Review of recent advances in pyroshock for space system

Zhang Minjie[1], **Xiang Shuhong**[2]
Beijing Institute of Spacecraft Environment Engineering, Beijing, China
National Key Laboratory of Science and Technology on Reliability and Environment Engineering, Beijing, China
[1]Corresponding author
E-mail: [1]*958657616@qq.com*, [2]*xshxsh638@sohu.com*

(Accepted 18 July 2014)

Abstract. Numerous pyrotechnic devices are used in aerospace vehicles to separate structural subsystems, deploy appendages, or activate on-board operational subsystems. The state-of-the-art for pyroshock prediction, design and test verification has not yet reached the maturity of other environmental disciplines, due to the complex, high-frequency nature of pyroshocks. However, recent advances in the analysis and simulation of pyroshocks have led to a better understanding of this environment. This paper presents an overview of the development of characterization of pyroshock, various experimental tests and simulations, analytical and numerical simulation for pyroshock prediction, and protecting techniques.

Keywords: pyroshock, analysis, prediction, simulation, experiment.

1. Introduction

Nowadays, the space industry uses more and more pyrotechnic devices to carry out various operations such as separation of structural elements, unlocking mechanisms (unfolding solar panels, etc.), or activation of onboard operating subsystems. Pyrotechnic shock, or pyroshock, is the transient oscillatory response of a structure to loading (high frequency, high magnitude stress waves) induced by the detonation of pyrotechnic devices incorporated into or attached to the structure.

The advantages of pyrotechnic devices include small size, light weight, stored energy, reliability, redundancy and adaptability to flight environments. Pyroshock rarely causes damage to structural members, but it can easily cause failures in electronic and optical components that are sensitive to high frequency energy. Many flight hardware failures have been attributed to pyroshock exposure, some resulting in catastrophic mission loss. The Air Force Research Laboratory Space Vehicles Directorate (AFRL/VS) conducted a survey of pyroshock flight failures revealing 83 shock related anomalies out of 600 launches, with over 50 % of these resulting in catastrophic failure [1].

Pyrotechnic devices may be divided into two general categories: point sources and line sources. Most line sources are very intense sources, and point sources are less intense sources. Pyroshock environments are broadly divided into three categories based on the magnitude and spectral content of the environment: near-field, mid-field, far-field [2]. The classification depends on the type and strength of the pyroshock device, the source/hardware distance, and the configuration details of the intervening structure. Details of Pyroshock Environmental Categories are listed in Table 1.

Table 1. Categories and characteristics of pyroshock environment

Pyroshock environment	Source/hardware distance/mm		Dominating factor	Peak acceleration/g	Spectrum content/Hz
	Point source	Line source			
Near-field	< 30	< 150	wave propagation	> 10,000	> 10,000
Mid-field	30-150	150-600	a combination of wave propagation and structural resonances	1000-10,000	3,000-10,000
Far-field	> 150	> 600	structural resonances	< 1,000	< 3,000

2. Experimental tests and simulation

Methods of predicting the response of a structure to pyroshock can be classified into two categories: experimental tests and non-experimental methods. Pyroshock environment experimental simulation can be created by optically, mechanically, or pyrotechnically exciting the structure [3]. Typical mechanical experimental methods include drop towers, gas guns, pendulum hammer, resonant fixtures, and Hopkinson/Kolsky bars, electrodynamic shakers, etc. L. K. Stewart [4] used high precision, computer-controlled hydraulic actuators at the Air Force Research Laboratory (AFRL) at Eglin Air Force Base, Florida, to fire a piston mounted with various impact materials at high velocities into the specified test article. The peak acceleration can be up to nearly 6000 g, and the frequency up to 100 kHz. The advantages of the system include a high level of repeatability and capability of effective modification of the types of loading and duration. J. R. Lee [5] used Laser-based shock wave propagation simulation as an advanced method.

Depending upon which of the three pyroshock environmental categories applies to the hardware, pyroshock testing for externally-induced shock environments may be achieved by using one of the following types of sources: for hardware exposed to near-field pyroshock, only a pyrotechnic device may be used; for hardware in the mid-field, both impact and pyrotechnic devices are used; for hardware in the far-field, all of these devices are used. The advantages and disadvantages of each method are summarized in Table 2.

