46th Annual Review of Progress
in Quantitative Nondestructive Evaluation
QNDE2019
July 14-19, 2019, Portland, OR, USA

QNDE2019-1234

QUANTITATIVE EVALUATION OF HYPERVELOCITY DEBRIS CLOUD-INDUCED PITTING DAMAGE USING NONLINEAR ULTRASONIC WAVES

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ABSTRACT

In a typical Whipple shield for protecting spacecraft from hypervelocity impact (HVI), the debris cloud, formed by the shattered material of the outer bumper layer, can commit multitudinous, disorderedly scattered pitting craters and cracks over a wide region in the rear wall layer. Pervasive but insidious, pitting damage typically features hundreds of small craters and cracks disorderedly clustered over a wide region, accompanying diverse microstructural damages. The pitting damage induces highly complex, mutually-interfering wave scattering in a linear regime, and triggers acoustic nonlinearity. In the pitted region the material plasticity and nonlinearity are remarkably intensified, and the contact acoustic nonlinearity (CAN) is introduced upon interaction between probing guided ultrasonic waves (GUWs) and pitting damage. Targeting at quantitatively evaluating the pitting damage, insight into the generation of high-order modes by pitting damage is achieved from the perspective of nonlinear GUW features. The theoretical analysis is validated via numerical simulations. On this basis, an in-situ structural health monitoring (SHM) framework using PZT wafer network is developed, with which, in conjunction with the use of a sensing path-based rapid imaging algorithm, the pitting damage in the shield can be monitored and characterized quantitatively and precisely.

Keywords: non-destructive evaluation, hypervelocity impact, pitting damage, nonlinear ultrasonic waves

NOMENCLATURE

A_1	magnitude at fundamental frequency
A_2	magnitude at double frequency
β'	nonlinearity damage index

1. INTRODUCTION

Pitting damage in spacecraft, arising from collisions between Whipple shield and micrometeoroids orbital debris (MMOD) – a specific impact known as “hypervelocity impact” (HVI, in exceed of 1 km/s), is a prevailing sort of material degradation and structural lesion in space assets. Far more than singular or multiple damage in regular forms, debris cloud HVI-induced pitting damage is clustered with hundreds of small craters and cracks disorderedly scattered over a wide area (“*pitted region*” hereinafter) (see Figure 1), accompanying diverse microstructure defects, *i.e.*, micro-voids, micro-cracks, recrystallized fine grains, and dislocation, *etc.*, (see Figure 2). It is therefore extremely challenging to detect and assess this form of pitting damage using conventional NDE approaches [1] and linear features of guided ultrasonic waves (GUWs) [2].

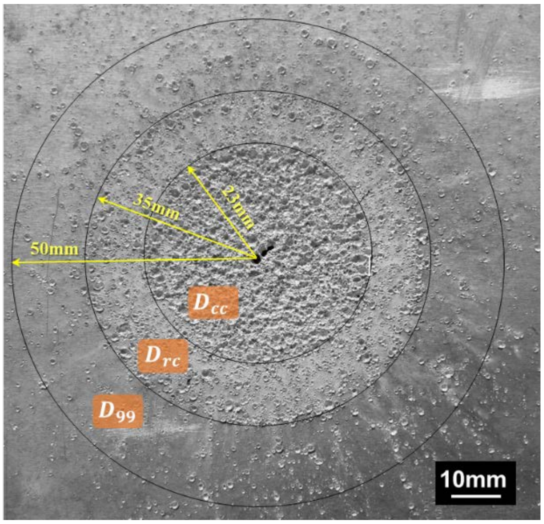

FIGURE 1: PITTED REGION UNDER NORMAL HVI (PROJECTILE SPEED: 5.931 KM/S)

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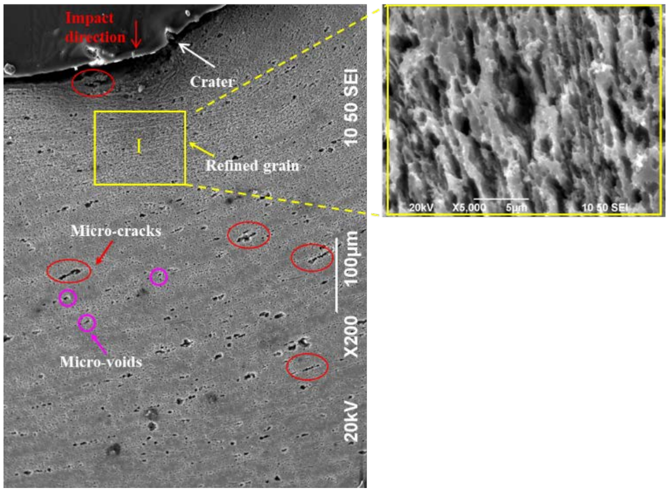

FIGURE 2: SEM IMAGE OF THE MICROSTRUCTURE UNDERNEATH THE PITTED REGION.

