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Characterization of Damage in Shielding Structures of Space Vehicles Under Hypervelocity Impact

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Abstract

The cluttering of meteoroids and orbital debris (MODs) on the low earth orbit poses a vast threat to the safety of orbiting space vehicles. Collision between MODs and space structures, a.k.a., hypervelocity impact (HVI), can result in catastrophic consequences, due to the extremely high velocity (of the order of km/s) between MODs and space vehicles. An active linear/nonlinear guided-wave-based approach for characterizing HVI-induced damage in a two-layer aluminum shielding structure (comprised of inner and outer layers) was developed. Aluminum spheres were discharged using a two-stage light gas gun, at an impact speed ~6 km/s to introduce HVI to the outer shielding layer. Compared to low-velocity impact (LVI), the instant large kinetic energy bore by HVI makes the outer plate penetrated, and then the generated debris cloud furthers impacts the inner plate, with numerous craters left. A hybrid active linear/nonlinear guided-ultrasonic-wave-based damage detection algorithm was proposed, to evaluate the damage on the inner layer. Combining the ease in implementation of the linear approach and the high sensitivity and baseline-free of the nonlinear approach to small damage, the active hybrid algorithm, offers a solution to the *in situ* perception and monitoring of HVI-induced damage to space vehicles.

Keywords: hypervelocity impact; ultrasonic guided wave; linear/nonlinear method

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1. Introduction

Low earth orbit is cluttered with numerous spacecraft, together with the coexistence of far more meteoroids and orbital debris (MOD). MODs travel at such high speeds (of the order of the first cosmic velocity) that even a small particle, if not evaded, can impact the spacecraft severely [1]. This kind of impact is commonly referred to as hypervelocity impact (HVI)—a scenario typically involving an impacting velocity over 1 km/s. Depending on the size and impact location, MODs-committed damage in space structures can take a variety of modalities, including recrystallization, cell dislocation, microcracks, microband extension, material vaporization, cratering, spall cracks, plastic zones, and macroscopic penetration, to name a few. Thus the safety of spacecraft is severely impacted by the potential HVI by MODs. In early 2016, the European-built Cupola added to the International Space Station in 2010 was impacted by possibly a paint flake or small metal fragment no bigger than a few thousandths of a millimeter across, leaving a 7 mm-diameter circular chip. Besides, anything above 1 cm could penetrate the shields of the Station's crew modules, and anything larger than 10 cm could shatter a satellite or spacecraft into pieces.

In response to the threat from HVI, two strategies have been considered. Firstly, multiple kinds of shielding structures, such as Whipple shield [2], stuffed Whipple shield [2], and multishock shield [3], have been developed and installed on space assets, to sacrifice the outer shielding structure for the protection of facilities or crew in the inner shielding structure. Secondly, an active detection strategy to evaluate the HVI induced damage is of significant usage and importance. A timely evaluation, followed by a corresponding quick remediation, could help avoid further degradation of the damaged structures, so as to reduce the risk of consequent system failure. Motivated by such an imperative need, a variety of sensing and diagnosis techniques has been deployed, to perceive HVI events and accordingly estimate the severity of HVI-committed damage [4].

Among the existing researches of damage detection technology, the active ultrasonic guided wave based technology is one preferred kind. Because of the high sensitivity to structural damages (around the size as the interrogated wave length λ), guided wave is frequently utilized in the damage detection research to monitor small damages such as fatigue cracks and delamination. Some representative algorithms include damage index (DI) [5], time reversal [6], those using Time-of-Flight [7], statistical modeling [8], and damage imaging algorithms [9].

All these methods listed above are based on the hypothesis that when encountering damage, guided wave will transmit, reflect or experience mode conversion in the surrounding damage area, which are called linear techniques. However, the committed damage in the inner plate by HVI usually presents a scattered area with numerous extremely small craters (< 1mm), which may not be easily detected through the linear techniques. In this backdrop, some nonlinear techniques of guided wave [10-12], where the received signal containing the information of interest is at a different frequency than the emitted signal, can even provide much higher sensitivity to microstructural changes.