Table 2. Advantages and disadvantages of various experimental test methods

	Advantages	Disadvantages
Pyrotechnic device	Capability to achieve the high accelerations and high frequencies; Most accurate.	Lengthy period of trial and error to finalize the test configuration; Various safety issues; Potentially large test-to-test variation; High cost.
Mechanical simulators	Relatively low operational cost; Predictable behavior.	Limited spectral capability; Long adjustment time to the requirement.
Electrodynamic shakers	General availability; Low operational cost; Known controllability.	Limited magnitude, spectra, and directional capability.

3. Non-experimental prediction

The analysis and prediction of pyroshock now cannot be done simply with analytical method. For simple structure as plates or beams, Hampton et al. [6] suggested discretized quasianalytical models, derived from a continuous analytical model (Euler–Bernoulli theory). These models are not easy to implement for more complex structures. For far-field pyroshock tests realized by the in-plane impact of a hammer pendulum on a plate including the test specimen, Alexander Lacher [7] predicted the acceleration field and the corresponding SRS semi-analytically by using Hertzian contact theory, the Galerkin-procedure and numerical integration in time domain. The results are compared with experimental data showing very good coincidence and allowing for a fast prediction of far-field pyroshock tests. Mauro Caresta [8] proposed a new method to predict the early-time response of a structure to an impact with a rigid or flexible body. The contact force is expressed with a Hertzian spring contact and the convolution between the Impulse Response Function. Using an assumption of randomness of the structure, only the modal density and the mass of the structure are needed in order to derive the Impulse Response.

Finite Element Method (FEM) and Boundary Element Method (BEM) are the most widespread approach to predict the low frequency response of a structure. Chen Min [9] used ANSYS/LS-DYNA to simulate the explosive process of pyrotechnic devices, and predicted the nonlinear dynamic response of material to explosive shock impact. Wang Junping [10] studied typical connecting structure of explosive bolts, and used ANSYS/LS-DYNA to model and simulate the three categories of shock loads to the connecting structure due to explosive bolts: shock wave induced by explosion, stress wave due to the sudden release of preloads of the bolts due to the unlock process, the impact of pyrotechnic device members hitting a certain part of the structure at a certain speed. The acceleration responses induced by these three loads are obtained. Mao Jianyong [11, 12] completed a simulation of explosive rods loading on cylindrical shell with the ALE-based method. The dynamic response of the structure, the propagation of shock wave and the physical images are obtained. The numerical and tested results agree well. The results showed that the additive two rubber layers can affect the modal characteristics of the test items. De Benedetti et al. [13] successfully simulated and validated finite element models of the dynamic behavior of printed circuit boards (PCBs) under pyrotechnic shock and the damping effect of the bolted junctions between the electronic unit and the shock plate.

BEM is another numerical method after FEM which attempts to use the given boundary conditions to fit boundary values into the integral equation, rather than values throughout the space defined by a partial differential equation. Compared to FEM, BEM effectively reduces the degree of freedom and has high accuracy.

FEM and BEM are deterministic methods which have some deficiencies at higher frequencies. As the wavelength decreases with the frequency, the number of elements has to be increased in the same way. This makes these methods, at high frequencies, costly in memory resources, modeling work, and postprocessing time.

The statistical energy analysis (SEA) is the most widely used theoretical framework for the analysis of the dynamic response of complex systems in high frequency range. In the SEA method, the structure is modeled as an assemblage of discrete subsystems that receive, dissipate, and transfer vibrational energy. The main advantage of SEA is the small size of the model, which is not related to the excited wavelengths, but only to the number of subsystems. The major drawbacks of SEA are the difficulty in establishing an appropriate model (particularly the choice of subsystems and the evaluation of the input parameters), the loss of information on the spatial distribution of the vibrational energy inside each subsystem and the incapability to provide the time history of the acceleration. Wang Junping [14] carried out a statistical energy analysis of pyroshock responses for complex structures. A statistical energy analysis combined with a virtual mode synthesis was performed to predict the pyroshock responses in a typical spacecraft structure. The results agreed with the general trends of the responses and their transfers at related conditions. Bodin [15] combined FEM and SEA to predict the response of an electronic equipment assembly submitted to high frequency shocks, with FEM providing the low frequency content of the acceleration and SEA, coupled to a local random phase reconstruction concept, providing the high frequency content. Dalton [16] used a virtual mode synthesis (VMS) method, which assumed that the modes were distributed over frequency according to the modal density estimation and that these modes collectively produced the frequency response envelope in each frequency band. The virtual mode residues were obtained by comparing the Frequency Response Function (FRF) magnitude of the virtual system with the one obtained by SEA.

