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Aerospace Science and Technology

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Study on pyroshock propagation through plates with joints and washers

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ARTICLE INFO

Article history:
Received 21 September 2017
Received in revised form 7 February 2018
Accepted 30 May 2018
Available online xxxx

Keywords:
Pyroshock
Pyrotechnics
Flexural waves
Hydrocodes
ANSYS AUTODYN
Shock response spectrum (SRS)
Pyroshock experiments
Pyroshock attenuation

ABSTRACT

Pyrotechnic release devices are widely used in various missions in order to reliably separate the structural parts of the system. However, the pyroshock induced by an explosive pyrotechnic event can lead to fatal malfunctions of the adjacent electrical components. In order to mitigate these pyroshock issues, an accurate understanding of the pyroshock propagation in structures is essential. In this study, an experimental setup for the pyroshock propagation experiments is developed with the pyroshock excitation using pyrotechnic initiators. The pyroshock propagation analysis environment with a commercial hydrocode is established and verified through comparison between the analysis and the experimental results. The pyroshock propagates through the thin plates in the form of flexural waves (or anti-symmetric Lamb waves). Using the established numerical and experimental techniques, the effects of the pyroshock attenuation by the joints and washers are investigated. The plates connected by joints with different materials and the plates connected by joints with inserted washers made of different materials and in different thickness are considered. The experimental and numerical results are in good agreement: the pyroshock attenuation is highly effective when the joints are made of higher density and stiffness materials and when the thickness of the washers is increased. The primary reason for the pyroshock attenuation due to the joints and washers is the flexural wave reflection at the discontinuities caused by acoustic impedance mismatching.

1. Introduction

Over the past several decades, pyrotechnic release devices have been used widely in numerous applications including launch vehicles, missiles, fighters, and more; these devices are used to reliably separate the structural parts of a system [1,2]. Pyrotechnic release devices are very attractive compared with other release devices based on non-explosive release actuators (NEAs) due to their merits of high power-to-weight ratio, high reliability, instantaneous operation with simultaneity, long-term storage capability, and inexpensive cost. Even though pyrotechnic release devices have been successfully adopted with high separation reliability, pyroshock can lead to fatal malfunctions of the adjacent electrical components, and this remains a critical concern [3]. Pyroshock, also known as pyrotechnic shock, is defined as the transient response of the structures, components, and systems due to the loading induced by the pyrotechnic devices attached to the structures [4]. Pyroshock is generally divided into three categories: near-field, mid-field, and far-field pyroshock [3]. Near-field pyroshock occurs next to the pyrotechnic device with a very high frequency and magnitude acceleration. Here, most of the energy is not transferred to the structural response and the stress wave propagation predominantly governs the pyroshock response. Mid- and far-field pyroshock can be observed away from the pyrotechnic source with a relatively low frequency and magnitude acceleration. The energy is concentrated at specific frequencies, unlike near-field pyroshock, due to the structural resonance. Although pyroshock can easily cause failure in electronic devices due to relay chatter, failures of circuit components, and short circuits due to small broken fragments [3], it rarely damages the supporting structures unless the pyrotechnic devices are used to break the structures intentionally. Furthermore, pyroshock propagates in terms of linear elastic waves to the surrounding structures without plastic deformation in most portions of the structures, except when in close proximity to the pyrotechnic devices [5].

In order to resolve these pyroshock issues, many researchers have investigated the characteristics of pyroshock propagation in structures. Traditionally, pyroshock issues have been experimentally investigated: the pyroshock was excited on test structures

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https://doi.org/10.1016/j.ast.2018.05.057
1270-9638/© 2018 Published by Elsevier Masson SAS.

and the propagated pyroshock was measured. The use of pyrotechnic devices for pyroshock experiments is generally accompanied by high cost and safety issues. Therefore, numerous pyroshock simulators with mechanical excitations have been proposed [3,6]. However, these simulators cannot provide sufficient pyroshock excitation because they occasionally have high frequency and magnitude. Furthermore, the measurement of pyroshock has been routinely conducted based on several standards [4,5,7]. Commercial accelerometers can be used to measure pyroshock with limited frequency ranges due to the resonance of the sensing parts. In order to measure the very high frequency content of pyroshock, laser Doppler vibrometers (LDVs) can be used.

Recently, two numerical analysis methods for pyroshock propagation have been proposed: the finite element method (FEM) and the statistical energy analysis (SEA)-based method; these are commonly used to estimate pyroshock propagation [6]. Even though FEM can analyze the stress wave propagation and the pyroshock propagation, it has extremely high computational costs to analyze the high frequency structural modes accurately [8]. Previous study that analyze the pyroshock propagation in structures and electronic units [9] has demonstrated that the pyroshock level estimation is only accurate in the low frequency range (under 1 kHz). In contrast, the SEA-based method was originally developed for high frequency vibro-acoustic analyses [10]. In order to analyze the transient response of the pyroshock propagation, the SEA method with virtual mode synthesis and simulation (VMSS) can be used [11]. In order to extend the capabilities of the SEA-based method into the mid-frequency range, the energy flow method (EFM) that combines the SEA-based method and the modal information obtained from FEM has also been proposed [10]. However, the SEA-based analysis only provides the spatially averaged pyroshock level of substructures and it cannot predict the pyroshock level at specific locations in the structures. Recently, analytic approaches to solve the pyroshock propagation have also been presented [12,13]; they provide accurate results, but are mathematically complex and only applicable to simple structures.