The current study is dedicated to fundamental understanding of interaction between both linear/nonlinear guided waves and HVI-committed damage, with an application to intuitively imaging the HVI-committed damage in space structures. Section 2 briefly introduces the principle of linear/nonlinear guided wave based damage characterization extraction. Detailed experiment about the HVI and damage detection is followed in Section 3, with final damage imaging results shown in Section 4.

2. Theory of linear and nonlinear guided wave based damage evaluation

For the guided wave based damage detection as shown in Fig. 1, there exists four basic steps, i.e. excitation, wave propagation, sensing and a final signal processing. Among the four steps, the last of which differs significantly between the linear and nonlinear methods, which in turn influences the setup of the first three steps. All the linear methods are based on the hypothesis that when encountering damage, guided wave will transmit, reflect or experience mode conversion in the surrounding damage area. Thus, the Huygens principle restricts the detectable damage size to be related to the size of the incident wave length. However, the nonlinear method, where the received signal containing the information of interest is at a different frequency than the emitted signal, shows much higher sensitivity to damage sizes and thus has been through much research in recent years.

Consider an isotropic homogeneous solid with purely elastic behavior, the nonlinearities of the medium that may contribute to nonlinear distortion of its guided ultrasonic waves can originate from three kinds of sources, including mainly the material, geometry and the damage-driven nonlinearity. The material nonlinearity is due to lattice anharmonicity (referring to the crystal vibrations that do not follow the simple harmonic motion) that always exists in the real material, and/or the defects in the material. These nonlinearity effects, though trivial, can generate higher order anharmonic ultrasonic waves propagating in such a medium. Theoretically, through a dedicate control of excitation signal to satisfy both requirement of phase matching and non-zero power flux [13], the faint second harmonic wave will accumulate along the propagation distance in the plate structure, which enables the nonlinear wave to be potentially utilized. A typical fundamental-second harmonic wave mode pair S1-S2, as illustrated in Fig. 1, separated from the raw sensing signals by Short Time Fourier Transform (STFT), shows a clear and still noticeable S2 mode (amplified by 20 times in S2 amplitude).

