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Fast Simulation of Pyroshock Responses of a Conical Structure Using Rotation-Superposition Method

Yongjian Mao[1], Yulong Li[2], Hanjun Huang[1] and Junping Wang[1]
[1]Institute of Structural Mechanics, China Academy of Engineering Physics, Mianyang 621900, Sichuan, China
[2]School of Aeronautics, Northwestern Polytechnical University, Xi'an 710072, Shaanxi, China
Email Address: liyulong@nwpu.edu.cn

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Abstract: In space engineering, the prediction of structural responses induced by pyrotechnic devices is important for protecting the space hardware, especially the electronic components. This paper presents a fast simulation of pyroshock responses of a conical space structure. Firstly, a finite element analysis was performed and the responses to a load element were obtained. Then, by introducing the quick method, Rotation-Superposition Method, the structural responses induced by various numbers of explosive bolts were predicted and the effects of non-simultaneous initiations were also analyzed. This study provides a high-efficiency approach for multi-case pyroshock responses prediction.

Keywords: Pyroshock, structural response, numerical simulation, Rotation-Superposition Method

1 Introduction

Presently, pyrotechnic devices are widely used in space engineering. The detonations of those pyrotechnic devices will induce high-level structural responses with the characteristics of high frequency, short duration and high peak acceleration [1]. This kind of shock environments will influence, or even damage the space hardware. According to Moening's statistic [2], a significant number of failures of space hardware, especially of electronic components, resulted from pyroshock environments. Thus, this problem is paid much attention by the engineers and scientists.

However, the prediction of pyroshock responses is difficult because of the lack of effective analytical techniques. Therefore, a number of researchers are attempting in numerical techniques development. Up to now, various kinds of numerical techniques have been proposed [3], including time history analysis (THA) [4,5], response spectrum analysis (RSA) [6], statistical energy analysis (SEA) [7] and a synthetic technique combining THA and SEA [1].

Traditionally, whichever method is used, each case needs a full analysis. Thus, for a multi-case problem, a corresponding number of simulations have to be performed. But the trouble of this way is that, a great number of hours are unavoidable for modeling and computing. As we know, various schemes are usually considered in design stage of a structure or system. Then a significant number of cases need to be analyzed in order to compare the different schemes. So, this practical engineering background requires a high-efficiency simulation technique to be developed.

This paper predicts the pyroshock responses of a cone-shaped structure in different cases by employing the quick method, Rotation-Superposition Method, which was originally proposed by Mao et al [8,9] for lateral shock responses calculation. Based on only one finite element simulation, the structural responses in various cases were obtained and compared. The example shows the method has very high efficiency in analyzing multi-case pyroshock problems.

2 Rotation-Superposition Method

The details of the Rotation-Superposition Method can be found in [8,9]. This section only gives a brief introduction.

2.1 Definition

Definition 2.1. Assume an axi-symmetrical structure V is loaded by $\mathbf{F}(r,\theta,z)$ in the area $\Omega(r,\theta,z)\subseteq V$, and $\mathbf{F}(r,\theta,z)$ can be decomposed as

$$\mathbf{F}(r,\theta,z,t)=\sum_{i=0}^{n-1}\mathbf{F}_i(r,\theta,z,t), n\geq 2\ , \tag{2.1}$$

where, r, θ and z denote the cylindrical coordinate system, t is time, n is the number of load subsets and $\mathbf{F}_i\,(i=0,1,\cdots,n-1)$ is the ith subset of $\mathbf{F}$. If $\Omega_i\,(r,\theta,z)\subseteq\Omega$ is the loading area of $\mathbf{F}_i$ and

$$\Omega_i\,(r,\theta-\Delta\theta_i,z)=\Omega_0\,(r,\theta,z), i=1,\cdots,n-1\ , \tag{2.2}$$

$$\mathbf{F}_i\,(r,\theta-\Delta\theta_i,z,t-\Delta t_i)=k_i\mathbf{F}_0\,(r,\theta,z,t), i=1,\cdots,n-1\ , \tag{2.3}$$

the load $\mathbf{F}$ on V is called a *load of rotational similarity*. Where, $\Delta\theta_i$ is the rotation angle and Δt_i denotes the potential time delay.