Therefore, a new numerical method that can analyze the pyroshock propagation in complex structures with a wide frequency range is necessary in order to efficiently resolve the pyroshock issues; this study proposes the use of hydrocodes for precise analysis of the pyroshock propagation. Hydrocodes were first developed in the late 1950s to numerically solve aluminum and steel impact problems [14]; they can analyze highly dynamic events that involve shocks through solving the conservation equations with material models [15]. They have been used to analyze diverse impact phenomena: composite materials in low velocity to hypervelocity impacts [16,17], collisions of space reentry vehicles [18,19], hypervelocity impacts on fused silica sheets [20], diverse impacts on ultra-high molecular weight polyethylene (UHMWPE) [21–23], and more. In addition, problems related to blast loads that require very expensive experiments have been investigated using hydrocodes [24–26]. In pyrotechnics related fields, the separation mechanisms of the pyrotechnic release devices have been analyzed using hydrocodes: explosive bolts [27,28], shaped charges [29,30], separation nuts [31] and so on. Recently, the numerical prediction of pyroshock generation from separation nuts and ridge-cut explosive bolts were proposed using hydrocodes [31,32].

In this study, a new numerical analysis method for pyroshock propagation using commercial hydrocodes (ANSYS AUTODYN) is presented. Unlike other conventional methods, the hydrocodes-based method can precisely analyze pyroshock propagation in complex structures with a wide frequency range. In order to verify the numerical method, the pyroshock propagation experiments were designed and prepared with the pyroshock excitation using pyrotechnic initiators. From the experimental and numerical results, the pyroshock propagation characteristics on simple plates are identified. Using the established numerical and experimental techniques, the effect of the pyroshock attenuation at the joints and washers connecting the plates were also investigated. Mechanical joints and washers are commonly recognized as pyroshock attenuation points along structures.

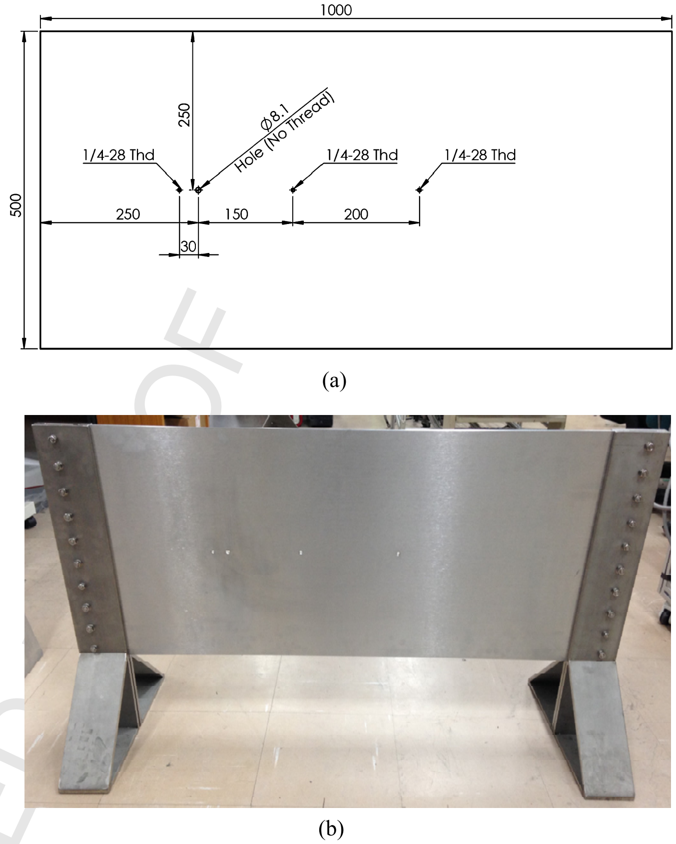

Fig. 1. Simple plate for pyroshock propagation experiments: (a) schematic and (b) manufactured simple plate and fixtures.

2. Pyroshock propagation experiments with simple plates

2.1. Experimental setup

For the pyroshock propagation experiments, a simple plate (1 m × 0.5 m × 5 mm) made from aluminum alloy 6061 was prepared. Three threaded holes for mounting the shock accelerometer and one non-threaded hole for attaching the initiator fixture were prepared as shown in Fig. 1(a). Two heavy stainless steel fixtures as seen in Fig. 1(b) were also prepared in order to clamp the plates. These stainless steel fixtures clamped the simple plate using compressive force only. The left and right sides of the plate were clamped using a 0.5 m × 0.02 m contact area.

The pyroshock was excited on the plates using pyrotechnic initiators. The excitations were applied to the point located 0.25 m to the left of the center of the plate. In order to attach the pyrotechnic initiators to the plates, an initiator fixture was designed and manufactured from stainless steel 304 as shown in Fig. 2. The initiator fixture was connected to the plate using a bolt connection. The volume of the cavity inside the initiator fixture was approximately 1 cm^3. In particular, the contact surface of the initiator fixture and plates was rectangular. A rectangular washer was also used to make both contact surfaces rectangular. This experimental setup enabled the assumption that the pyroshock was excited on plates with rectangular surfaces. The pyrotechnic initiators PC 800 fabricated by Hanwha Corporation were used. Here, the PC 800 ini-

Please cite this article in press as: J. Lee et al., Study on pyroshock propagation through plates with joints and washers, Aerosp. Sci. Technol. (2018), https://doi.org/10.1016/j.ast.2018.05.057