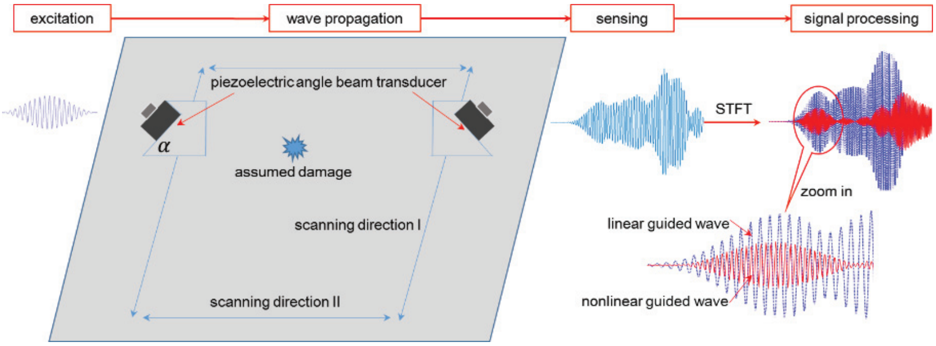

Fig. 1 Illustration of linear and nonlinear guided wave based damage evaluation

3. Experiment

3.1. HVI setup

The two-stage light gas gun was used to launch projectiles (aluminum 2024-T4, ~ 6 km/s, ø 4.5mm) into the outer target plate (aluminum 2024-T4, 1 mm in its thickness), being 300 mm × 300 mm in the in-plane dimension, as a means of producing controlled HVI, as shown in Fig. 2 (a). The high pressure gas of nitrogen, filled in the first-stage tube with a relatively large cross section, propels the piston to compress the second-stage tube with a much smaller cross section filled with gas of hydrogen. Once a set pressure value is met, the hydrogen gas will break through an aluminum membrane with pre-made notch. Then a three-pedal sabot with capsuled projectile – aluminum sphere – will be accelerated to a desired hypervelocity. Following the separation of the projectile from the sabot by a pneumatic separator, the aluminum sphere impacts the target structure at the desired velocity, which is measured according to the difference of arrival time between two magnetic induction coils with a distance of 50 mm. A two-layer shielding structure was fabricated and then placed at the rear cavity of the two-stage light gas gun. A frame was designed to fix the concerned inner plate (3 mm in its thickness) that was connected with the outer plate.

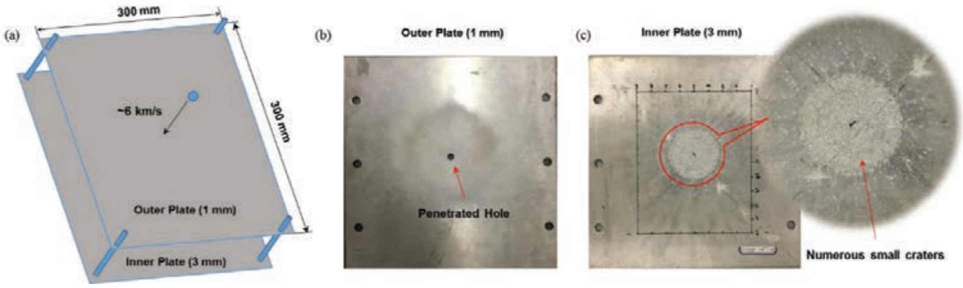

Fig. 2 (a) Schematic of HVI experiment; (b) Photograph of the outer plate being penetrated; and (c) Photograph of the inner plate with numerous small craters

The central spot of the outer plate is easily penetrated by the vast instant kinetic energy carried by the projectile. The shattered projectile, together with some jetted portion of the outer plate, further impacts the inner plate, if not penetrated, with numerous small craters scattering over a large area, as shown in Fig. 2 (c). The central area is filled with continuous small craters, while the surrounding area with separated small craters, which demands an effective and sensitive method to fully evaluate the distribution of the craters.

3.2. Damage detection setup

A high power amplifier (RITEC® advanced measurement system RAM-5000 SNAP) offers the source signal for wave generation. The RAM-5000 SNAP is able to modulate two individual wave forms, i.e. a continuous high frequency ultrasonic signal and a low frequency Hanning window signal, to generate a modulated ultrasonic excitation with its peak-to-peak voltage value around 1000 V. In this setup, a 20-cycle Hanning-window-modulated sinusoidal toneburst at a central frequency of 1.14 MHz was excited. The longitudinal wave piezoelectric transducer converts the electrical signal to mechanical response, which is then transmitted into a Plexiglas wedge with ultragel as the couplant. Finally, with calculated incident angle according to Snell's law, required ultrasonic guided wave propagates in the in-plane direction of the plate structure through a further coupling with honey between Plexiglas wedge and the concerned inner plate (3 mm in the thickness). The testing focuses on mode pair S1-S2, with corresponding frequency-thickness product of 3.42 MHz mm - 6.84 MHz mm, as shown in Fig. 3 (small variation between theoretical and experimental frequency is allowed considering variation of plate parameters). In such a scenario, a phase matching condition, i.e., phase velocity of S1 and S2 mode are both equal to the longitudinal wave velocity in the propagation medium, is satisfied. Two piston longitudinal wave piezoelectric transducer (KRAUTKRAMER®, ø 25.4 mm) with central frequency of 1 MHz and 2.25 MHz (as actuator and receiver, respectively) were selected for the concerned inner plate. With the receiver's optimal frequency around 2.25 MHz, the faint S2 mode can be optimally collected, while the dominant S1 mode can still be sensed owing to the broad sensing range of the transducer.

