Aerospace Science and Technology 80 (2018) 572–586

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Overview and application of FEM methods for shock analysis in space instruments

Andrés García-Pérez[a,*], Félix Sorribes-Palmer[a,1], Gustavo Alonso[a], Ali Ravanbakhsh[b]

[a] Instituto Universitario de Microgravedad "Ignacio Da Riva" (IDR/UPM), Universidad Politécnica de Madrid, Pza. Cardenal Cisneros 3, 28040 Madrid, Spain
[b] Institute of Experimental and Applied Physics, Christian-Albrechts-Universität zu Kiel (IEAP-CAU), D-24118, Kiel, Germany

ARTICLE INFO

Article history:
Received 5 March 2018
Received in revised form 8 May 2018
Accepted 22 July 2018
Available online 25 July 2018

Keywords:
Shock
Space instrument
Finite element model
Structural verification
Transient analysis
Response spectrum analysis

ABSTRACT

Spacecraft are subjected to severe mechanical loads, especially during the ascent phase of the launch. Among several vibrational environments, shock loads, which are caused mainly by the activation of pyrotechnic devices used for the separation of the payloads and the different stages of the launcher, are transmitted throughout the entire structure and reach the scientific instruments of the spacecraft. Therefore, it is important to verify if the space instruments can withstand this environment, considering the nature of the shock, which generally consists in an intensive and short load. In recent years, the demand of numerical analyses to predict the responses of the structures against shocks is increasing and, for this reason, it is necessary to establish adequate numerical methods, taking into account the complex mathematical treatment and the uncertainty in the load characterization. The purpose of this paper is to present the application of different methods to calculate the required structural results for a space instrument subjected to the shock environments using a finite element model (FEM). The procedures for each method, the type of the results that can be calculated and the comparison of the results are described in this paper. The objective is to select the most suitable analysis method for shock loads based on the precision of the results and the capability of obtaining all the variety of data for a complete evaluation of the structure.

1. Introduction

A mechanical environment that combines high static acceleration, low and high frequencies vibrations and shock loads, is generated during the launch operation in space missions. These loads are transmitted to the equipment and components of the spacecraft through the mechanical interfaces. Hence, the structural verification of spacecraft and their instruments is a fundamental requirement, where each type of the mechanical loads must be simulated by test and analysis to qualify the mechanical design [1,2].

When a shock load is propagated throughout the entire structure, it generates tension–compression, flexural and shear waves which are reflected, dissipated and diffracted at mechanical interfaces. The response acceleration has a transient and oscillatory behavior, with high positive and negative peaks, which is rapidly decreased with the time. In terms of frequency, the shock response is composed mainly by the system natural frequencies (typically at lower frequency) and by the frequencies from the external loading, usually at high frequency.

The shock environment is divided into the following categories depending on the distance of the measured point or the analyzed part with respect to the shock source [3,4]:

- The near-field shock environment occurs when the analyzed structure is near the shock source. The signal presents very high acceleration peaks (more than 5000 g) and very high frequency content (it can reach 1 MHz), due to that the wave is dominated by direct wave propagation.
- The mid-field shock environment is characterized by a combination of direct propagation and structure resonances, which generates a signal with high peaks between near and far-field shocks and frequency content until 100 kHz.
- The far-field shock environment appears to a distance far enough from the shock source, where the wave is dominated by the structural modal behavior. The response signals present high peaks but lower than from near and mid fields environments and with a frequency content not higher than 10 kHz.

---

[*] Corresponding author.
E-mail addresses: andres.garcia.perez@upm.es (A. García-Pérez), felix.sorribespalmer@v2c2.at (F. Sorribes-Palmer), gustavo.alonso@upm.es (G. Alonso), ravanbakhsh@physik.uni-kiel.de (A. Ravanbakhsh).

[1] Graz University of Technology, Inffeldgasse 21/A, 8010 Graz, Austria.

https://doi.org/10.1016/j.ast.2018.07.035
1270-9638/

Each launch authority must specify the shock loads generated by its launch vehicle during its operation taking into account all of the different causes. Due to the difficulty to elaborate a shock specification by transient acceleration functions, the adopted criterion in space industry is to represent the shock environment by a SRS curve [4]. A time acceleration function can be converted into the corresponding SRS curve by calculating the maximum peak acceleration of the response of a single degree of freedom system (SDOF) when the aforementioned acceleration time function is applied to the base [5]. The SRS curve is built establishing the dependency of the peak value of the response acceleration with the natural frequency of the SDOF, for a constant value of damping (the standard value for shock is 0.05). For space structures subjected to a far-field shock environment, the SRS are composed typically by an initial ramp from 100 Hz to a cut-off frequency (between 1000 and 2000 Hz) in a log–log graph, followed by a section of constant SRS until 10000 Hz [4]. The specification should be accompanied by a description of the expected time signal shape and duration, which typically is oscillatory and with a characteristic duration of 20 ms.

