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

# QNDE2019-1234

# DAMAGE DETECTION IN STIFFENED COMPOSITE STRUCTURES WITH WAVE FIELD IMAGING METHOD

**Kaihong Zheng, Zheng Li[1], Jie Zhou, Jianlin Chen, M. Saqib Hameed**
Department of Mechanics and Engineering Science, College of Engineering, Peking University, Beijing 100871, China

## ABSTRACT

*Wave field imaging method has been an effective visualization method in damage detection since the past decades. However, existing imaging methods still have problems when applied to complicated composite structures. In this paper, an improved adjacent wave subtraction (AWS) method is proposed to visualize damage in stiffened composite structures. A robust time window is illustrated to enhance the anomalous wave signals and improve the imaging results. The method is proved to be effective in stiffened composite panels with numerical simulations and experiments.*

Keywords: wave field imaging, composite structures, non-destructive evaluation

## NOMENCLATURE

| | |
|---|---|
| $T_W$ | time window |
| $u$ | displacement |
| $t_d$ | time delay |
| $dx$ | distance between two adjacent points |
| $v_g$ | group velocity |
| $DI$ | damage index |
| $r$ | adjustable parameter |
| $N_T$ | sample points during time window |
| $\alpha$ | length of time window |
| $T$ | period of excitation signal |

## 1. INTRODUCTION

With the development of aeronautics and astronautics, many advanced smart materials have been applied in these areas. Among these materials, composites have occupied an important position for their high strength-to-weight and stiffness-to-weight ratios, designable flexibility, and anticorrosion, etc. Stiffened composite panels, the most common composite structures, further enhance the strength, rigidity and stability more effectively. However, the non-destructive evaluation (NDE) in such complicated composite structures is still faced with many challenges. Wave field imaging method, as a newly developed method in the past ten years, is an effective way to visualize multiple and different kinds of damage. There are several kinds of wave field imaging methods like ultrasonic scan imaging [1], probability-based diagnostic imaging [2], time-reversal imaging [3], pulsed laser scan imaging [4] and phased arrays imaging [5]. Among these wave field imaging methods, pulsed laser scan imaging has outstood for its high accuracy and simple algorithm. Compared with traditional C-scan, pulsed laser scan imaging is superior in structures with thin thickness. There are several different algorithms to enhance the pulsed laser scan imaging, namely Laplacian image filtering [6], frequency-wavenumber domain filtering [7] and adjacent wave subtraction (AWS) [8] and so on. Among these algorithms, AWS method is more effective and robust in complicated structures, but this method still need to be developed to be more sound and systematic.

In this paper, we improved the AWS method with new time window selection and time matching method based on Lamb wave properties. Numerical simulations and experiments have verified this method to be effective in stiffened composite structures.

## 2. DAMAGE DETECTION WITH WAVE FIELD IMAGING METHOD

### 2.1 Improved AWS method

Lamb waves in composite laminate are quite complicated, especially in complex structures like stiffened composite panels. The complexity sets big obstacle in traditional damage detection methods, like time of flight (ToF) based method [9, 10]. The AWS method, first proposed by J.-R. Lee and his colleagues [8], is an effective alternative to overcome this obstacle. This method takes advantage of the anomalous wave signals in the damage area. The damage like debonding, delamination or fiber broken in the structure will reflect Lamb waves forth and back many times and trap some energy in the damage area, which cause the anomalous Lamb waves, generally like standing wave. In healthy area, without disturbance of damage, Lamb waves at adjacent points are similar to each other during a certain period which is defined as time window $T_W$, and they only have some

[1] Contact author: lizheng@pku.edu.cn

 

time delay and a little attenuation in amplitude. While in damaged area, signals at adjacent points are much different from each other, which makes the AWS method feasible to detect damage in complicated structures. In our improved method, the anomalous wave at point $(x, y)$ is defined as second order difference

$$\Delta u(x, y, i) = u(x + \Delta x, y, i - t_d) + u(x - \Delta x, y, i + t_d) - 2 * u(x, y, i) \quad (1)$$

where $t_d$ is the time delay between the adjacent points, $t_d = \frac{dx}{v_g}$, $dx$ is the distance between two adjacent points and $v_g$ is the group velocity of the Lamb wave. The damage index is defined as

$$DI(x, y) = \sum_{i=1}^{N_T} \Delta u^r(x, y, i) \quad (2)$$

where $r$ is a parameter that can be adjusted to distinguish the damage according to damage type, and $N_T$ is sample points during the time window $T_W$,

$$T_W = \frac{x}{v_g} + \alpha T \quad (3)$$

where $\alpha$ is the length of the time window, and $T$ is the period of the excitation signal.