2.2 Formulation

It is assumed that only a linear elastic problem is considered, and the axi-symmetrical structure is loaded by $\mathbf{F}$, a load of rotational similarity. Now decompose $\mathbf{F}$ into $\mathbf{F}_i\,(i=0,1,\cdots,n-1)$ according to Eq. (2.1), then the responses to $\mathbf{F}_i$ can be denoted as

$$\mathbf{R}_i=\mathbf{R}_i\big(r,\theta,z,t\big), i=0,1,\cdots,n-1\ , \tag{2.4}$$

where, $\mathbf{R}$ denotes the components of structural responses in the cylindrical coordinate system, such as stress, strain and acceleration. If $\mathbf{R}_0 = \mathbf{R}_0(r,\theta,z,t)$ has been obtained, then the responses to $\mathbf{F}_i$ is

$$\mathbf{R}_i(r,\theta,z,t) = k_i\mathbf{R}_0(r,\theta-\Delta\theta_i,z,t-\Delta t_i),\ i=1,\cdots,n-1, \tag{2.5}$$

where, $k_i = \mathbf{F}_i/\mathbf{F}_0$ is determined by Eq. (2.3). Thus, the responses to $\mathbf{F}$ can be given as

$$\mathbf{R}(r,\theta,z,t) = \sum_{i=0}^{n-1}\mathbf{R}_i = \sum_{i=0}^{n-1}k_i\mathbf{R}_0(r,\theta-\Delta\theta_i,z,t-\Delta t_i). \tag{2.6}$$

3 Problem and Modeling

3.1 Problem Description

The sketch of the conical structure is given in Figure 3.1. The entire structure consists of two conical shells and an electronic component simplified as a thick-wall cylindrical shell. This structure is connected with a rocket vehicle by explosive bolts uniformly located in the bigger-end plane. At a scheduled time in flight, the explosive bolts are initiated, and the structure separates from the vehicle. Now the responses at location *P*, i.e. the pyroshock environments of the component need to be analyzed for design.

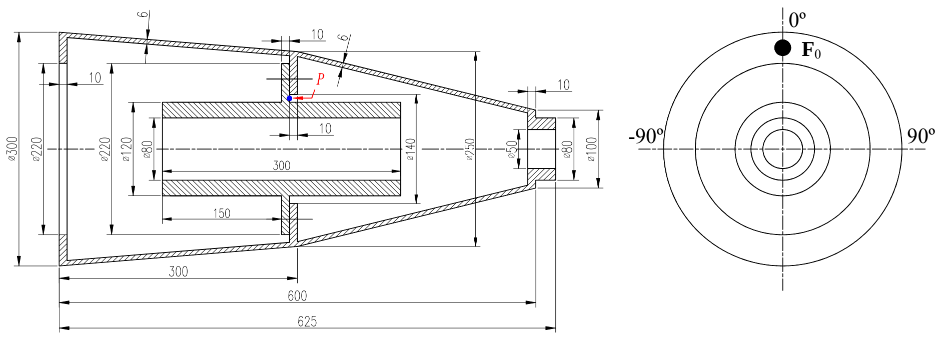

Figure 3.1: Sketch of the conical structure.

The load of a single explosive bolt can be simplified as a uniform dynamic pressure with the amplitude 250MPa, pulse duration 50μs and loading area Φ20mm. In fact, this load corresponds an impulse of 1.96N·s.

Because of the uniformity of the explosive bolts, and its locations and load directions, the loads have the characteristics of rotational similarity according to the above definition 2.1. So the problem can be solved by the Rotation- Superposition Method.

3.2 Finite Element Modeling

The finite element software ANSYS/LS-DYNA is used for modeling and simulation. The 1/2 model (0º-180º) is built as shown in Figure 3.2.

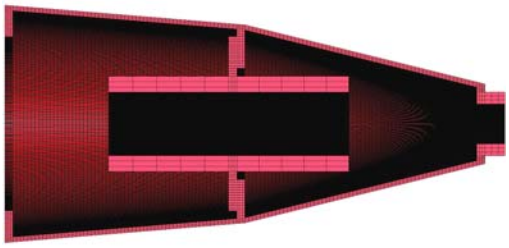

Figure 3.2: Finite element model of the conical structure.

The model is meshed into 211680 SOLID 164 elements, with 281219 nodes. All the materials are described by the linear elastic constitutive model with the mass density 7.83×10^3kg/m^3, elastic modulus 207GPa and Poisson's ratio 0.28. The 0º-180º section is set as plane-symmetrical boundary condition, and the others are kept free. Let $\mathbf{F}_0$ denote the load element located at 0º. The pressure amplitude is 1MPa, and the loading area is the outer surface of the corresponding elements as shown in Figure 3.1.

4 Results

4.1 Acceleration Reponses to $\mathbf{F}_0$

Firstly, a part of axial (*Z*-direction) acceleration histories (at the circumference corresponding to point *P*) are obtained as shown in Figure 4.1. These curves will be used to calculate the acceleration responses to various numbers of explosive bolts.

