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Characterizing hypervelocity (>2.5 km/s)-impact-engendered damage in shielding structures using *in-situ* acoustic emission: Simulation and experiment

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ABSTRACT

Pervasive in outer space, hypervelocity impact (HVI), caused by man-made debris (a.k.a. space junk) and natural micrometeoroids, poses a clear and tremendous threat to the safe operation of orbiting spacecraft, and it will possibly lead to the failure of a space exploration mission. Addressing such an issue, damage in a downscaled two-layer space shielding assembly, engendered by HVI events with an impact velocity up to 4 km/s, was characterized quantitatively, using *in-situ* measured acoustic emission (AE) induced under HVI. A hybrid model, based on three-dimensional smooth-particle hydrodynamics and finite element, was developed, to achieve insight into the traits of HVI-induced AE waves and HVI-caused damage. Proof-of-concept simulation was accomplished using the hybrid model, in which a projectile, at various impact velocities, impinged a series of shielding assembly of different thicknesses, in a normal or oblique manner. Experimental validation was implemented, and HVI-induced AE waves were *in-situ* acquired with a built-in piezoelectric sensor network integrated with the shielding assembly. Results from simulation and experiment show qualitative consistency, demonstrating the capability of the hybrid model for depicting HVI-produced shock waves, and the feasibility of *in-situ* measurement of HVI-induced AE signals. Taking into account the difference and uniqueness of HVI against other ordinary impact cases, an enhanced, *delay-and-sum*-based imaging algorithm was developed in conjunction with the built-in sensor network, able to “visualize” HVI spots in pixelated images accurately and instantaneously.

1. Introduction

The recent quantum leap in space technology has intensified innovative quests by humans to penetrate outer space. A great number of spacecraft can now be found in low Earth and geosynchronous orbits, circling Earth with a velocity of the order of kilometers per second. However, the cluttering of meteoroids and man-made orbital debris (MOD, colloquially called *space junk*), which are ubiquitous in the Earth orbit, may pose an impending threat to the safety and integrity of orbiting spacecraft. MOD particles, though small in size, travel at such high speeds that even a small object can puncture the shielding layer of spacecraft and then impinge inner structures. This sort of impact is commonly referred to as “hypervelocity impact” (HVI) – a scenario in which the impact velocity (>1 km/s usually) is at such a high degree that the strength of the materials upon impact is sufficiently small compared to their inertial forces [1, 2]. Day by day, massive space junk from abandoned, exploded and collided space vehicles emerges, and becomes new MOD. According to NASA, 20,000+ pieces of MOD particles larger than 10 cm, 500,000+ sized between 1 and 10 cm, and tens of millions smaller than 1 cm, are conservatively estimated to exist in low Earth and geosynchronous orbits [3]. The impact from any of them to spacecraft can functionally compromise the craft's integrity, possibly resulting in immediate mission abortion with catastrophic consequences. Representatively, in 1996, MOD particles from a French rocket, which had exploded a decade earlier, impacted a French satellite, leading to vast damage to the satellite [4]. In 2007, a de-commissioned meteorological satellite was destroyed by a missile in an anti-satellite test. Although this HVI event was intentionally introduced by China for removing the de-commissioned satellite from the orbit, the 3000+ pieces of new MOD particles consequently produced in the test

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have posed severe HVI risk to other spacecraft, arousing a great deal of controversy from the public [4].

Over the years, NASA and the Department of Defense in the U.S. have been working co-operatively to establish a Space Surveillance Network, aimed at tracking MOD particles that are greater than 5 cm in sizes [5]. With this network, conjunction assessments and collision avoidance maneuvers can be implemented, whereby to counter MOD particles included in the surveillance network. Nevertheless, almost none of the available assessment or avoidance techniques is able to deal with the cases in which MOD particles are smaller than 5 cm [5]. Therefore, prevention of HVI and evaluation of HVI-induced damage, once an attempt to evade MOD particles fails, are the top priority among those endeavors to enhance the survivability, integrity, and durability of space systems, whose importance cannot be overemphasized [2, 6–9].

HVI is significantly different from a low-velocity (several tens meters per second) or high-velocity (up to the order of 10^2 m/s) impact. As a result, the HVI-engendered damage in space structures manifests itself with a high degree of complexity, taking a diversity of modalities due to the much greater kinetic energy that HVI carries and releases during the transient impact. Depending on the size and speed of an MOD particle and the impact location as well, HVI-induced damage can be recrystallization, cell dislocation, micro-cracks, micro-band extension, material vaporization, cratering, spall cracks, plastic zones, and macroscopic penetration or orifices to name a few [1, 2, 10].

To minimize a possible HVI risk to spacecraft, a variety of shielding mechanisms (e.g., Whipple shield [11], stuffed Whipple shield [11], and multi-shock shield [12]) has been designed. A well-installed shielding structure, together with the rear wall of spacecraft, may block an MOD particle with its size not greater than 100 μm (at a normal HVI velocity); but a shielding structure in most instances fails to intercept particles beyond 1 cm [13]. Upon penetration of the outer shielding layer, MOD particles produce shattered debris (forming a debris cloud), to subsequently impinge the inner space structures and cause pitting-like damage scattered chaotically over a large area on the inner structure.

