Damage Size and Depth Estimation on Composite Structures with Wavenumber Analysis

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ABSTRACT

This paper describes the use of wavenumber filtering for damage detection and thickness estimation with a signal-frequency standing wave excitation on composite structures. Using a single, fixed frequency excitation from a mounted piezoelectric transducer, the full steady-state wavefield could be obtained using a Laser Doppler Vibrometer (LDV) with a mirror-tilting device. After scanning in high speed, a wavenumber filtering is applied to determine the dominant wavenumber components of the measured wavefield, which could be used for indicative of structural damage. Mapping processes based on local wavenumber filtering is then carried out for damage area visualization . In order to estimate the depth of the damaged area, the Lamb wave equation is employed and the wavenumber components are converted into the depth information. Several experiments are performed on composite structures with different types of damage, including debonding and delamination on composite plates, to demonstrate the capability of the proposed techniques. The results demonstrate that the techniques are very effective in in quantitative damage estimation with the potential for quick inspection of a variety of composite structural components.

1 INTRODUCTION

The use of composite materials for structural systems has increased because of their lightweight and high strength. However, the use of composites leads to various types of failure modes, including delamination, fiber breakage, matrix cracking, and fiber-matrix debonding. Delamination appears to be the most frequent failure mode, usually caused by imperfect fabrications, cracks in matrix materials, impacts by foreign objects, or other hazardous service environments [1]. The delamination substantially reduces the stiffness and the buckling load capacity, which, in turn, influences the structure's stability characteristics. In order to ensure safe and reliable operation, great amounts of research efforts have focused on the development of cost-effective nondestructive evaluation (NDE) techniques for composite structures. The traditional NDE techniques usually require various precaution and lengthy inspection [2,3,4]. In recent years, techniques based on ultrasonic waves such as acoustic and Lamb waves have been extensively studied for damage detection of composite structures[5,6,7]. Lamb waves are mechanical waves corresponding to vibration modes of plates with a thickness on the same order of magnitude as the wavelength. The changes in wave attenuation, reflection, or time-of-flight are typically used to detect and locate damage with various signal processing techniques. The advances in sensor and hardware technologies for efficient generation and detection of Lamb waves and the need to detect sub-surface damage in laminate composite structures, particularly those used in aircraft industries, has led to a significant increase in the studies that use Lamb waves for detecting defects in composite structures. However, it is a well-known fact that Lamb waves in composite plates travel relatively short distances compared to metallic counterparts because of high damping present within the material. In order to obtain an acceptable signal to noise ratio, one often needs to employ significantly increased numbers of sensors and actuators for composite plate monitoring. In addition, data retrieval and management may not be trivial, and a large data storage

capacity is required to process and compare the measured data. The large number of sensors/actuators may also lead to frequent sensors/actuators failures, which produce false-indications regarding the structural health and negates the effectiveness of the techniques.

With these reasons, researchers turn their attentions to non-contact sensing for actuation [8,9,10,11,12] or sensing [13,14,15,16] of wave propagations. Especially, scanning laser Doppler vibrometers (LDV) technology enables the measurements of the full wavefield data of propagating ultrasonic waves in a structure. With the high spatial resolution scanning, these technologies enable the visualization of the full wavefield, which, in turn, produces the detailed images of the defects. Lee et al., [8] developed a unique system, referred to as Ultrasonic Propagation Imaging (UPI), where a Q-switched laser pulse is utilized to excite a surface of structures and an embedded sensor is used to measure subsequent propagated waves. With the use of several signal processing tools, various types of damages (corrosion, cracks, debonding, etc.) could be identified by the damage-induced reflected and scattering waves. [9, 10, 11, 17].