Other prediction methods include: Takashi Iwasa [17] proposed a simplified model to predict the pyroshock environment near the V-band clamp separation device. The model was based on a single degree of freedom system and calculated a free vibration after releasing, which was derived from the release mechanism of the device. Comparing simulation results with test ones showed that the model approximately predicted the pyroshock response near the device. R. Ruotolo [18] presented a spectral element matrix (SEM) for anisotropic, laminated composite beams. It is based on the first order shear deformation theory and takes into account both the shear deformation as well as rotatory inertia, whose effects can be very important at high frequencies. The spectral matrix is derived by considering the propagation of waves into the structural media and solving the corresponding wave equation. The proposed spectral element was employed to demonstrate its capability to perform pyroshock analysis. An idealized satellite structure made by sandwich beams was analyzed, and the shock response spectrum evaluated at several locations. Usik Lee

[19], Namita Nanda [20] developed the method.

The dynamic simulation of mechanical structures requires an accurate knowledge of the excitation forces, which are unknown and cannot be directly measured. It is essential to have access to the applied forces. Brossard et al. [21] and Dharaneepathy et al. [22] investigated the effects of air blast on shell structures, showed that the pressure wave load can be described by a sine-exponential model depending on two parameters: the angle of the incident shock, and the reduced parameter, which represents the ratio between the radial distance R from the center of the explosion and the cube root of the chemical energy E. David Wattiaux [23] suggested an identification procedure of the pyrotechnic excitation using an approach by equivalent mechanical shock EMS, which replaces the actual excitation by a localized force applied on the FE model at the center of the explosive device. The amplitude and duration of the force were tuned using the following process to minimize the difference between experimental and simulated SRS, so as to generate equivalent acceleration fields. F_{max} and τ is the intensity and duration of the impact (triangular symmetrical profiles), N is the number of measurement points on the plate and j is the node number:

$$\varepsilon = \min_{F_{max},\tau} \sum_{f=1000\,Hz}^{10kHz} \sum_{j=1}^{N_{SRS}} \left| SRS_j^{measured} - \mathrm{SRS}_j^{simulated}(F_{max},\tau) \right|^2. \quad (1)$$

This approach was validated in Thales Alenia Space ETCA (Charleroi-Belgium) and showed good agreements with experimental results. For a given amount of explosive charge, similar EMSs was identified when different configurations were used.

4. Pyroshock protecting techniques

Based on a better understanding of the pyroshock environment, protecting techniques are developed in terms of energy absorbing and isolation. Shape memory alloy is used for absorbing and dissipating pyroshock energy for its pseudoelasticity [24]. Metal rubber damper is studied and showed promising characteristics for space applications [25]. The isolation of pyroshock energy can be achieved by increasing the discontinuity in the intervening structure [26]. Details of pyroshock protecting techniques can be seen in [27].

5. Conclusion

To get a better understanding of pyroshock environment needs the combination of experimental, analytical and numerical methods. This paper reviews the application and development of these methods for further research so as to establish a method that is more applicable to aerospace industry.

References

[1] **Eugene R. Fosness, Steven J. Buckley, Waylon F. Gammill** Deployment and release devices efforts at the Air Force Research Laboratory Space Vehicles Directorate. American Institute of Aeronautics and Astronautics, 2001.
[2] Pyroshock test criteria. NASA Technical Standard, NASA-STD-7003, USA, 2011.
[3] **Xiang Shuhong** The test technology of spacecraft mechanics environments, 2008.
[4] **Stewart L. K., Durant B., Wolfson J., Hegemier G. A.** Experimentally generated high-g shock loads using Hydraulic Blast Simulator. International Journal of Impact Engineering, Vol. 69, 2014, p. 86-94.
[5] **Lee J. R., Jeong H. M., Kong C. W.** Wave propagation visualization in an experimental model for a control rod drive mechanism assembly. Nuclear Engineering and Design, Vol. 241, 2011, p. 3761.

[6] **Hampton E., Nygren P., Li, H.** Analytical shock response of a transversely point-loaded linear rectangular plate. Proceedings of the Eighth Biennial ASME Conference on Engineering Systems Design and Analysis, Torino, Italia, 2006.

[7] **Alexander Lacher, Nikolas Jungel, Utzvon Wagner, Annette Bager** Analytical calculation of in-plane response of plates with concentrated masses to impact and application to pyroshock simulation. Journal of Sound and Vibration, Vol. 331, 2012, p. 3358-3370.

[8] **Mauro Caresta, Robin S. Langley, Jim Woodhouse** Transient response of structures with uncertain properties to nonlinear shock loading. Journal of Sound and Vibration, Vol. 332, 2013, p. 5821-5836.

