Acta Astronautica 137 (2017) 222–231

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Dynamic load synthesis for shock numerical simulation in space structure design

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ABSTRACT

Pyroshock loads are the most stressing environments that a space equipment experiences during its operating life from a mechanical point of view. In general, the mechanical designer considers the pyroshock analysis as a very demanding constraint. Unfortunately, due to the non-linear behaviour of the structure under such loads, only the experimental tests can demonstrate if it is able to withstand these dynamic loads. By taking all the previous considerations into account, some preliminary information about the design correctness could be done by performing "ad-hoc" numerical simulations, for example via commercial finite element software (i.e. MSC Nastran). Usually these numerical tools face the shock solution in two ways: 1) a direct mode, by using a time dependent enforcement and by evaluating the time-response and space-response as well as the internal forces; 2) a modal basis approach, by considering a frequency dependent load and of course by evaluating internal forces in the frequency domain. This paper has the main aim to develop a numerical tool to synthetize the time dependent enforcement based on deterministic and/or genetic algorithm optimisers. In particular starting from a specified spectrum in terms of SRS (Shock Response Spectrum) a time dependent discrete function, typically an acceleration profile, will be obtained to force the equipment by simulating the shock event.

The synthetizing time and the interface with standards numerical codes will be two of the main topics dealt with in the paper. In addition a congruity and consistency methodology will be presented to ensure that the identified time dependent loads fully match the specified spectrum.

1. Introduction

During the first three-four minutes of the launch phase satellites undergo the entire mechanical loads in terms of quasi-static and dynamic enforcements. In fact, during this phase, the spacecraft experiences the inertial loads. They are given by the launcher motion, the random dynamic loads coming from the propulsion and the impulsive event deriving from the pyroshock bolts used for the separation of the satellite from the launcher and for the deployment of the solar arrays or antennas, if any. Let us consider that the solid and liquid rockets produce a pressure and acoustic field that enforce the structure. Each of these three types of solicitations must be taken into account during the design phase of the satellite and of its relevant assemblies and sub-assemblies components.

It is well known that the design of the equipments and of the S/C (spacecraft) must retain a qualification load scenario that is higher than the operative one. In particular if we refer to an electronic equipment, typically it faces a pyroshock qualification campaign that consists in three pulses per each coordinate axis with a total amount of nine shocks [1–3].

Of course, the shock dynamic response is one of the most demanding tasks from a mechanical point of view since it involves not only the equipments and the S/C design, but also the EEE (Electrical, Electronic and Electromechanical) parts procurement and their relevant placement into their units. Infact when a designer face the dimensioning of a specific unit he must to take also the shock dynamic response for the EEE selection into account. A typical example of this aspect is the relays selection (relay is a typical electro-mechanical shock sensitive part). This component exist as standard part and shock-resistant one. The procurement of this EEE part, and similar ones, shall takes into account the pyroshock dynamic response to properly design the equipment under consideration.

In order to have a rough idea of the problem let us consider a reference case relevant to the procurement of a shock-sensible EEE part: the OCXO (Oven Controlled Crystal Oscillator). Briefly the OCXO component is very sensitive to the dynamic loads. In fact it contains a quartz membrane that during its oscillation gives the reference clock to a dedicated circuit. By considering the brittle nature of the OCXO quartz and its reduced size (about ten cubic centimeters) it is

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http://dx.doi.org/10.1016/j.actaastro.2017.04.023
Received 14 January 2017; Accepted 19 April 2017

mandatory to consider its mechanical characteristic, during the design phase of the equipment and of course to monitor its correct functional status during the relevant qualification test campaigns. Usually an initial screening is performed at quartz level where a dedicated test is done by loading the crystal with a half sine-pulse (3 pulses per each axis). After the screening, the OCXO is assembled and a second qualification campaign with a pyroshock profile (3 pulses per each axis) is performed. Once again, if the OCXO assembled device passed the test, it is first integrated into the hosting equipment, then connected to the electrical circuits. Finally this new assembled unit, is undergone to a third qualification campaign with the pyroshock profile (3 pulses per axis). Once the unit passes this qualification test at equipment level it will be finally integrated at S/C level where it will face the last qualification test campaign inside the S/C. On account of this, the OCXO device undergoes more than 27 pulses at the end of the qualification phase. What is described above is relevant to the EQM (Engineering Qualification Model) and represents a desired overestimation of the real loads. In order to be confident the whole S/C is able to withstand them.

It is worth to note that criticalities, which could arise during the qualification test campaign, could be reduced and eventually removed by performing a robust design for each EEE component and the relevant assembled unit as well.