Guided wave propagation patterns are complicated and difficult to analyze due to their dispersive and multimodal behaviors. Hence, most guided wave damage detection techniques require to separate a single wave mode. This separation could be accomplished based on wavenumber analysis. Rogge and Cara [12] used a laser Doppler vibrometer to measure the wave field data for composites and showed that the estimation of local wavenumber can lead to effective and quantitative evaluation of the size and the depth of delamination in composite plates. Ruzzene et al. [13] applied both instantaneous and local wavenumber filtering to the guided wave field data for damage quantification. Michaels et al. [19] separate propagating, converted, and reflected modes using wavenumber filtering, which are often required to analyze multimode guided wave field. The techniques mentioned above have one characteristic in common; they are measuring the transient waves. However, because these waves have so little energy in composite structures, resulting in low signal to noise ratios (SNR), there are several problems arise, including increasing numbers of sensors and actuators and excessive averaging. In order to overcome such problems, the use of standing waves, instead of using traveling waves as in the previous studies, has been recently proposed [18,19]. They measured the full-field wave field using a scanning LDV under steady-state excitations of a fixed frequency. Damage is then visualized by tracking the wavenumber of the excited response through wavenumber-domain processing.

Based on these studies, our study begins to effectively visualize damage on various composite structures using the standing wave analysis. We developed a scanning system consists of a LDV and a mirror-tilting system to measure full wavefield while a piezoelectric transducer provides a steady-state excitation at a single frequency on a structure. After the scanning process completed, wavenumber-based signal processing tools, including Local Wavenumber Mapping(LWM) and Acoustic Wavenumber Spectroscopy(AWS), are implemented in order to detect and visualize the damaged area. Several experiments with composited plates are conducted for validation of the proposed methods. The theory behind this technique and experimental results are presented in the following sections.

3. DAMAGE VISUALIZATION BASED ON WAVENUMBER

When using steady-state waves for damage detection, it is important to extract time-invariant parameters of the wave that could be used as a damage sensitive feature. Wavenumber, the inverse of wavelength, has a fixed value for a given frequency, thickness, and material properties. Therefore, if there is a change in such properties, it will result in changes in wavenumber, which allow one to detect and locate structural damage. Therefore, in this technique, the wavenumber is used as a key parameter to extract a damage sensitive feature.