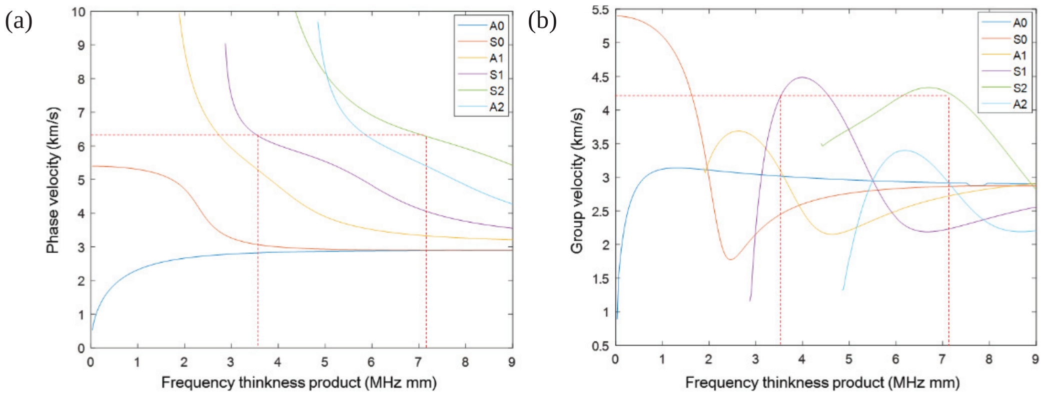

Fig. 3 (a) phase velocity vs. frequency thickness product; and (b) group velocity vs. frequency thickness product.

4. Results

An accumulation experiment of second harmonic wave was firstly carried out on a larger intact plate with the same material as the damaged inner plate. One advantage of choosing S1-S2 mode pair lies in their fastest group velocity among all the generated waves, as shown in Fig. 3(a), which facilitates the extraction of corresponding wave packets (see Fig. 4 (a)) and a further quantitative analysis about the accumulation effect. A relative acoustic nonlinearity parameter β' [12] is defined as

$$\beta' = \frac{A_2}{A_1^2}, \tag{1}$$

where A_1 and A_2 are the magnitudes of wave packet of S1-S2 mode pair extracted by STFT. An almost linear accumulation of β' along the propagation distance shown as Fig. 4 (b) corroborates the theoretical analysis [13]. Besides, the error bar, whose value is the standard deviation of four repeated measures, is in a small range, verifying the stability and reliability of the experiments. With the faint yet strengthened nonlinear guided wave, a further analysis targeting the damaged inner plate committed by HVI was performed with the same experiment setup.

Twenty scanning channels were shown in Fig. 5 (a), where the actuator and receiver move in parallel 20 mm each time, covering a monitoring area of 160 mm × 200 mm. Both the wave packet magnitudes of S1-S2 mode pair were extracted as Fig. 4 (a). A further calculated β' (see Fig. 5 (b)) not only shows a highlighted channel with damage, but also a stable low value on channels without damage. Essentially this nonlinear parameter β' offers a baseline-free rationale to locate the damage, considering the channel without damage offers the baseline for channels with damage.

