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Numerical study on separation shock characteristics of pyrotechnic separation nuts

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ABSTRACT

This paper establishes a finite element model of pyrotechnic separation nuts and simulates the whole separation process based on the explicit dynamic codes LS-dyna with Arbitrary Lagrange-Euler (ALE) algorithm. The separation shock generated in the unlocking process is analyzed in detail and the results reveal that the pyrotechnic explosion shock and strain energy shock are two sources for the whole separation shock. Besides that, the influence of prestress on the separation shock and its two shock sources is also researched. The results show that the prestress could strengthen all three shocks, especially the strain energy release shock. This paper also compares the shock response spectrum (SRS) of the three shocks and finds that the SRS of separation shock is equal to the envelope of the SRS of pyrotechnic explosion shock and strain energy release shock. In the model of this paper, the pyrotechnic explosion shock plays a dominant role in the frequency range of 100 Hz to 10 KHz. The conclusions got in this work are helpful to insight the mechanism of separation shock and can provide a reference for the design of separation nuts.

1. Introduction

In aerospace engineering, pyrotechnic separation nuts are widely used as the fastener and unlocking device of spacecraft and launcher [1]. In the process of launch, the spacecraft and launch vehicle are connected reliably with the separation nut. When the separation signal is received, the separation nut begins to unlock and the spacecraft is released. At the same time, a shock, namely separation shock with the characteristics of transient, wide frequency band and high magnitude is generated [2–4] and propagated to the spacecraft structure board. This separation shock would not destroy the main structures of spacecraft, but it may easily cause damage to some electronic components and other precision equipment which are sensitive to the environment of high frequency and amplitude [5]. Some common faults caused by the separation shock such as the failing of welding point, fracturing of ceramic material and so on can even lead to the failure of whole space mission [6]. Because of the significant influence of separation shock on spacecraft reliability, many institutions and scholars have developed a series of studies on separation shock since 1960s.

The studies of the separation shock mainly focus on experiments, theoretical analysis and numerical simulations. In the aspect of experiments, the National Aeronautic and Space Administration (NASA) carried out lots of separation shock tests and obtained a large number of first hand experiment data. Among those data, the NASA summarized the experiment model skills and formulated relevant standards [4] about the separation shock tests. In addition, the European Space Agency (ESA) [7], Sandia National Laboratories (SNL) [8] and United States Military [9] also made some researches on separation shock tests. Up to now, the experimental studies on separation shock have been mature and can be used to effectively control the failure caused by separation shock. As to the theoretical analysis, the experimental extrapolation is widely used in engineering. And the experimental extrapolation mainly includes the empirical model method [6], data extrapolation [6] and sub-structure path extrapolation three methods, which can all be used to predict the magnitude of shock on structures based on engineering experience and similar test data. However, the obvious drawback about these methods is that they have a large dependence on the existing test data and the predicting results tend to be conservative. Compared with the expensive costs of experiments and conservative results of theoretical methods, numerical calculations have the advantages of ultra-low expenses and reliable results and are widely used in recent years with the rapid development of computer and algorithm. Hydrocodes [10] is an explicit dynamic finite element or finite difference codes used to solve the Fluid-Structure Interaction (FSI) problems under the load of high frequency and transiency, such as the explosive detonation, high speed impact and large deformation of

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structures. Benson [11] elaborated on the basic theories of explicit finite element and finite difference. Some commercial software like the ANSYS/LS-dyna, ANSYS/Atuodyn and MSC/Dytran based on hydrocodes has been developed and used to study the separation shock. Lee et al. [12] reviewed the characteristics of pyroshock, and believed that the hydrocodes is suitable to simulate the pyroshock. Smirnov et al. [13,14]developed a mathematical model and numerical tool for supercomputer modeling of hydrogen-oxygen components mixing and chemically reacting in rocket combustion chambers. By using this method, they further simulated the un-steady processes of ignition and combustion in engines of different types. Mao et al. [15] presented the numerical techniques of pyroshock environment prediction, such as the time-domain finite element analysis (FEA), statistical energy analysis (SEA) and mentioned that the hydrocodes can be used to simulate the initiation-explosion process in near-field. Lee et al. [16–18] introduced the mechanism of ridge-cut explosive bolts and simulated the work process using the Autodyn, where the simulation results are consistent with experiment. Kafle et al. [19] analyzed the shock generation and propagation process of explosive bolts by utilizing the Autodyn. Furthermore, the Virtual Mode Synthesis (VMS) was also applied to predict the shock response of satellites. Shmuel and Goldstein [20–22] set up the finite element models of pyrovalves and bolt cutters and made simulations with LS-dyna3D. Besides that, the effects of important parameters like the amount of explosive and friction on the bolt cutters were also investigated.

