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Refinement of defect detection in the contact and non-contact ultrasonic non-destructive testing of wind turbine blade using guided waves

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Abstract

The guided waves are widely used for the inspection of many composite structures as they can travel up to long distance along the thickness of the structure. Most of the times, the experimental investigations standalone is not able to locate and size the damages or defects due to dispersive, superimposed and scattered guided wave modes. Hence signal refinement of ultrasonic guided wave signals is required for identifying and characterizing the defects. In this work, disbond type defects presented on different locations of the segment of the wind turbine blade are estimated by applying the signal refinement techniques after experimental analysis. The experiment was carried out on a 1005 x 870 mm segment of wind turbine blade manufactured using a composite glass fiber reinforced plastic material. Two defects on the trailing edge (with diameter 15 and 25 mm) and three defects on the main spar (with diameters 25, 51 and 81 mm) of the WTB segment were investigated. The combination of macro fiber composite transducer, contact type and air-coupled transducers were used to transmit and receive the ultrasonic guided waves. The signal processing techniques are applied to the experimental signals for the estimation and characterization of defects.

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Keywords: Guided wave; composite; signal processing; transducer; ultrasound

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1. Introduction

Ultrasonic guided wave (UGW) testing in one of leading nondestructive testing (NDT) techniques for the inspection of structures with an aerodynamic shape such as the wing of aircraft or a blade of a wind turbine, which operate under

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dynamic loads (Mrazova (2013)). There are many contacts and non-contact methods or transducers are available to perform the UGW testing and their usage depending on the requirement of the testing techniques and accessibility of the structure (Tiwari and Raisutis (2016)). For the effective visualization of damages and defects on the structure, the most widely used experimental technique is the two-dimensional scanning or C-scan. But the time-consuming nature and inefficiency to scan the complex geometrical objects, the C-scan procedure is not possible for the real-time applications (Imielińska, Castaings et al. (2004), Fahr (2013)). Hence, the researchers are working on how to extract the information from a single B-scan or A-scan. But the experimental results comprising of a B-scan or A-scans are not enough for the identification of size and position of irregularities and defects. Moreover, the phenomenon of scattering, reflection, mode-conversion, attenuation of UGW during the interaction of defective regions introduce more complexity in the inspection process. Hence, irrespective of the type of UGW testing (*e.g.* contact or non-contact type methods), the signal refinement is necessary by applying the suitable signal processing techniques on the received UGW by experimental analysis.

The most widely used signal processing techniques for the refinement of UGW signals are Hilbert transform (HT), discrete wavelet transform (DWT), short-time Fourier transform (STFT), cross-correlation, empirical mode decomposition (EMD), variational mode decomposition and split spectrum signal processing etc. ((Tiwari, Raisutis, and Samaitis (2017), Shankar and Karpur et al. (1989), Michael (2009), Zhang and Ren (2010), Tiwari and Raisutis (2018)). It may not be possible to refine the UGW by only one of these techniques. In most of the cases, a mixed signal processing approach is required depending on the complexity of wave modes.

The objective of this research is the refinement of UGW signals acquired from one-dimensional scanning for the analysis of disbonds on the segment of wind turbine blade (WTB). The segment was constructed from glass fiber-reinforced plastic (GFRP) material. The multi-layered structure of the WTB consists of a skin layer (dye coating with GFRP), glue/foam layer and a GFRP foundation layer. Due to the complexity associated with the multi-layered structure of composite, variable thickness and the arbitrary curved surface of the WTB, the orientation and position of transducers are as important as the appropriate signal processing for further analysis and the detection of defects. The experiments are performed by the low-frequency (LF) ultrasonic system developed at Ultrasound Research Institute of Kaunas University of Technology. Two different experiments were performed on differently sized defects. In the first experiment, P1-type macro-fiber composite (MFC) transducer ((MFC P1 Type (2018), Tiwari and Raisutis et al. (2018), Tiwari and Raisutis et al. (2017)) is used for transmitting the guided lamb waves and piezoceramic contact-type transducer is used to receive the UGW signals. The disbond-type defects having diameters of 25 mm and 51 mm located on the main spar are inspected. During the second experiment, a pair of air-coupled transducers fixed on a movable panel is used to analyze the 15 mm and 25 mm diameter defects (located on trailing edge) and 81 mm diameter defect located on the main spar. After receiving UGW signals in both cases, the wavelet transforms, variational mode decomposition techniques etc. are applied for the refinement of signals. In this way, size and location of defects are analyzed. The paper is organized in the following manner.