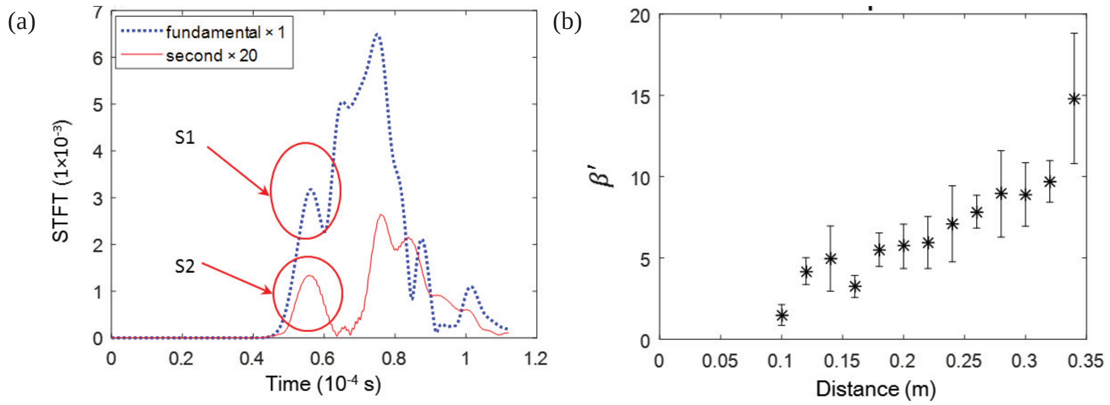

Fig. 4 nonlinear guided wave accumulation experiment (a) wave packet of fundamental S1 (×1) and second harmonic S2 (×20) by STFT; and (b) relative acoustic nonlinearity parameter.

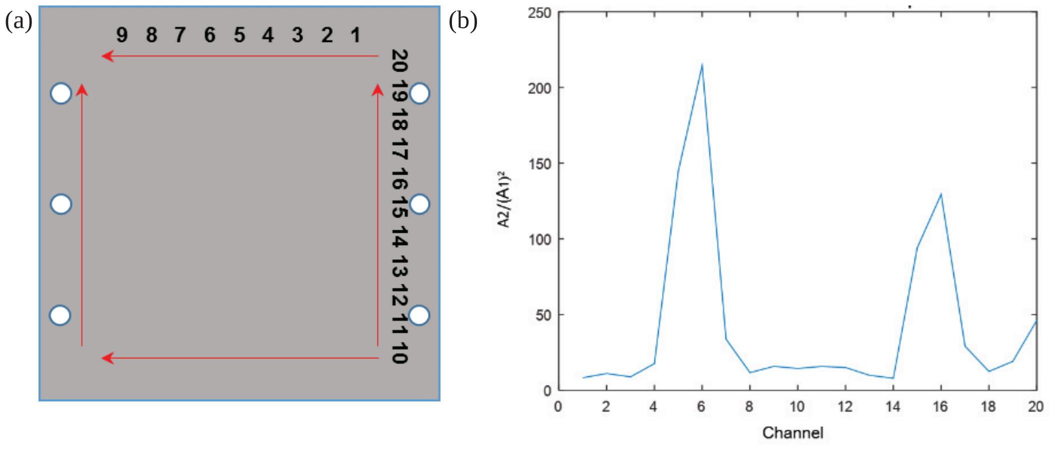

Fig. 5 (a) scanning channel; and (b) relative acoustic nonlinearity parameter β'.

Take all the β' as DIs into the reconstruction algorithm for probabilistic inspection of damage (RAPID)[14]. The imaging from a single channel (see Fig. 6 (a)) was accumulated one by another, to form an intuitive damage imaging (see Fig. 6 (b)), to indicate the scattering of craters.

5. Further development and conclusions

With the longitudinal wave transducer mounted on the angle beam, a successful active linear/nonlinear guided wave based damage detection targeting the scattered craters induced by hypervelocity impact (HVI) was realized. However, the mechanism how the scattered craters influence the propagation of fundamental and second harmonic guided wave is also worth an in-depth exploration. Considered as some further development, the proposed damage detection method, featuring high sensitivity and baseline-free, will be further incorporated with a piezoelectric wafer network (to replace the bulky transducer currently used) with little weight and volume penalty to the host structure, so as to realize a potential online and in situ monitoring to HVI.