[9] **Chen Min, Sui Yunkang, Yang Zhiguang** Numerical simulation of exploding separation for aerospace pyrotechnical actuated separation device. Initiators and Pyrotechnics, Vol. 5, 2007, p. 5-8.

[10] **Wang Junping, Mao Yongjian, Huang Hanjun** Numerical simulation for impulsively loading mechanism of a point pyrotechnic separation device. Journal of Vibration and Shock, Vol. 32, No. 2, 2013.

[11] **Mao Yongjian, Li Yulong, Miao Yinggang, Chen Ying, Huang Hanjun, Zhang Qingping** Numerical simulation of loading cylindrical shell by explosive rods (I): Fluid-Structure Interaction Simulation. Chinese Journal of High Pressrue Physics, Vol. 26, Issue 2, 2013, p. 155-162.

[12] **Mao Yongjian, Li Yulong, Miao Yinggang, Chen Ying, Huang Hanjun, Zhang Qingping** Numerical simulation of loading cylindrical shell by explosive rods (II): Uncoupling Analysis and Experimental Validation. Chinese Journal of High Pressrue Physics, Vol. 27, Issue 1 2013, p. 76-82.

[13] **de Benedetti M., Garofalo G., Zumpano M., Barboni R.** On the damping effect due to bolted junctions in space structures subjected to pyroshock. Acta Astronautica, Vol. 60, 2007, p. 947-956.

[14] **Wang Junping, Mao Yongjian, Huang Uanjun, Dong Longlei** Application of statistical energy analysis method in prediction of pyroshock responses. Spacecraft Environment Engineering, 2011.

[15] **Bodin E., Brévart B.** Pyrotechnic shock response predictions combining statistical energy analysis and local random phase reconstruction. The Journal of the Acoustical Society of America, Vol. 112, Issue 1, 2004, p. 156-163.

[16] **Dalton E. C.** Ballistic shock response by an extension of statistical energy analysis. Proceedings 63rd Shock and Vibration Symposium, 1992.

[17] **Takashi Iwasa, Qinzhong Shi** Simplified SRS prediction method for pyroshock source of V-band clamp separation devices. 48th Structures, Structural Dynamics, and Materials Conference, Honolulu, Hawaii, 2007.

[18] **Ruotolo R.** A spectral element for laminated composite beams: theory and application to pyroshock analysis. Journal of Sound and Vibration, Vol. 270, Issue 2004, p. 149-169.

[19] **Usik Lee, Daehwan Kim, Ilwook Park** Dynamic modeling and analysis of the PZT-bonded composite Timoshenko beams: Spectral element method. Journal of Sound and Vibration, Vol. 332, 2013, p. 1585-1609.

[20] **Namita Nanda, Kapuria S., Gopalakrishnan S.** Spectral finite element based on an efficient layerwise theoryfor wave propagation analysis of composite and sandwich beams. Journal of Sound and Vibration, Vol. 333, 2014, p. 3120-3137.

[21] **Brossard J., Desrosier C., Purnomo H., Renard J.** Pressure loads on a plane surface submitted to an explosion. Proceedings of the 19th International Symposium on Shock Waves, Marseille, France, 1995.

[22] **Dharaneepathy M. V., Keshava R. M. N., Santhakumar A. R.** Critical distance for blast-resistant design. Computers and Structures, Vol. 544, 1995, p. 587-595.

[23] **David Wattiaux, Olivier Verlinden, Calogero Conti** Prediction of the vibration levels generated by pyrotechnic shocks using an approach by equivalent mechanical shock. Journal of Vibration and Acoustics, Vol. 130, Issue 4, 2008.

[24] **Se-Hyun Youn** Development of a three-axis hybrid mesh isolator using the pseudoelasticity of a shape memory alloy. Smart Materials and Structures, Vol. 20, 2011, p. 1-12.

[25] **Jin Ming, Xue Qianguang, Tian Liqiang, Song Xinbo** Experimental study on vibration and shock characteristics of Metal rubber damper. Reliability and Environment Experiment of Electronic Deveices, Vol. 30, Issue 2, 2012, p. 49-57.

[26] **Nancy Ann Winfree, Joseph Hyunchul Kang** Mechanical filter for sensors. Patent No. US7706213 B2, 2010-04-27.

[27] **Zhang Huan, Liu Tianxiong, Xiang Shuhong, Li Changjiang, Zhang Qingming** Spacecraft pyroshock protecting techniques. Spacecraft Environment Engineering, Vol. 2, 2014.