Important information about the shock nature as duration or excitation frequencies is lost when only the SRS curve is considered. In the cases where the shock specification of a space structure consists in a SRS curve, the only available information about the shock is the maximum peak acceleration of the structure simplified as a SDOF excited on its base by an unknown acceleration time function. This fact implies that the structure can be verified considering any transient load which meets with the specified SRS. Therefore, when the definition of an input acceleration time function from the SRS specification is required to test or analyze a satellite or a space instrument, extra information must be added to create the acceleration function. This fact implies that different functions can be used to evaluate the same shock environment. The input acceleration function can be obtained from several numerical methods as damped sinusoids decomposition, wavelet synthesis [5] or with the modal characteristics of the analyzed structure [6].

There are different ways to simulate shock loads in space systems [3,4] with the aim to verify if these structures can withstand this environment. The most used verification approach is the shock testing [7], which can be done by electromechanical shakers or by the test facilities where the shock is generated by mechanical impacts using hammer pendulums [8–12] or shooting projectiles [13–15].

Nowadays, the demand of numerical analyses to prove the structural reliability with a certain accuracy is increasing due to the difficulty to know from the shock test data the required results such as stresses, forces and accelerations in the critical parts. The state of the art for shock analysis has not reached the level of maturity as for the other loads such as static or sine vibration due to the high frequency content. There are some aspects that hinder the numerical treatment of this type of loads, such as short duration, broad range of excitation frequencies (typically from 100 to 10000 Hz for far-field environment), nonlinearity and the other effects in the propagation of the shock waves like the attenuation caused by distance and discontinuities in bolted interfaces of the structure. For these reasons, different analysis methods have been proposed and studied to calculate the structural behavior resulted from shock loads [16], where the required results as stresses, strains, forces and accelerations are necessary to evaluate the integrity of the space structures.

Finite Element Analysis (FEA), which is the most employed method in space industry for static and dynamic structural analyses, can be adequate to analyze small structures like space instrument subjected to a far-field shock load because its response is mainly dominated by the modal behavior. Nonlinear effects as attenuation due to the distance have less impact on the results for these structures. FEA method has been validated in several aspects simulating shock loads and comparing with the test data. In [17], different modeling techniques for a PCB (detailed FEM with 3D elements and simplified FEM with 2D elements) are studied simulating the shock load by transient analysis getting a good correlation with the test results for both models. In [18] the influence of the parameters that define an input load represented by a trapezoidal force impulse in a FEM transient analysis is studied and correlated with test results. The modeling of joints is evaluated in [19] for a truss frame structure under shock load, and the effects of a new damping definition for bolted joints of space structures is studied in [20]. In [21] the effect of the nonlinear modeling for the clamp band joint is evaluated in a coupling dynamic FEM of a launcher and spacecraft system subjected to vibration and impact excitations, and in [22] the characteristics of the design of the clamp band are studied to evaluate several structural parameters on the attitude of separating satellite, dynamic envelope of clamp band and the separation shock. Other studies employ detailed FEM with 3D elements to have more accurate results of shock analyses [23–27], with the disadvantage of time consuming and the big amount of output data. Alternative numerical approaches to simulate shocks are the Statistical Energy Analysis (SEA) method, which can be combined with FEA [28] or with Virtual Mode Synthesis and Simulation (VMSS) [29], Spectral Element Method (SEM) [30] and hydrocodes [27]. The advantage of FEA approach compared to the other numerical approaches is that it is a widely used method in the space industry for static, sine vibration and random vibration structural analyses and can also be easily implemented for shock analysis using the same FEM or with few modifications. FEA approach provides an acceptable prediction for small structures, where it is less problematic to have a sufficiently fine mesh without an excessive quantity of nodes to achieve the appropriate accuracy for the shock simulations.

The purpose of this paper is to present a complete overview of the different methods of shock analysis using the finite element model of a space instrument, indicating the characteristics and the results that can be calculated for each analysis. The simulation results are compared to the shock test data to determine the precision of each analysis method. One of the main conclusions of the work is that despite the required computational time comparing with the rest of the methods, the modal transient analysis is the most complete and accurate of the studied methods, getting an acceptable prediction of the structural behavior of the instrument under the shock environment.

2. STEP instrument for Solar Orbiter spacecraft

The Supra Thermal Electrons and Protons (STEP) instrument constitutes together with other instruments (the Electron Proton Telescope – High Energy Telescope (EPT-HET) instrument, the Suprathermal Ion Spectrograph (SIS) and the Instrument Control Unit (ICO)) the Energetic Particle Detector (EPD) payload for the ESA-NASA Solar Orbiter spacecraft, which is scheduled to be launched in 2019. The main objective of the Solar Orbiter project is to obtain a better understanding of the heliosphere characteristics.

The STEP instrument (Fig. 2.1) has been designed by a research team at the Institute of Experimental and Applied Physics (IEAP) of the Christian Albrechts University of Kiel (CAU) in Germany. STEP consists of two detectors of low energy electrons and protons (in the range of 3 keV to 100 keV). Both detectors are mounted on an electronic box, and two radiators are included to evacuate the excess of heat in the instrument. Further details about the scientific objectives of STEP instrument as well as Solar Orbiter EPD can be found in [31].