4.2 LASEAR SCANNING SYSTEM AND MEASUREMENT PROCEDURE

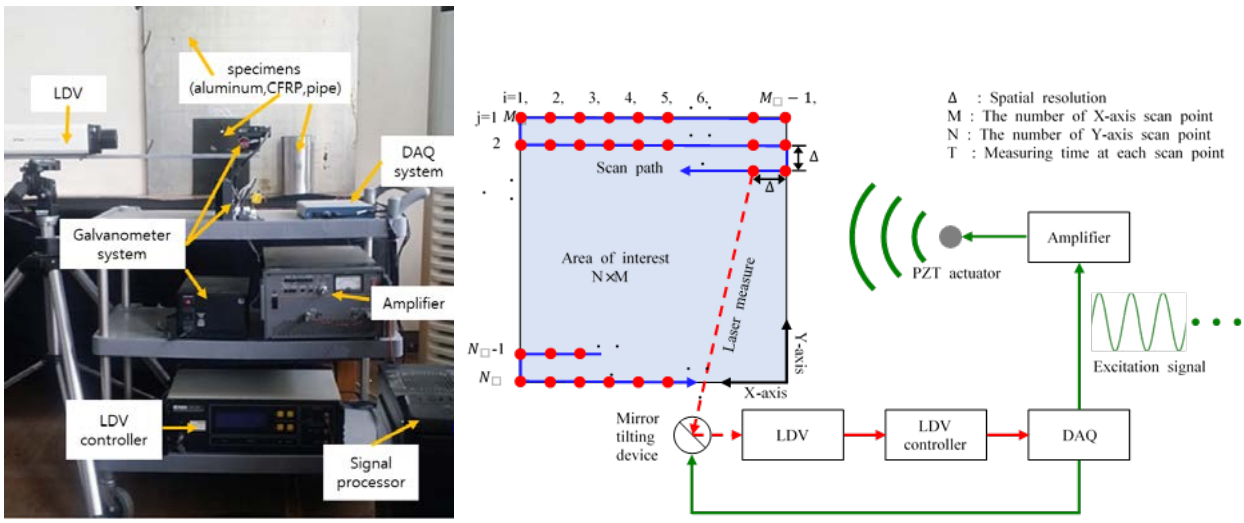


Figure 1: laser scanning system and data acquisition process

A laser scanning system for full wave field measurements consists of following components which are 1) Piezo transducer for a single, ultrasonic actuation, 2) Data acquisition device to generate an ultrasonic wave and to measure subsequent structural responses, 3) Laser Doppler Vibrometer, 4) A mirror-tilting system to control the position of laser sensing points and 5) A signal processor. A piezo transducer is attached on the surface of a plate and generates a standing wave at high frequency (> 50 kHz). Because of standing wave excitations, a structure experiences the steady state responses, which are measured in the size of T x N x M by the system. T is the time data of each sensing point, and N and M are the number of spatial points in the x and y directions. The excitation frequency is normally set at higher than 80 kHz with the sampling frequency of 1MHz. Once structural responses are measured, the steady-state response, $r(x,y)$ of the excitation frequency is extracted by applying Discrete Fourier Transform. Because a steady-state response at the excitation frequency eliminates other frequency components, high signal to noise ratio could be obtained.

$$r(x,y) = \frac{1}{T}\sum_{t=0}^{T} v[x,y,t]exp(-j2\pi ft) \tag{1}$$

3.1 ACOUSTIC WAVENUMBER SPECTROSCOPY

This technique was developed by Flynn et al. [16]. As shown in figure 2, the response function has steady-state response of the wave field. If a damage presents in a certain area of structures, the wavelength will be modified in that specific area, which is the base of this technique. First, the wave field domain is converted to wavenumber domain by conducting 2D FFT. The filter bank is then generated by gradually increasing the radius of torus with a certain width in the wavenumber domain, where the radius, kc, corresponds to the dominant wavenumber in a filter bank. Each wavenumber component is extracted after the measurement matrix passes through the generated wavenumber filter bank. As the next step, each extracted result is reconstructed and spatial envelope is calculated. Finally, damage is visualized by searching a certain wavenumber that maximizes amplitude of the spatial envelope.

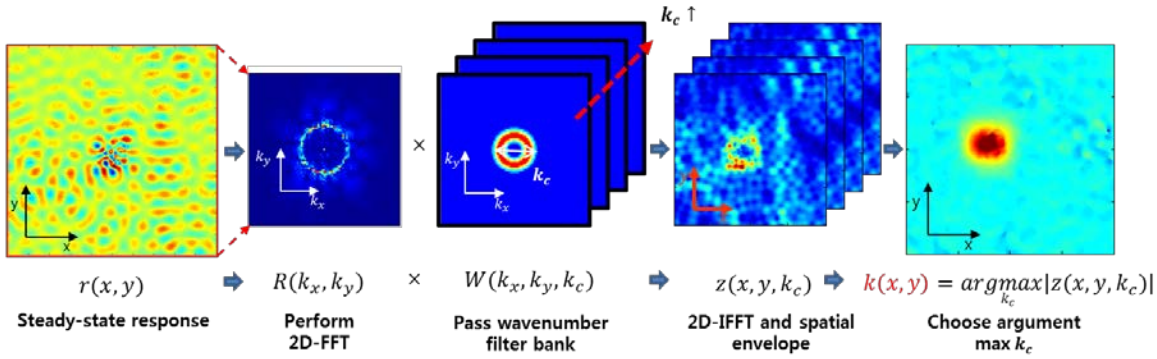


Figure 2: Diagram showing the Acoustic Wavenumber Spectroscopy process

3.2 LOCAL WAVENUMBER MAPPING

The procedure of damage identification and visualization of LWM also starts from the same response function which is used in AWS. In this technique, the dominant wavenumbers of a local window are extracted and mapped to the entire surface to detect the damaged area. Fisrt, a patial wave field in a local window is extracted and converted to the wavenumber domain. In order to reduce the magnitude of side lobes in the wavenumber domain, a hanning window is applied to the extracted wave field. The domainant wavenumber is identified after performing 2D FFT, and finally, the estimated wavenumber is mapped at every window position for damage visualization.