To reduce the influence of the reflected waves by the complicated structures, a short time period after the excitation signal reaching at the scanning point is the most considerable time window. Considering this, $S_0$ mode wave is chosen for its high speed in low frequency domain.

### 2.2 Numerical simulation

To verify the method in the former part, numerical simulation is conducted in a stiffened composite panel shown in Figure 1. The ply sequence of the skin sheet is [0/90/90/0], and the lamina thickness is 0.15 mm. The damage location and size are shown in Figure 1. The excitation signal is a 5.5-cycle sinusoidal tone burst at central frequency 259kHz. The out-of-plane displacement U3 is extracted from simulation and acquisition interval is 3 mm on the whole panel. After processed by the improved AWS method, the result is shown in Figure 2. It is obvious that the damage can be located accurately with this method.

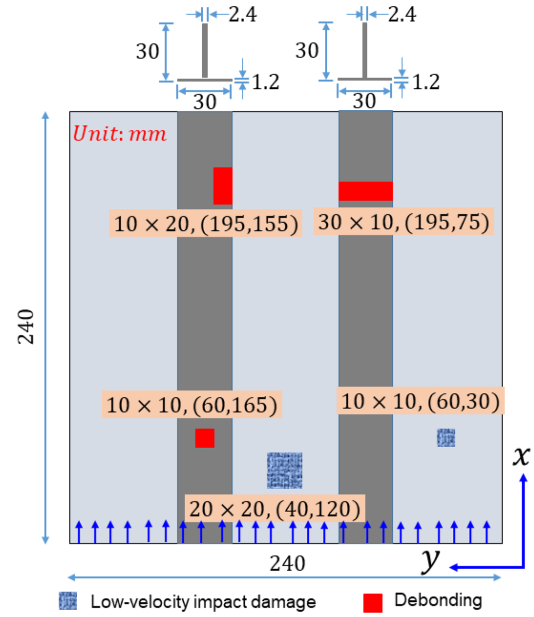


**FIGURE 1**: STIFFENED COMPOSITE PANEL USED IN NUMERICAL SIMULATION

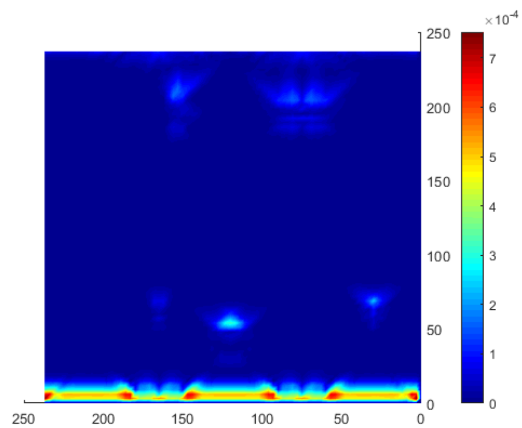


**FIGURE 2:** WAVE FIELD IMAGING RESULT WITH IMPROVED AWS METHOD

### 2.3 Experiment

In order to validate the efficiency of the proposed method, experiment was conducted using a stiffened composite panel. Multiple debonding and low-velocity impact damage were introduced to the stiffened panel. Figure 3 shows the overall experimental setup. From the experiment results, it is confirmed that the method is effective to detect multi-damage in stiffened composite panel.