To facilitate the estimation of the residual integrity of the spacecraft upon HVI, the impact location and severity of HVI-caused damage must be evaluated accurately and instantaneously. Based on the evaluation, remedial actions can be applied before the damage reaches a critical level, whereby to prevent an impacted structure from further deteriorating and to weaken the risk of a cascading failure of the entire space system. This is of vital importance and necessity for those spacecraft with long service time or with large surfaces exposed to the space environment. Addressing such significant and imminent needs, several sensing and diagnostic techniques have been deployed, as typified by those using acoustic emissions (AEs) [14, 15], acceleration-based detection [16], thermography [17], calorimetry [18], fiber optic sensor-based detection [19], resistor-based detection [20], microwave emissions [21], and camera-based surface inspection [22]. All these techniques have been systematically graded by the Inter-Agency Space Debris Coordination Committee [13], in terms of the levels of their respective sensitivity, accuracy, and manipulability, and AE ranked top among all the above mentioned techniques.

Representatively, Forli [14] initiated a series of investigation for the European Space Agency's (ESA) Columbus module (part of the International Space Station) in the early 1990s, to evaluate the feasibility of using an AE-based impact sensor network to detect HVI spots. In the study, twelve bulky AE ultrasonic transducers were used to determine impact localization, with a detection error of approximately 0.4 m. Schäfer and Janovsky [15] attached six bulky ultrasonic transducers onto an aluminum alloy panel and a sandwich panel apiece of Columbus module, via which AE signals during HVI were captured. Conventional triangulation was carried out to locate HVI spots in these two panels, by assuming that HVI-induced waves propagate at a constant velocity throughout the entire panels. Though conducted on ground, these proof-of-concept tests have demonstrated the capability and effectiveness of AE-based detection for locating HVI spots. It is noteworthy that in all these deployments of AE-based detection, the following hypotheses are usually applied:

I. the velocity of HVI-induced wave is constant;
II. there is only one wave mode; and
III. wave dispersion can be largely ignored.

In other words, the difference between HVI and other ordinary impacts (i.e., low- or high-velocity impact) is not a factor to be considered during the previously reported algorithm development for HVI characterization [14, 15].

However, in HVI, shock waves are generated under extreme material compression that behave differently from elastic waves in ordinary impacts. Multiple wave modes co-exist, each featuring a particular velocity, complex dispersive attributes, and severe phase distortion. Together, these effects can obfuscate damage-associated signal features and create vast difficulties in precisely ascertaining the arrival time of AE, accordingly diminishing localization accuracy, provided that a conventional triangulation algorithm is applied with the three hypotheses enumerated above. Prosser et al. [23] experimentally examined the AE signals generated in both HVI ($1.8 \sim 7$ km/s) and low-velocity impact (< 0.21 km/s) cases, and concluded that the extensional wave modes dominate the signal energy in HVI, whereas the flexural wave modes prevail in low-velocity impact; and compared with low-velocity impact, HVI-induced wave signals feature much larger magnitudes and wider frequency ranges in which the wave energy distributes. This study has revealed that the uniqueness and difference of HVI, compared with other ordinary impacts, shall be addressed towards accurate evaluation of HVI-engendered damage.

Targeting a real time and *in-situ* characterization capacity for real-time awareness of HVI occurrence and accurate evaluation of HVI spots in space shielding structures, the present study is dedicated to fundamental interrogation of HVI-induced AE waves, via numerical simulation and experiment. With the understanding of the unique propagation characteristics of AE waves, an HVI spot in a downscaled two-layer space shielding assembly was located using *in-situ* measured AE waves that were captured with a built-in sensor network comprising miniaturized lead zirconate titanate (PZT) sensing elements. An enhanced, *delay-and-sum*-based imaging algorithm, addressing the difference and uniqueness of HVI compared with other ordinary impacts, was developed for projecting the detected HVI spots into pixelated images. The proposed method in this paper possesses several merits over the others: (1) the miniaturized PZT wafer-formed sensor network endows the monitoring system with an ability of *in-situ* monitoring of HVI during spacecraft orbiting; (2) quantitative characterization of HVI, including localization of HVI spot, facilities immediate estimate of the severity of HVI-induced damage and offers guide for further repair and replacement; and (3) the proposed imaging algorithm can pinpoint the HVI spot without human intervention or interpretation.

This paper is organized as follows. To begin with, Section 2 describes a dedicated model developed based on three-dimensional smooth-particle hydrodynamics (SPH). With the model, numerical simulation is implemented to depict the unique characteristics of HVI-induced AE waves. Using experiment and numerical modeling, three HVI scenarios are examined in Section 3, in which a projectile, at various impact velocities, impinges a series of shielding assembly of different thicknesses, from normal to oblique impact, and from non-penetration to penetration of the outer shielding layer. The built-in sensor network developed for *in-situ* AE measurements is also illustrated in this section. HVI-generated AE signals, respectively obtained from numerical simulation and from *in-situ* measurements are comparatively analyzed in Section 4. To characterize HVI spots in the shielding layer, a diagnostic imaging approach, originating but enhanced from a *delay-and-sum*-based triangulation method, is developed and elaborated in

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