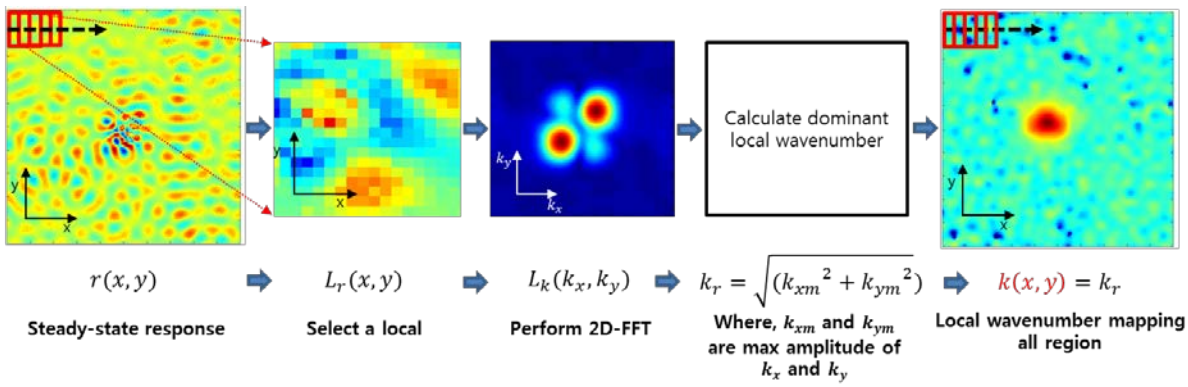


Figure 3: Diagram showing the Local Wavenumber Mapping process

As presented, the damage detection method presented in this paper uses a single, fixed frequency excitation and provides the following advantages [16].

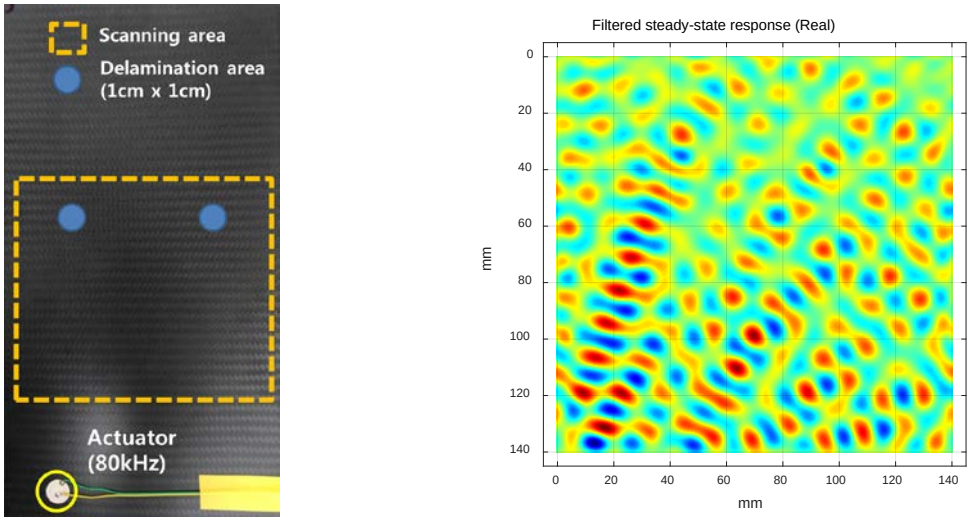
- Energy is effectively “pumped” into structures, resulting in the higher magnitude of waves.
- The delay time to wait until previous waves completely die out is not required for continuous measurements.
- Only a few cycles of wave measurements are sufficient to capture the wave behaviors at each scanning point.

4. EXPERIMENT RESULTS AND DISCUSSION

The process described in this section is applied to several composite structures to demonstrate the superior performance. Failure modes, delamination and de-bonding of composite plates, are considered.

