient response of the structure. Given that it's not always easy to identify accurately the experimental damping ratio, it has been fixed, in the FE model, a damping ratio of 1%. The RMS value of the acceleration in each 1/3 octave range is relatively well reproduced except the vinicity of 10 kHz.

7. Parametrical analysis

The interest of the responsibles of the TAS ETCA pyroshock test facilities is to reduce the costs of a complete pyroshock qualification campaign. As said before, the longer part of a campaign is the calibration stage. The approach by mechanical shock allows to begin a pyroshock qualification by a preliminary parametrical study of the best set-up chosen on base of the TAS ETCA pyroshock data base. This way allows to have an idea of the influent parameters for the different possible configurations.

Of course, as the objective of a numerical parametrical effect is to win time during calibration stages, model validations are not always performed. The objective is to have a good feeling about the more interesting parameters of the set-up. For example, consider a traditional double plate configuration: one base plate made of steel (thickness=10mm) and one mounting plate made of aluminium (thickness=6.5mm)

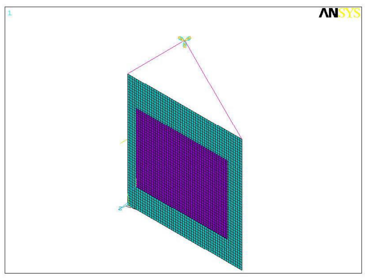


Fig. 7.1: Example of set-up modelling

A lot of parameters can be studied to know their influence on the SRS measured on the mounting plate. The following figures show some numerical results got for this set-up when a triangular impulsion (F = 10000 N - τ = 100 μs) is injected at the base plate level. The excitation and the measurements are only considered along axis Z (perpendicular to plates)

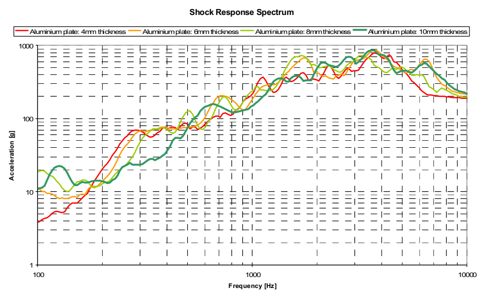


Fig.7.2: Influence of the thickness of the mounting plate

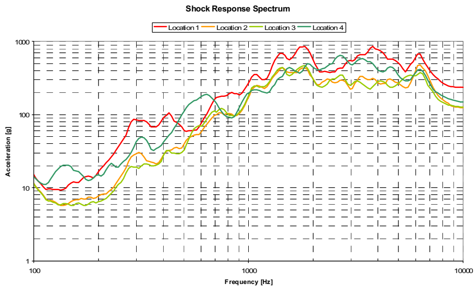


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Fig. 7.3: Influence of the explosive location (on the steel base plate)

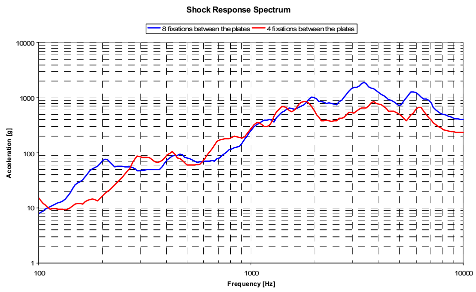

Fig. 7.4: Influence of the number of fixations between the plates

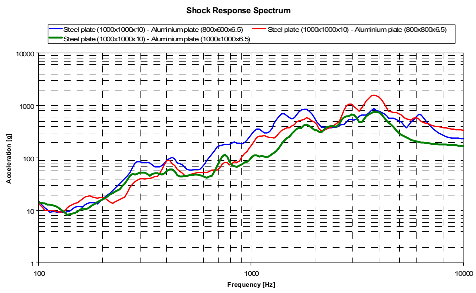

Fig. 7.5: Influence of the dimensions of the mounting plate

The next graph shows the comparison between a simulated SRS (with optimised parameters F = 189000N - τ = 140 μs) and an experimental SRS obtained with the set-up of Figure 7.1.