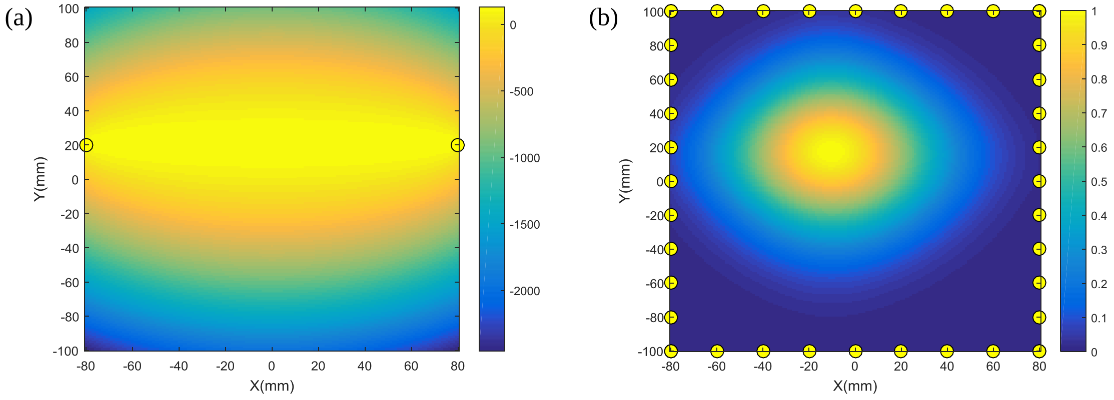

Fig. 6 RAPID imaging for (a) single channel of 16; and (b) all the 20 channels

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References

[1] Murr L E, Quinones S A, Ferreyra T E, Ayala A, Valerio O L, Hörz F, et al. 1998 The low-velocity-to-hypervelocity penetration transition for impact craters in metal targets *Materials Science and Engineering: A* 256 166-182.
[2] Christiansen E L 1993 Design and performance equations for advanced meteoroid and debris shields *International Journal of Impact Engineering* 14 145-156.
[3] Cour-Palais B G, Crews J L 1990 A multi-shock concept for spacecraft shielding *International Journal of Impact Engineering* 10 135-46
[4] IADC WG3 Sensor Systems to Detect Impacts on Spacecraft. 2013.
[5] Ihn J-B, Chang F-K 2004 Detection and monitoring of hidden fatigue crack growth using a built-in piezoelectric sensor/actuator network: I. Diagnostics *Smart materials and structures* 13 609-620.
[6] Miao X, Wang D, Ye L, Lu Y, Li F, Meng G 2011 Identification of dual notches based on time-reversal Lamb waves and a damage diagnostic imaging algorithm *Journal of Intelligent Material Systems and Structures* 22 1983-1992.
[7] Qiu L, Liu M, Qing X, Yuan S 2013 A quantitative multidamage monitoring method for large-scale complex composite *Structural Health Monitoring* 12 183-196.
[8] Lu Y, Ye L, Su Z, Zhang L, Li C 2008 Artificial neural network (ANN)-based crack identification in aluminum plates with Lamb wave signals *Journal of Intelligent Material Systems and Structures* 20 39-49.
[9] Wang C H, Rose J T, Chang F-K 2004 A synthetic time-reversal imaging method for structural health monitoring *Smart materials and structures* 13 415-423.
[10] Chillara V K, Lissenden C J 2016 Review of nonlinear ultrasonic guided wave nondestructive evaluation: theory, numerics, and experiments *Optical Engineering* 55 011002.
[11] Lissenden C, Liu Y, Rose J 2015 Use of non-linear ultrasonic guided waves for early damage detection *Insight-Non-Destructive Testing and Condition Monitoring* 57 206-211.

[12] Hong M, Su Z, Wang Q, Cheng L, Qing X 2014 Modeling nonlinearities of ultrasonic waves for fatigue damage characterization: Theory, simulation, and experimental validation *Ultrasonics* 54 770-778.
[13] Liu Y, Chillara V K, Lissenden C J 2013 On selection of primary modes for generation of strong internally resonant second harmonics in plate *Journal of Sound and Vibration* 332 4517-4528.
[14] Zhao X, Gao H, Zhang G, Ayhan B, Yan F, Kwan C, et al. 2007 Active health monitoring of an aircraft wing with embedded piezoelectric sensor/actuator network: I. Defect detection, localization and growth monitoring *Smart Materials and Structures* 16 1208-1217.