4.2 CFRP PLATES WITH DELAMINATION DAMAGE

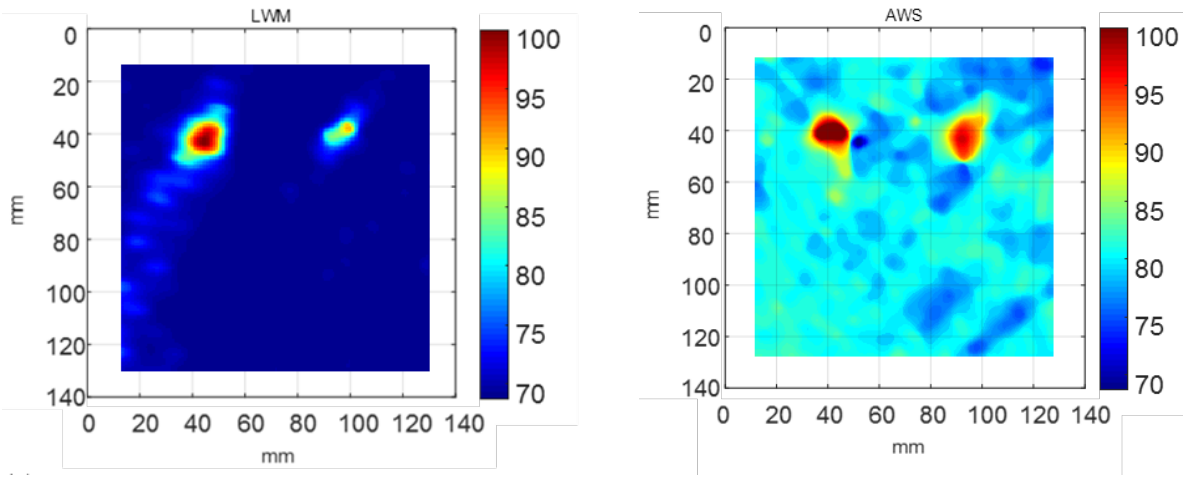
The test structure is shown in Figure 4(a). The dimension of the plate is , 500 x 300 x 1 mm. One piezoelectric (APC 850, disk type, 25.4 mm diameter) actuator was mounted on one surface of the plate, as an excitation device, as shown in the figure. The excitation frequency of the piezo actuator was set to 80 kHz and the measurements were taken in the area of 140 x 140 mm at the spatial resolution of 0.5 mm. It took less than 5.7 second to complete the entire scan of the area. Damage is introduced into the plate by repeated impacts given by a hammer. No physically visible damage was identified during this process. Figure 4(b) shows the steady-state response of the plate under the given excitation. It shows a complicated wave pattern and is hard to identify the delamination area.



(a) (b)

Figure 4 .Composite plates with delamination damage (a), The steady-state response, r(x,y) of the CFRP(b)

In order to detect and quantitatively assess the delamination area, wavenumber-based damage visualization techniques, AWS and LWM, are applied and the results are shown in Figure 5. From the figure, it is clear that both method could detect the damage area and size with high accuracy. The wavenumber of the delamination area was estimated around 1.5cm^{-1} by both methods, while the undamaged area is less than 2.0 cm^{-1}

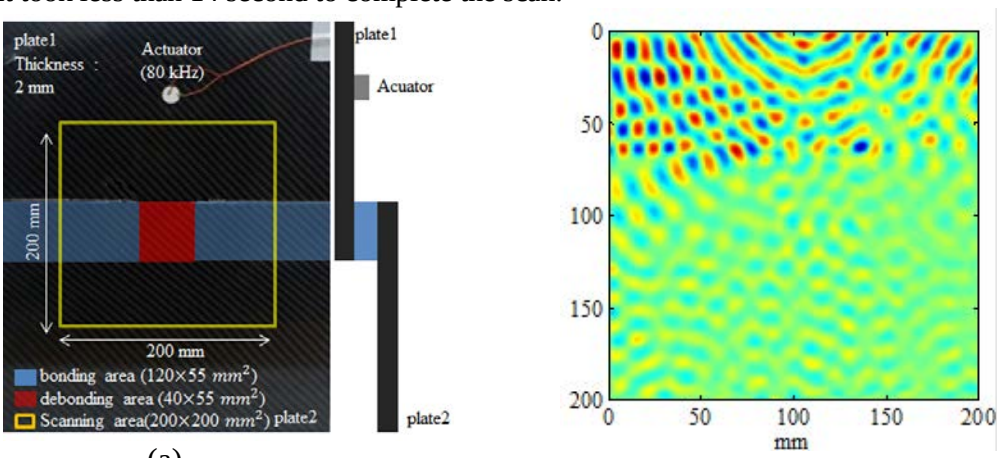


(a) (b)

Figure 5 Delamination area estimation LWM(a), AWS(b)