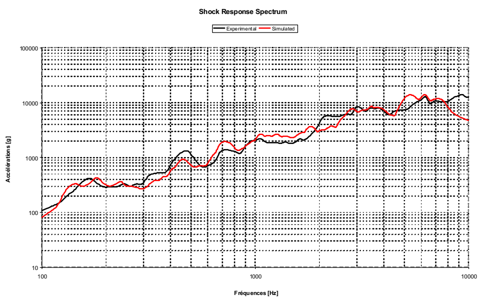

Fig. 7.6: Comparison between simulated and experimental SRS

8. New configuration development

8.1. Objective

The objective is to achieve a new configuration of the Thales ETCA pyroshock test facilities to reach a high level specification in, at least, two directions, for one shock. The equipment to qualify is an ETCA Micro-Unit Modular concept. Its mass is about 8 kg. A modelled view of the package is given at the next figure.

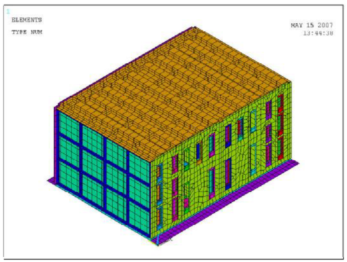

Fig. 8.1: ETCA Micro-Unit Modular package

If necessary, two shocks can be performed to reach the specification in the three directions. In proceeding in this way, one axis would be tested two times at nominal level.

8.2. Specification

The levels to reach in this project are given by the following table. No tolerances are previous at this stage of the development.

Frequency [Hz]	Acceleration [g]
100	60
2000	3000
10000	3000

Table 8.1: Specification to reach

8.3. Preliminary experimental shocks

As the shock must be performed with nominal levels in two axes at least, the choice of the vertical configuration has quickly be done. In using a base plate on which we will fix a mounting tool in the perpendicular direction, we can benefit of the intensity of the explosive charge in its main direction and of the rotation of the set-up around its centre of gravity in a second direction.

The first configuration used is a steel base plate and a steel square represented at the next figure:

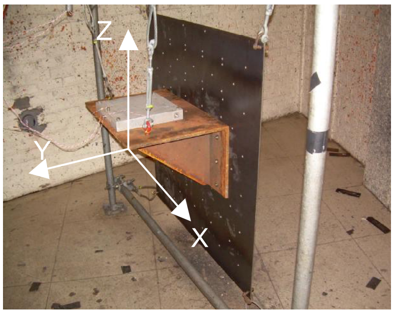

Fig. 8.2: Steel plate with steel square (test set-up 1)

Experimental shock response spectra are shown in the following graph.

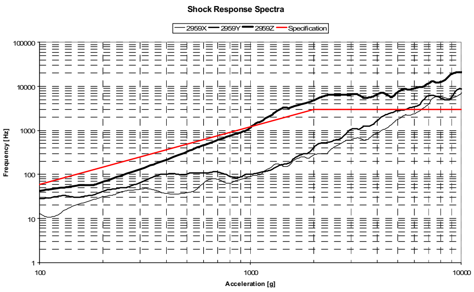

Fig. 8.3: Experimental SRS - Test set-up 1

We can see, on these results, that the levels reached at the extremity of the square are under the specification. Only the axis Z seems to be able to achieve the nominal SRS. It's interesting to see that the "rotation" of the set-up is very profitable to reach the SRS in the direction perpendicular to the face where the equipment would be mounted. Of course, for that, the explosive charge has to be placed under the centre of gravity of the assembly. The weight of the square seems to be a problem to get high levels in the two other directions.

Another configuration has been envisaged. The steel plate has been kept, but the steel square has been replaced by an aluminium block assembled in the same way to the base plate.

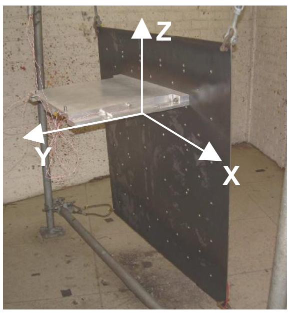

Fig. 8.4: Steel plate with aluminium block (test set-up 2)

Experimental shock response spectra are shown in the following graph.