The simplest way to achieve a robust design is to perform numerical simulations. In the case of pyroshock loads the main issue is the description of the time dependent load due to the complexity of its spectrum profile and to the high non-linearity of the system.

The main aim of this paper is to propose a fast and efficient way to describe the shock loading profile. In Section 2 the standard applied procedure will be introduced to get confidence with the shock problem. In Section 3 a new methodology to describe the shock spectrum will be discussed and in the following Section 4 and 5 a case study will be proposed and the relevant numerical results will be investigated. Section 6 closes this paper by highlighting the main explored topics and by summarizing the obtained results.

2. Standard procedure

The equipment realization, from the design activities to the qualification campaign, faces the shock as one of the most important topics to be addressed since the on-board EEE components are shock-sensitive. Common applied standards foresee the application of restricted procedures for the equipment qualification. In particular the EQM units typically withstand three SRS (Shock Response Spectrum) shocks for each coordinate axis for a total amount of nine pulses. During the experimental qualification test the equipment supplier must ensure that the energy seen by the assembly is compliant with the one specified by the program requirements in terms of SRS.

Fig. 1 shows a typical shock test results plot where four different curves can be identified. The first one is the specified requirement curve whereas the other three curves are relevant to the response measured on the equipment. In particular the behaviour along the direction of the force is reported on the curve named Shock 3–3, whereas the cross-talks (e.g. the cross-coupled effects) are reported on the curves named Shock 3–1 and Shock 3–2.

The most important difference between a vibration test and a shock one is that in the former one the measurement chain is monitored by a controller (i.e. a software installed in a piloting computer) that drives the enforcement to match the test requirements. On the contrary, in the shock test the measurement chain is an open-loop system where the equipment is enforced by ensuring the imposed excitation within a predefined range and by recording the response.

As far as the shock requirements are concerned, they specify an SRS mask (acceleration vsfrequency) and two tolerances, a positive tolerance and a negative one, see Fig. 2.

The ESA ECSS experimental standard rules constrain the shock test by imposing some conditions to be satisfied (1):

- the imposed pulse must be limited inside a positive and negative tolerance. At present the standard foresees +6 dB and −3 dB with respect to the nominal spectrum;
- the 50% of the enforcing spectrum must be equal or bigger than the nominal one;
- the tested equipment must be monitored with two accelerometers, placed along the diagonal of the unit base plate. This is necessary to verify the fulfillment of the above requirements.

The above requirements are mandatory to guarantee that the equipment under test will be subjected to a proper level of energy to ensure the representativeness of the test itself.

Since the shock response is a high non-linear dynamic response, predicting tools, such as the ones based on the mathematical models and the relevant numerical simulations, are hard to be properly tuned. So experimental tests are always mandatory. Nevertheless a preliminary estimation of the response under pyroshock enforcement could help the designers to reduce the probabilities to have a catastrophic failure during the qualification campaign.

Commercial and commonly used numerical tools (i.e. FEM tools) face the shock problem in two different ways basically based on the time domain and the frequency domain description of the load input mask. A standard approach is to apply the shock load with an enforcement in the time domain and to record the response measured on the structure in the frequency domain. Of course in order to match the specified requirements it is important to properly describe the applied enforcement. The simplest way to numerically apply a shock input to an equipment model is to use a half-sine pulse where a half-period sine acceleration function represents the shock event. It is worth to note that the use of half-sine function is not representative of a

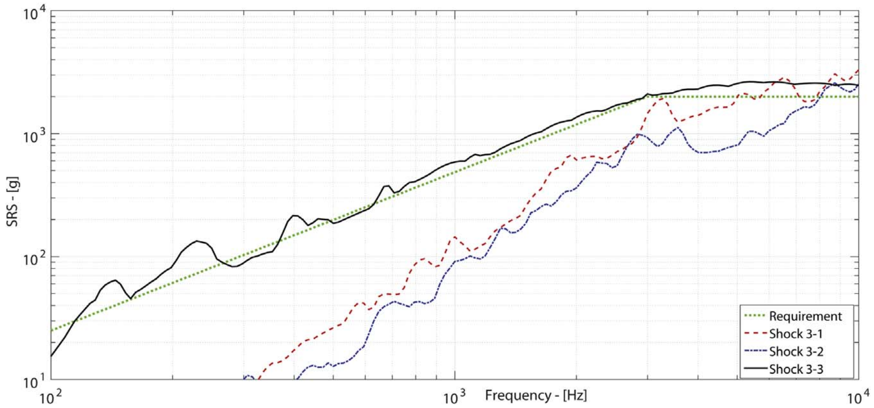

Fig. 1. Typical Pyroshock Test Curves.