Mechanical Systems and Signal Processing 76-77 (2016) 424–440

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Stochastic shock response spectrum decomposition method based on probabilistic definitions of temporal peak acceleration, spectral energy, and phase lag distributions of mechanical impact pyrotechnic shock test data

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ARTICLE INFO

Article history:
Received 19 February 2015
Received in revised form
26 January 2016
Accepted 3 February 2016
Available online 19 February 2016

Keywords:
Pyrotechnic shock
SRS decomposition
Peak Ratio
Energy Ratio
Decay rate
Mechanical impact shock test

ABSTRACT

Most of the times pyrotechnic shock design and test requirements for space systems are provided in Shock Response Spectrum (SRS) without the input time history. Since the SRS does not describe the input or the environment, a decomposition method is used to obtain the source time history. The main objective of this paper is to develop a decomposition method producing input time histories that can satisfy the SRS requirement based on the pyrotechnic shock test data measured from a mechanical impact test apparatus. At the heart of this decomposition method is the statistical representation of the pyrotechnic shock test data measured from the MIT Lincoln Laboratory (LL) designed Universal Pyrotechnic Shock Simulator (UPSS). Each pyrotechnic shock test data measured at the interface of a test unit has been analyzed to produce the temporal peak acceleration, Root Mean Square (RMS) acceleration, and the phase lag at each band center frequency. Maximum SRS of each filtered time history has been calculated to produce a relationship between the input and the response. Two new definitions are proposed as a result. The Peak Ratio (PR) is defined as the ratio between the maximum SRS and the temporal peak acceleration at each band center frequency. The ratio between the maximum SRS and the RMS acceleration is defined as the Energy Ratio (ER) at each band center frequency. Phase lag is estimated based on the time delay between the temporal peak acceleration at each band center frequency and the peak acceleration at the lowest band center frequency. This stochastic process has been applied to more than one hundred pyrotechnic shock test data to produce probabilistic definitions of the PR, ER, and the phase lag. The SRS is decomposed at each band center frequency using damped sinusoids with the PR and the decays obtained by matching the ER of the damped sinusoids to the ER of the test data. The final step in this stochastic SRS decomposition process is the Monte Carlo (MC) simulation. The MC simulation identifies combinations of the PR and decays that can meet the SRS requirement at each band center frequency. Decomposed input time histories are produced by summing the converged damped sinusoids with the MC simulation of the phase lag distribution.

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http://dx.doi.org/10.1016/j.ymssp.2016.02.005
0888-3270/

1. Introduction

Pyrotechnic shock is one of the structural design and test requirements for space systems and payloads. Most of the pyrotechnic shock devices produce extremely high accelerations across the broad frequency range. As a result, numerous mission critical failures associated with pyrotechnic shock events have been reported in the past [1,2]. Pyrotechnic shock design and test requirements are typically provided in Shock Response Spectrum (SRS). The SRS describes the maximum absolute temporal response of a single degree of freedom system subjected to an arbitrary transient input at the base. Natural frequency of the single degree of freedom system and structural amplification factor (Q) are the two unknowns in the SRS calculation. It is customary to use $Q=10$ during the SRS calculation at each prescribed natural frequency of the system.

One of the issues associated with the SRS is that the process is irrevocable. The actual input or the environment in which the pyrotechnic shock requirement was derived from cannot be produced from the SRS. Therefore, a decomposition process takes place if the source time history needs to be estimated. There are many papers written in this topic. Smallwood [3], Kern and Hayes [4] and Fisher and Posehn [5] are a few of the many available publications describing mathematical methods that can decompose the SRS into temporal waveforms. During the shock tests using vibration shakers, the shaker control algorithm typically decomposes the user-specified SRS requirement using wavelet decomposition method [6]. While these methods provide the mathematical functions that can decompose the SRS, variables of the methods such as the peak acceleration, decay, damping, number of cycles, phase lag, etc. are estimated arbitrarily as long as the produced temporal input satisfies the SRS requirement. As a result, these methods could produce transient waveforms that may have completely different temporal characteristics from the realistic pyrotechnic shock test data while meeting the SRS requirement.

The proposed method uses damped sinusoids described with the Peak Ratio (PR) and decay rate at each band center frequency. As stated earlier, the PR is defined as the ratio between the maximum SRS and the temporal peak acceleration and the Energy Ratio (ER) is defined as the ratio between the maximum SRS and the RMS acceleration at each band center frequency. The two new definitions describe damage creating mechanisms of the pyrotechnic shock input and their relationship with the response spectra. The decay rate simulates a decay of the RMS energy and is obtained by matching the ER of the damped sinusoid to that of the test data that the damped sinusoid is to simulate. Phase lag among the damped sinusoids is estimated by measuring the time delays of the temporal peak accelerations from the time of the temporal peak acceleration at the lowest band center frequency. This stochastic process has been applied to more than one hundred pyrotechnic shock test data measured from the MIT Lincoln Laboratory (LL) designed Universal Pyrotechnic Shock Simulator (UPSS) to produce probability density functions of the decomposition variables such as the PR, ER, decay rate, and the phase lag. The UPSS is a mechanical impact test apparatus that can simulate a wide range of pyrotechnic shock requirements [7]. Unlike vibration shakers, the UPSS produces standing and propagating waves of an aluminum plate and provides significantly more realistic mechanical impedance at the interface of a test article. Therefore, by anchoring pyrotechnic shock test data measured from the UPSS to the damped sinusoids, the decomposed temporal input functions are expected to be much more realistic and refined. Using the probability density functions of the decomposition variables, Monte Carlo (MC) simulation of the damped sinusoids is conducted at each band center frequency with the SRS requirement as the constraint. This process identifies the PR and decays converging to the SRS within the user-defined tolerance. Finally, decomposed waveforms are obtained by summing the converged damped sinusoids with the MC simulation of the phase lag distribution. A group of realistic temporal input functions satisfying the SRS requirement is produced as a result.

2. Process of stochastic SRS decomposition method

2.1. Pre-processing scheme

Fig. 1 shows the flowchart of the proposed method and Fig. 2 shows a photo of the UPSS [7]. The UPSS is comprised of an aluminum plate and the steel support table. The size of the aluminum plate is 1 m by 1 m with 2.54 cm thickness. The UPSS weighs approximately 136 kg with the plate and the support table combined. The input time histories are generated by the broadband resonant response of the plate due to impulsive excitations created by the portable nail guns. During each test, quality of the data was assured by investigating the velocity of each signal decreasing to zero value in the time domain. The first step of the proposed method is pre-processing of the test data measured at the interface of the test articles. The pre-processing is comprised of two steps. First, it captures the data from the absolute temporal peak acceleration to the one percent of its magnitude. Second, it identifies and removes the offset from each test data. The pre-processing scheme automatically defines the duration of each time history allowing an “apples-to-apples” comparison among the RMS values. As stated earlier, in this stochastic analysis, the RMS value represents the energy level of a time signal calculated between the absolute temporal peak acceleration and the one percent of its magnitude. Fig. 3 shows an exemplary raw test data and its pre-processed data. The pre-processing scheme eliminated a small offset in the raw test data. Since the negative temporal peak occurred before the positive temporal peak, the negative temporal peak was not captured during the pre-processing. The pre-processing scheme has been applied to more than one hundred input time signals.

The shock test data were collected using Dytran shock accelerometers that can measure at least 10,000g with a flat frequency response up to at least 20,000 Hz. Time histories were collected using DataFlex-1000A data acquisition system