To circumvent the deficiency, nonlinear features of GUWs have been increasingly exploited, in accordance with the fact that damage introduces nonlinearity to a probing GUWs, more or less, which could be more sensitive than linear features to undersized damage [3].

In this study, a PZT network-based characterization framework, allying linear with nonlinear features of GUWs, in conjunction with the use of a sensing path-based rapid imaging algorithm, is developed whereby the hypervelocity debris cloud-induced pitting damage can be depicted and characterized quantitatively and precisely.

2. THEORY AND EXPERIMENT

2.1 Theory

When a GUW traverses a pitted region, the nonlinear effects of pitting damage, along with the material plasticity, will modulate GUW propagation, diverting partial wave energy from the excitation to other frequency bands, in particular the double or triple frequency (*i.e.*, second- or third-order harmonic generation) – introducing nonlinear attributes to the captured GUW signals.

On top of the intrinsic material nonlinearity and geometric nonlinearity, additional sources of nonlinearities in the pitted region are introduced, mainly including the enhanced material nonlinearity (induced by refined grain, dislocation, *etc.*) and the contact acoustic nonlinearity (CAN, induced by micro-cracks/voids).

A nonlinearity damage index β' is established to quantify the degree of nonlinearity extracted from a probing GUW when it traverses a pitted area, which reads (based on the authors' previous works [4-5])

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

where A_2 signifies the magnitude of the probing GUW excited at fundamental frequency, and A_2 the magnitude of the pitting-damage-induced additional nonlinearity to the GUW at double frequency.

2.2 Experiment

A built-in sensor network, comprising of sixteen miniaturized and lightweight PZT wafers (denoted by Sen_i (i=1,2,……， 16)) mounted on surface of the rear wall layer, is configured (see Figure 3). Each PZT is alternatively used as actuator and sensor, forming a pair of sensing paths covering the entire pitting damage region. Model pair S_0-S_0 (0.9-1.8 MHz mm) with quasi phase-velocity matching are investigated to gain an insight into the accumulative nature of β' in the experiment. Covering the entire inspection region, each sensing path in the sensor network independently captures linear/nonlinear GUW features to calculate the damage index.

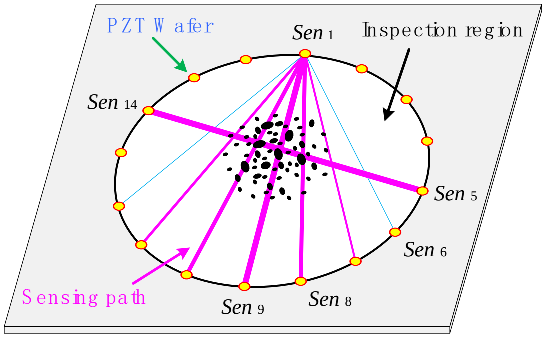

FIGURE 3: PZT NETWORK COVERAGE FOR NORMAL HVI-INDUCED PITTING DAMAGE CHARACTERIZATION

3. RESULTS AND DISCUSSION

Figure 4 illustrates the second harmonic S_0 mode extracted from three representative sensing paths (*i.e.*, Sen_1-Sen_9, Sen_1-Sen_8 and Sen_1-Sen_6) traversing the inspection region, with more pitting craters and cracks in the sensing path, changes in second harmonic mode will be remarkably intensified, leading to higher damage index β'. Inversely, it is feasible to describe the pitting damage quantitatively in terms of variation in β'.