4.3 CFRP PLATES WITH DEBONDING DAMAGE

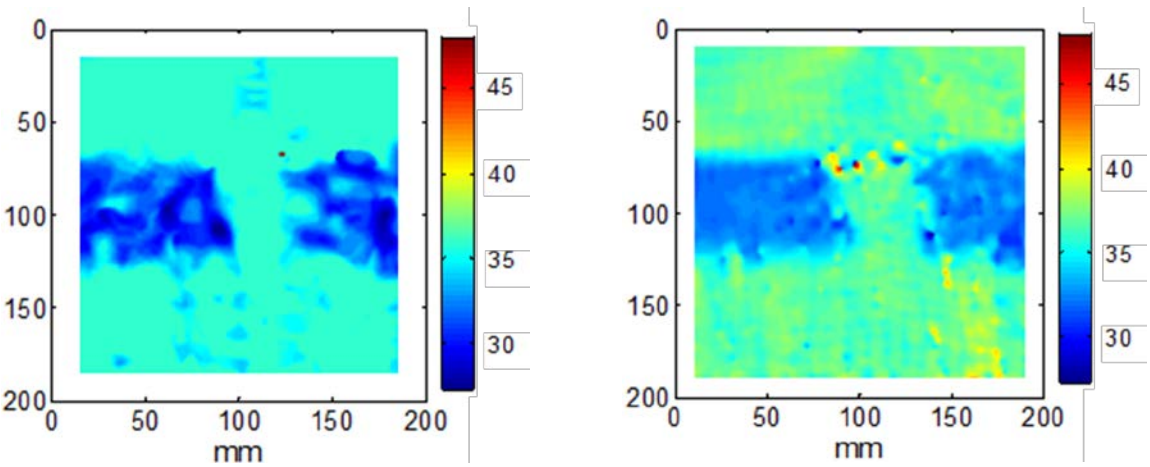
Frequently, composite plates are bonded together to form a desired structure. If the bonding process is imperfect or if there are extern load present, the debonding may occur. Our next experiment includes the debonding detection in two jointed composite plates. Two 2-mm thick composite plates are bonded together with the area of 120 x 55 mm. The debonding was created by inserting a thin release paper (40 x 50 mm) in the middle of the bonding area. The test structure is shown in Figure 6 (a). The same experimental setup was used as in the previous experiment. The excitation frequency was 80 kHz and the scanning was performed in the area of 200 x 200 mm at the spatial resolution of 0.5 mm. It took less than 14 second to complete the scan.



(a) (b)

Figure 6 Composite plates with debonding(a), The steady-state response, r(x,y) of the bonded plates(b)

Figure 6 (b) shows the steady-state response of the bonded plates. At the top, the response shows similar to the pattern of traveling waves due to the high damping present in a structure. As the wave propagates toward the bonded area, the steady-state responses become the superposition of the propagate and bonding-edge reflective waves. From the naked eye, it is impossible to distinguish the debonded area.



(a) LWM (b) AWS

Figure 72 : Debonding area estimation

Figure 7 show the results after applying LWM and AWS. It is very clear from the results that the debonded area is clearly visualized with these techniques. There are some noisy components appeared in both methods.

The test results confirm the effectiveness of wavenumber filtering for damage detection with a signal-frequency standing wave excitation on composite structures. With a minimum instrumentation and signal processing, the condition of a structure can be quantitatively assessed. The damage indicator feature used in this study, the wavenumber variation, is well-correlated to the extent of delamination.

5. CONCLUSION

The damage detection technique, which utilizes a steady-state wavefield data acquired by a scanning LDV, is developed and tested for composite structures. Two signal processing methods are also implemented, including acoustic wavenumber spectroscopy and local wavenumber mapping. For validation of the proposed technique, several experiments were conducted with composite plates with delamination and debonding damage. Experimental results show that structural damage was clearly and accurately identified. These results prove that the use of standing wave with wavenumber analysis is very effective to evaluate several types of damage on composite structure. The authors are currently investigating the further enhancement of the sensitivity of the proposed method to much smaller defects in a structure and the assessment of quantitative information, such as depth or delamination layer.

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REFERENCES

[1] Zou, Y., Tong, L., and Steven, G.P. Vibration-based Model-Dependent Damage (Delamination) Identification and Health Monitoring For Composite Structures – A Review. J Sound and Vibration, 2000 ;230(2):357-378.