The numerical simulation studies mentioned above are mainly concentrated on the separation device of explosive bolts. There are few published papers about another device - separation nuts. The Silverman and O'Quinn [23] made some researches on the pyrotechnic separation nut SN9400 and pointed out that the deflagration of explosive, release of strain energy and the collisions of the inner components are the three shock sources. Zhang et al. [24] simulated the dynamic shock process of the separation nut and obtained the load curve at the interface between satellite and launcher. Wang et al. [25] also made an investigation on separation nuts by using the Autodyn. And they further studied the effects of preload level and the amount of explosive on the shock response, and revealed that the amount of explosive mainly has an effect on the explosive side, while the preload level mainly has an effect on the non-explosive side.

Although some progress about pyrotechnic separation nuts has been made, there are still some disadvantages about the research of separation shock mechanism and the effects of prestress on separation shock and its two shock sources. The relationship between separation shock and its two shock sources are also seldom reported. In order to better understand the mechanism of separation shock and its two shock sources, the finite element model of separation nuts is firstly established, and then the whole process of separation unlocking is simulated by using the ALE algorithm. What's more, the effects of prestress on the separation shock and two shock sources are discussed. At last, the relationship between separation shock and the two shock sources is revealed.

2. Finite element model

2.1. Separation mechanism

As shown in Fig. 1, the pyrotechnic separation nut consists of explosive, housing, separator, locking piston, threaded segments and bolt. Before separation, the structure board is compressed closely by the separation nut with prestress to obtain reliable connection stiffness. Once got the separation instruction, the explosive located in the housing begins to ignite and detonate, immediately resulting in high temperature and pressure product gas and filling in the whole housing chamber. At the same time, the product gas causes pyrotechnic explosion shock. After that, the locking piston moves down under the action of product gas until the radial constraint to the threaded segments is relieved. Finally the threaded segments are unlocked under the action of separator, releasing the strain energy stored in structure board and bolt, causing strain energy release shock.

2.2. Modeling process

Considering the complexity of model, some professional commercial software is used and the framework of model building is illustrated in Fig. 2. The whole analysis process is carried out in the following steps. The first step is to make a simplification about separation nuts and obtain the material parameters of separation nuts and explosive by experiments or related papers. And the second step is to build up the finite element model. In this step, the geometry model and finite element grid are dealt with three-dimensional modeling software Pro/E and pretreatment software HyperMesh respectively. In addition, the prestress is also considered by defining the key words and loaded on the structures in dynamic relaxation process. Finally the finite element model is computed with the explicit dynamic codes ANSYS/LS-dyna. And the acceleration SRS of the measure point is compared with the experiment. The model would be accepted if the SRS of experiment result is located in the range of ± 6 dB of simulation SRS. Otherwise, the separation nut model needs to make a further adjustment and then the aforementioned process is carried out again until the simulation result is consistent with experiment.

2.3. Material model

Because of strong explosion impact produced by high pressure detonation product gas, some element stress in the separation nut could exceed the yield stress, which causes the structure of separation nuts to present the characteristic of plastic even fluid. Therefore, the Johnson-Cook (JC) constitutive model is introduced to describe the high strain rate mechanical behavior of separation nuts. The yield stress σ_y is defined as:

$$\sigma_y = (A + B\varepsilon^n)\left(1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)(1 - T^{*m}) \quad (1)$$

where, A is static yield stress, B is hardening constant, n is hardening exponent, C is constant related with strain rate, $T^* = (T\text{-}T_0)/(T_m\text{-}T_0)$, T_m is the melting temperature, T_0 is room temperature, m is constant related with temperature. As the structure board has a long distance with separation shock source and stress still remains in the range of elastic, the simple linear elastic constitutive model is used to it. The specific parameters of separation nuts (30CrMnSiNi2 steel) and structure board (Al6061) are listed in Table 1.

In order to simulate the explosive detonation, the equation of state (EOS) which shows the relationship between pressure and volume must be defined. The classical trinomial EOS of JWL adopted in this paper is shown Eq. (2). And the three items in JWL control the high, medium and low pressure range respectively.

$$p = A\left(1 - \frac{\omega}{R_1\gamma}\right)e^{-R_1\gamma} + B\left(1 - \frac{\omega}{R_2\gamma}\right)e^{-R_2\gamma} + \frac{\omega E}{\gamma} \quad (2)$$

where, $\gamma = V/V_0$ is relative volume, V is volume, E is inner energy. A, B, R_1, R_2, ω are underdetermined parameters which can be obtained by cylinder explosion experiment. The specific parameters of explosive TNT are listed in Table 2.

2.4. ALE algorithm

The Lagrange, Arbitrary Lagrange-Euler (ALE) and Smoothed Particle Hydrodynamics (SPH) are three methods which are most commonly used in the simulation of explosive detonation process. In Lagrange algorithm, the explosive material is attached to elements deforming with the motion of explosive material and interacting with