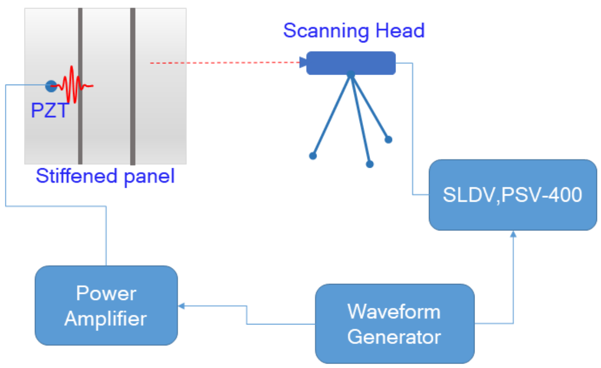


**FIGURE 3:** EXPERIMENTAL SETUP TO DETECT THE DAMAGE IN STIFFENED COMPOSITE PANEL

## 3. RESULTS AND DISCUSSION

The improved AWS method in this paper is successfully applied to detect multi-damage in stiffened composite panel containing different damage types. From the research, time window is found to be a very important parameter in this method. A suitable time window can lower unwanted noise and enhance anomalous waves, which will greatly improve the imaging quality. In our study, when $\alpha = 0.5$, the result is the best. While time matching is a minor factor to affect the imaging result. The noise level is lower with second order difference in equation (1) comparing with first order difference. In equation (2), the parameter $r$ of the damage index $DI$ is set to be 1 in our cases, and it can be adjusted according to the damage type.

## 4. CONCLUSIONS

In this paper, the improved AWS method is introduced to detect multiple damage in stiffened composite panels. Numerical simulation and experimental test have verified this improved wave field imaging method. From the results in this paper, the following points can be addressed:

(1) $S_0$ mode wave is more suitable in AWS method for its fast speed in low frequency domain.
(2) Time matching and time window based on Lamb wave characteristics are more effective to distinguish anomalous waves.
(3) The second order difference of Lamb wave signals can illustrate the damage in complex structures more obviously with lower noise.

## ACKNOWLEDGEMENTS

This work has been supported by National Natural Science Foundation of China under grant No. 11672004.

## REFERENCES

[1] D. K. Hsu, “Nondestructive Evaluation of Sandwich Structures: A Review of Some Inspection Techniques,” *Jnl of Sandwich Structures & Materials*, vol. 11, no. 4, pp. 275–291, Jul. 2009.
[2] D. Wang, L. Ye, Y. Lu, and Z. Su, “Probability of the presence of damage estimated from an active sensor network in a composite panel of multiple stiffeners,” *Composites Science and Technology*, vol. 69, no. 13, pp. 2054–2063, Oct. 2009.
[3] C. H. Wang, J. T. Rose, and F.-K. Chang, “A synthetic time-reversal imaging method for structural health monitoring,” *Smart Mater. Struct.*, vol. 13, no. 2, pp. 415–423, Mar. 2004.
[4] S. Yashiro, J. Takatsubo, and N. Toyama, “An NDT technique for composite structures using visualized Lamb-wave propagation,” *Composites Science and Technology*, vol. 67, no. 15, pp. 3202–3208, Dec. 2007.
[5] J. Rajagopalan, K. Balasubramaniam, and C. V. Krishnamurthy, “A phase reconstruction algorithm for Lamb wave based structural health monitoring of anisotropic multilayered composite plates,” *The Journal of the Acoustical Society of America*, vol. 119, no. 2, pp. 872–878, Jan. 2006.
[6] H. Sohn *et al.*, “Delamination detection in composites through guided wave field image processing,” *Composites Science and Technology*, vol. 71, no. 9, pp. 1250–1256, Jun. 2011.
[7] M. Ruzzene, “Frequency–wavenumber domain filtering for improved damage visualization,” *Smart Mater. Struct.*, vol. 16, no. 6, pp. 2116–2129, Oct. 2007.
[8] J.-R. Lee, C. Ciang Chia, C.-Y. Park, and H. Jeong, “Laser ultrasonic anomalous wave propagation imaging method with adjacent wave subtraction: Algorithm,” *Optics & Laser Technology*, vol. 44, no. 5, pp. 1507–1515, Jul. 2012.
[9] B. Li, Y. Liu, K. Gong, and Z. Li, “Damage localization in composite laminates based on a quantitative expression of anisotropic wavefront,” *Smart Mater. Struct.*, vol. 22, no. 6, p. 065005, Apr. 2013.
[10] J. Chen, Z. Li, and K. Gong, “Nondestructive testing method based on lamb waves for localization and extent of damage,” *Acta Mech. Solida Sin.*, vol. 30, no. 1, pp. 65–74, Feb. 2017.