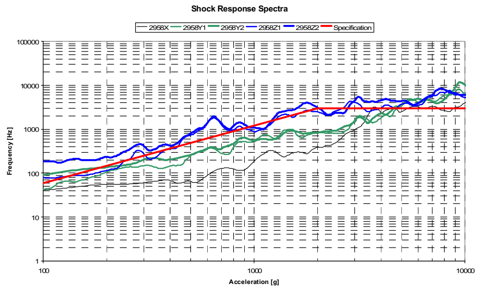

Fig. 8.5: Experimental SRS - Test set-up 2

The last results are encouraging. We see that the axis Z is higher than the specification for almost all the frequency range. The axis Y (in shock wave main direction) stays far from the nominal level. It would be difficult to achieve the shock with such configuration.

8.4. Parametrical study of a new configuration

As explained before, the using of finite element models of the test facilities and the equivalent mechanical shock can give a good idea of parameters which have an influence on the measured SRS. The two experimental set-up used before have shown it was interesting to have a mounting plane for the equipment, perpendicular to the base plate of the set-up. With such configuration, the axis Z (perpendicular to the equipment mounting plane) reaches high levels. The problem is to bring axis Y at higher levels than these got in the last tests. To do that, our choice was to make a new tool with a form of square (as set-up 1). To optimise its conception some simulations have been done. Triangular impulsion has been injected in the direction perpendicular to the base plate of the set-up (main direction of the shock wave)

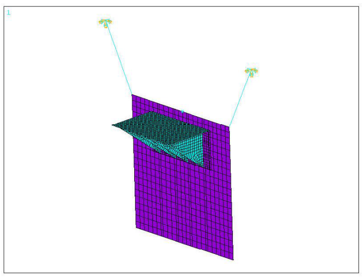

Fig. 8.6: FEM model of the new test set-up

Some numerical comparisons have been performed before making this new tool: influence of the material, the number of stiffeners, the thickness. Some results are presented here under. The values of the amplitude and duration of the triangular impulsion used here are 100000N and 100 µs.

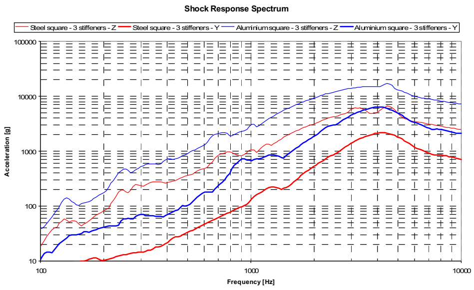

Fig. 8.7: Influence of the material

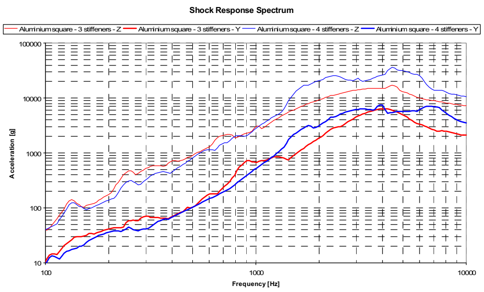

Fig. 8.8: Influence of the number of stiffeners

All the numerical results helped us to choice the design of the new tool. An aluminium square with four stiffeners which can be disassembled was drawn and made by TAS ETCA.