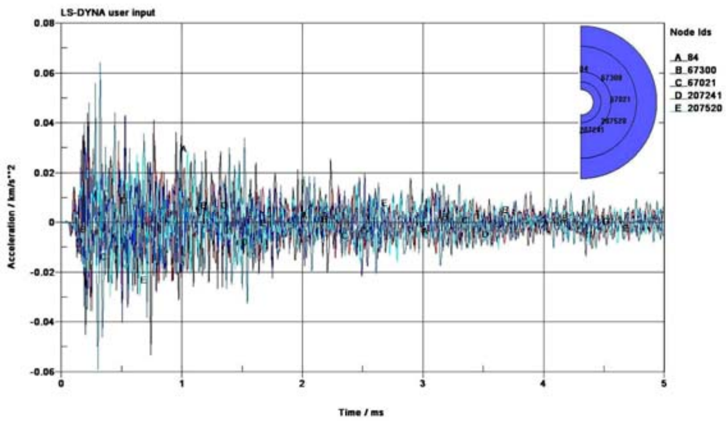

Figure 4.1: Acceleration responses to $\mathbf{F}_0$. Five acceleration histories, A, B, C, D and E were recorded, corresponding to the nodes 84, 67300, 67021, 207520 and 207241, respectively. The corresponding circumferential angles are 0º, 45º, 90º, 135º and 180º, respectively.

4.2 Acceleration Responses to 4 and 8 Bolts

For the condition of 4 explosive bolts, according to the axi-symmetry of the structure, rotational similarity of the loads and the plane symmetry of the problem, the acceleration response at the point *P* can be derived as

$$A_{(4)} = 250\left[a(0°) + a(90°) + a(-90°) + a(180°)\right] = 250\left(a_{84} + 2a_{67021} + a_{207241}\right), \tag{4.1}$$

The derivation of the above equation can be illustrated by Figure 4.2, and the result is given in Figure 4.3(a). Similarly, the acceleration response to 8 bolts is

$$A_{(8)} = 250\left(a_{84} + 2a_{67300} + 2a_{67021} + 2a_{207520} + a_{207241}\right), \tag{4.2}$$

as shown in Figure 4.3(b).

4.3 Acceleration Responses to 4 Bolts Non-simultaneously Initiated

Consider the initiation delays of the 4 explosive bolts as: 0ms at 0º, 0.25ms at ±90º and 0.5ms at 180º, then the acceleration response at the point *P* can be expressed as

$$A'_{(4)} = 250\left[a_{84}(t) + 2a_{67021}(t+0.25) + a_{207241}(t+0.5)\right]. \tag{4.3}$$

The corresponding result is plotted in Figure 4.3(c).

4.4 Shock Response Spectrum (SRS) Analysis

The maximum SRS curves calculated from the acceleration histories shown in Figures 4.3(a), (b) and (c) are given in Figure 4.3(d).

From Figure 4.3(d), we can find that the SRS to 8 explosive bolts is higher than that to 4 bolts. This is mainly because the total impulse of 8 bolts is much higher than 4 bolts. Meanwhile, the SRS to 4 bolts simultaneously initiated is a little higher than non-simultaneous initiations. This is mainly because the non-simultaneous initiations affect the energy concentration and output.

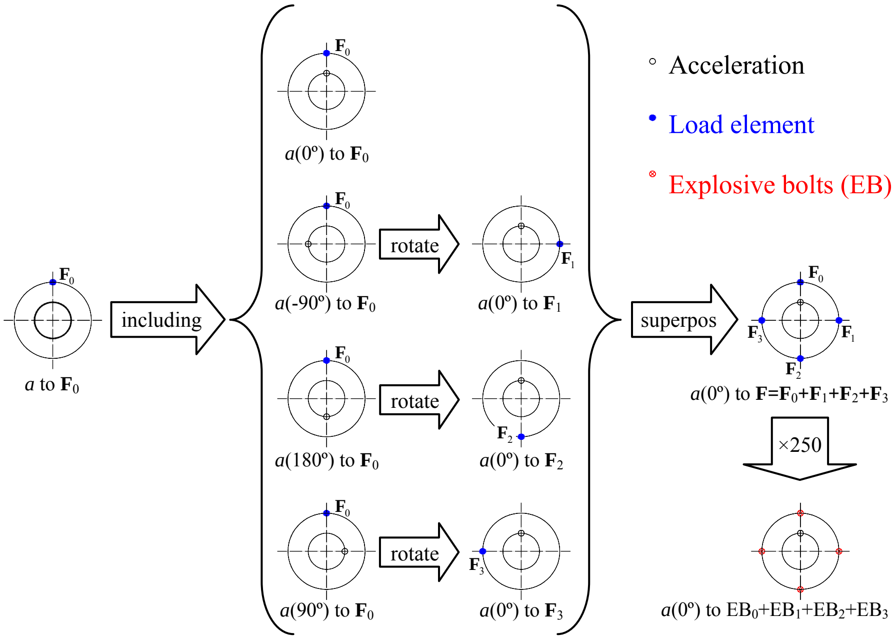

Figure 4.2: Illustration of the Rotation-Superposition Method for calculating responses to 4 bolts by the responses to a single load element $\mathbf{F}_0$.