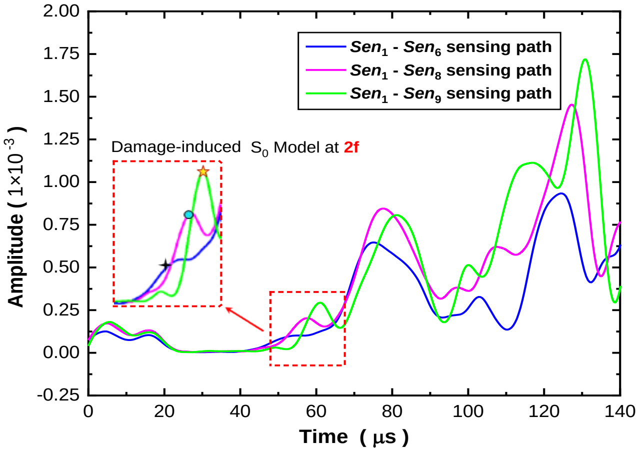

FIGURE 4: SPECTRUM AT DOUBLE EXCITATION FREQUENCY FOR REPRESENTATIVE SENSING PATHS

With the damage index obtained from all sensing paths, the pitting damage can be pinpointed and the severity evaluated quantitatively with the reconstruction algorithm for probabilistic inspection of damage (RAPID) [6]. The occurrence of pitting damage, consisting of three typical pitted regions, *i.e.*, D_{cc}, D_{rc}, D_{99}, is identified quantitatively and intuitively by highlighting pixels with outstanding field value (see Figure 5). It is noteworthy that for a specific point, the severer the pitting damage is, the higher the damage index will be, it is therefore that the remarkably high field values are displayed in the central region of pitting damage and relatively small field values are observed for some pixels adjacent to the region of pitting damage, giving users an intuitive and quantitative perception about the pitting damage. The location and sizes of the reconstructed area are consistent with the real damage.

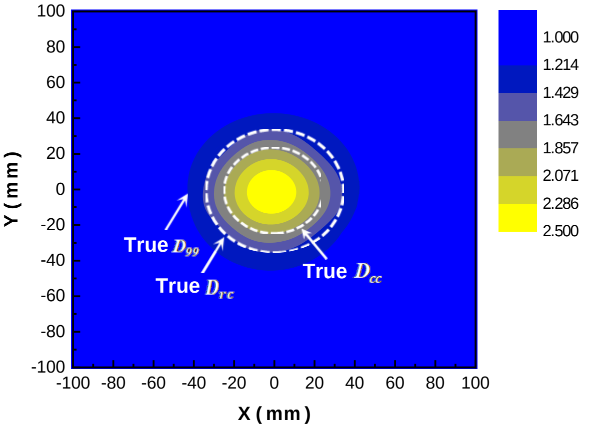

FIGURE 5: DAMAGE IMAGING WITH RAPID UNDER NORMAL HVI

4. CONCLUSION

In this study, a characterization framework based on linear/nonlinear features of GUWs, is developed to quantitatively and precisely depict and monitor the debris cloud HVI-induced pitting damage in a typical dual-layered Whipple shield. Experimental result shows that the pitting damage is successfully identified and quantitatively characterized with a PZT sensor network. Compared with conventional, bulky piezoelectric transducers, PZT wafers used in this study are lightweight and small, rendering a capacity of *in-situ* monitoring and evaluation of debris cloud HVI-induced pitting damage.

ACKNOWLEDGEMENTS

REFERENCES

[1] Moser, D.; Poelchau, M. H.; Stark, F.; Grosse, C., Application of nondestructive testing methods to study the damage zone underneath impact craters of MEMIN laboratory experiments. Meteorit Planet Sci 2013, 48, (1), 87-98.

[2] Hall, J. S.; Fromme, P.; Michaels, J. E., Guided wave damage characterization via minimum variance imaging with a distributed array of ultrasonic sensors. J. Nondestruct. Eval. 2014, 33, (3), 299-308.

[3] Dutta, D.; Sohn, H.; Harries, K. A.; Rizzo, P., A nonlinear acoustic technique for crack detection in metallic structures. Struct. Health Monit. 2009, 8, (3), 251-262.

[4] Wang K, Liu M, Su Z, et al. Analytical insight into “breathing” crack-induced acoustic nonlinearity with an application to quantitative evaluation of contact cracks[J]. Ultrasonics, 2018, 88: 157-167.

[5] Liu M, Wang K, Lissenden C J, et al. Characterizing Hypervelocity Impact (HVI)-induced pitting damage using active guided ultrasonic waves: from linear to nonlinear[J]. Materials, 2017, 10(5): 547.

[6] Zhao, X.; Gao, H.; Zhang, G.; Ayhan, B.; Yan, F.; Kwan, C.; Rose, J. L., Active health monitoring of an aircraft wing with embedded piezoelectric sensor/actuator network: I. Defect detec