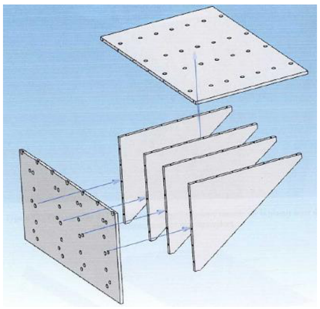

Fig. 8.9: Design of the tool

Some complementary simulations were done to have more information about the others parameters: explosive charge location, thickness and material of the base plate…

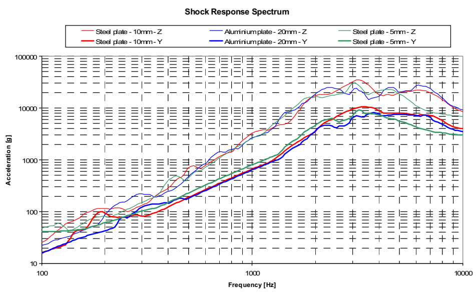

Fig. 8.10: Influence of the thickness & material of base plate

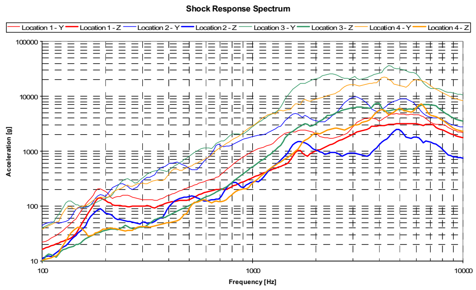

Fig. 8.11: Influence of the excitation location

The influence of the mass of the equipment must be taken into account during a calibration stage. So, before beginning the experimental validation of the new configuration, a dummy of the equipment has been made an represents the same global mass and interface fixations as the real unit.

8.5. Experimental validation of the new test set-up

The new complete set-up is shown at the next figure. We can see the base steel plate (thickness: 10 mm), the new aluminium square, and the dummy of the equipment to test.

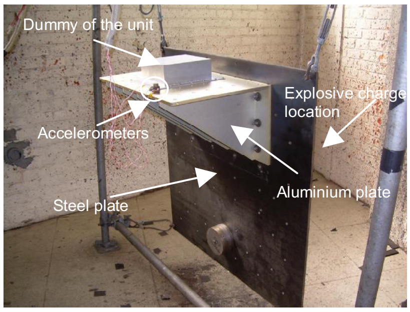

Fig. 8.12: New set-up configuration

The new test configuration gives good experimental results (see an example here under). The nominal specification imposed for the studied ETCA Micro-modular equipment to qualify will be easily exceeded. It's important to remark that this set-up will allow to reach request SRS in the three directions in only one shock.

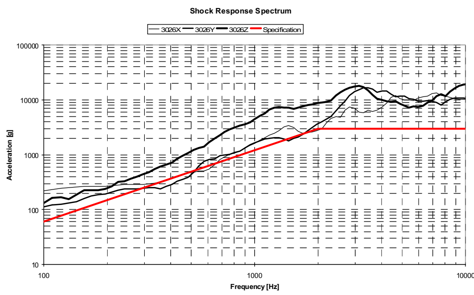

Fig. 8.13: Experimental results

All the results and the way explained in this paper shows the interest to combine numerical simulations and experimental know-how of ETCA pyroshock facilities users.

9. Conclusions and Perspectives

This paper has presented the main pyroshock test facilities commonly used by Thales Alenia Space ETCA to qualify and determine the capability of its electronic equipments to meet requirements after exposure to the extreme expected shock environment in flight.

The difficulty for pyroshock test facilities responsibles if to choose the best configuration which leads to the expected specification. For that, TAS ETCA owns a pyroshock data base composed of more than 3000 shocks performed since the development of the facilities.

The cost and the time necessary to realise a pyroshock test campaign are mainly due to the calibration stage. That why it’s interesting to have a new help to reduce the duration of this step. For that, with the help of the “Faculty of Engineering of Mons”, the notion of Equivalent Mechanical Shock has been developed and FE models of different configurations have been created. These tools allow to have a first approach before beginning calibration shocks to know the influence of main parameters of the set-ups.

This paper described the main steps of a complete calibration stage using this new help. The objective was to develop and make a new mechanical tool to reach a high level specification in, at least, two direction in one shock.

With the help of numerical tools (FE models of the facilities, equivalent mechanical shock) and the know-how of ETCA, the tool developed by ETCA gave results which allow to reach the requested specification in the three directions in one shock. It shows the capability of Thales Alenia Space ETCA.

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