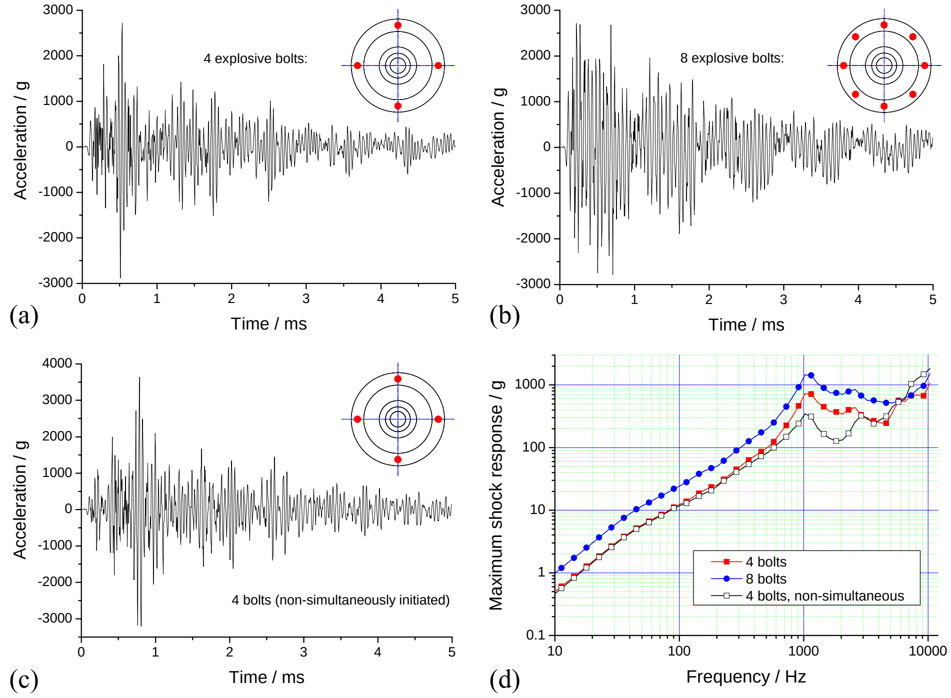

Figure 4.3: Acceleration responses and SRS analysis in various load cases. (a) Acceleration response to 4 explosive bolts. (b) Acceleration response to 8 explosive bolts. (c) Responses to 4 bolts non-simultaneously initiated. (d) SRS analysis.

5. Summary

Pyroshock responses prediction is of importance for design of space structures. But presently it is difficult because of the lack of efficient simulation techniques, especially for multi-case analyses. This paper presents an application example of the Rotation-Superposition Method in predicting pyroshock responses. The example shows that the quick method has very high efficiency and convenience in multi-case structural responses prediction. Using that, the responses in various cases can be superposed only based on one finite element simulation. This study provides a good approach for high-efficiency prediction of pyroshock responses.

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Yongjian Mao received his PhD degree in solid mechanics from Northwestern Polytechnical University in 2010. He is currently an associated professor in Institute of Structural Mechanics, China Academy of Engineering Physics. He has more than 20 papers published in journals. His research interests are in the areas of structural shock dynamics and dynamic behaviors of materials.

Yulong Li received his PhD degree in solid mechanics from Northwestern Polytechnical University (NPU) in 1991. He worked in University of California, San Diego in 1996, and worked in The Johns Hopkins University in 1996–2000. He is currently a professor in School of Aeronautics, NPU. Up to now, he has 4 books and over 150 papers published. His research interests are in the areas of dynamic behaviors of materials and structural shock dynamics.

Hanjun Huang received his MS degree in engineering mechanics from China Academy of Engineering Physics (CAEP) in 2003. He is currently an assistant professor in Institute of Structural Mechanics, CAEP. His research interests are in the areas of experiments and numerical simulations of structural shock dynamics.

Junpin g Wang received his MS degree in engineering mechanics from Xi'an Jiaotong University in 2010. He is currently an assistant professor in Institute of Structural Mechanics, China Academy of Engineering Physics. His research interests are in the areas of experiments and numerical simulations of structural shock dynamics.