[2] De Beer, F. C., Coetzer, M., Fendeis, D., & Silva, A. D. C. E. Neutron radiography and other NDE tests of main rotor helicopter blades. J Applied radiation and isotopes, 2004;61(4) : 609-61 6.

[3] Philip, J., Rao, C. B., Jayakumar, T., & Raj, B. A new optical technique for detection of defects in ferromagnetic materials and components. J NDT & E International, 2000 ;33(5):289-295.

[4] Li, Y, Lalita U, and Satish S. U. Three-dimensional defect reconstruction from eddy-current NDE signals using a genetic local search algorithm. J Magnetics, IEEE Transactions 2004; 40(2):410-417.

[5] Badcock R.A. and Birt, E.A. The Use of 0-3 Piezocomposite Embedded Lamb Wave Sensors for Detection of Damage in Advanced Fiber Composites. J Smart Materials and Structures, 2000;9(2):291-297.

[6] Ihn, J.B. and Chang, F.K. Detection and monitoring of hidden fatigue crack growth using a built-in piezoelectric sensor/actuator network: II. Validation using riveted joints and repair patches. J Smart Materials and Structures, 2004;13(3):621-30

[7] Kessler, S.S., Spearing, S.M., and Soutis, C., "Damage Detection in Composite Materials using Lamb Wave Methods," Smart Materials and Structures, 2002;11(2):269-278.

[8] Lee, J. R., Jeong, H., Ciang, C. C., Yoon, D. J., & Lee, S. S. Application of ultrasonic wave propagation imaging method to automatic damage visualization of nuclear power plant pipeline. J Nuclear engineering and design. 2010;240(10):3513-3520.

[9] Lee, J. R., Chong, S. Y., Jeong, H., & Kong, C. W. A time-of-flight mapping method for laser ultrasound guided in a pipe and its application to wall thinning visualization. J NDT & E International, 2011;44(8):680-691.

[10] Lee, J. R., Jeong, H., Ciang, C. C., Yoon, D. J., & Lee, S. S. Application of ultrasonic wave propagation imaging method to automatic damage visualization of nuclear power plant pipeline. J Nuclear engineering and design, 2010;240(10):3513-3520.

[11] Chia, C. C., Jeong, H. M., Lee, J. R., & Park, G. Composite aircraft debonding visualization by laser ultrasonic scanning excitation and integrated piezoelectric sensing. J Structural Control and Health Monitoring. 2012;19(7):605-620.

[12] Iwasawa M, Mizutani Y, Nishino H, et al. Estimation of five elastic stiffness coefficients of unidirectional glass fiber reinforced plastic by laser generated ultrasonic. J Adv. Compos. Mater. 2012;11:121-135.

[13] Rogge, M D., and Cara AC L. Characterization of impact damage in composite laminates using guided wavefield imaging and local wavenumber domain analysis. J Ultrasonics 2013;53(7):1217-1226.

[14] Michaels, T E., Michaels, J E., and Ruzzene. M. Frequency–wavenumber domain analysis of guided wavefields. J Ultrasonics. 2011;51(4) 452-466.

[15] Ruzzene, M. Frequency–wavenumber domain filtering for improved damage visualization. J Smart Materials and Structures 2007;16(6): 2116.

[16] Yu, L, Z Tian, and Leckey C AC. Crack imaging and quantification in aluminum plates with guided wave wavenumber analysis methods." J Ultrasonics 2015;65:203-212.

[17] Abbas, S H, Truong, T C, and Lee, J R , FPGA-based ultrasonic energy mapping with source removal method for damage visualization in composite structures, Advanced Composite Materials, 2016 (Submitted)

[18] Flynn, E B. Embedded Multi-Tone Ultrasonic Excitation and Continuous-Scanning Laser Doppler Vibrometry for Rapid and Remote Imaging of Structural Defects. EWSHM-7th European Workshop on Structural Health Monitoring. 2014.

[19] Flynn, E. B., and Jarmer, G. J. High-speed, non-contact, baseline-free imaging of hiddden defects using scanning laser measurements of steady-state ultrasonic vibration. J Structural Health Monitoring 2013: 1186-1193