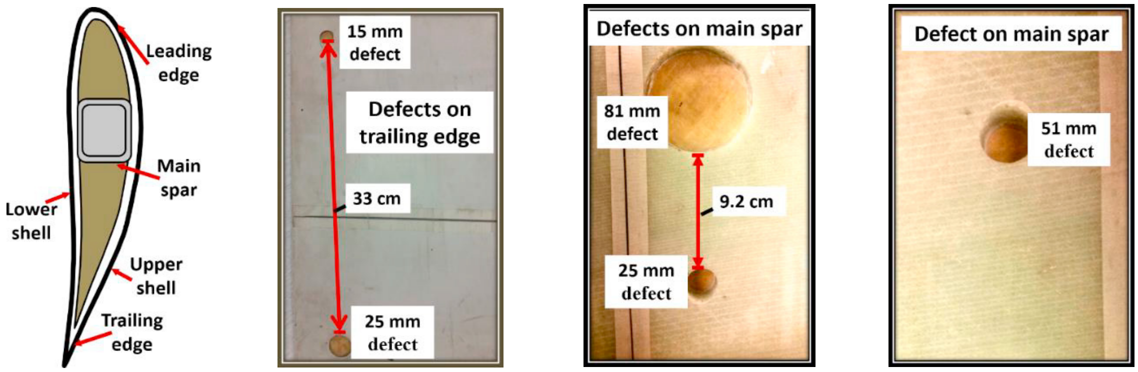
- Section 2 presents the information about sample, experiment investigation using MFC-piezoceramic transducer and air-coupled transducer pair.
- Section 3 presents the results after refinement of UGW signals. The results of estimation of only 51 mm defect are presented in this paper.
- The conclusions of research are presented in Section 4.

2. Experimental analysis

The schematic of WTB segment and photo view showing all defects are shown in Fig. 1(a-d). A schematic of WTB segment showing aerodynamic shape is shown in Fig. 1(a). The disbond type defects of different sizes located on trailing edge and main spar of the segment are presented in Fig. 1(b-d).

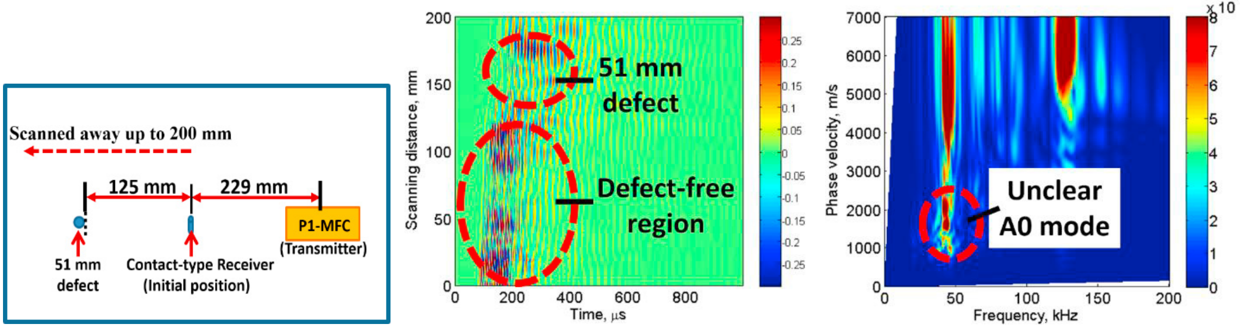
2.1. Experimental analysis using MFC-piezoceramic pair

The experiment was performed to perform the linear scanning over the disbond-type defects having diameters 25 mm and 51 mm located on the main spar. The P1-type MFC transducer is excited with 41.38 kHz, 3 period signal with Gaussian shape and the contact-type piezoceramic transducer were scanned away up to 200 mm to record the UGW signals. The MFC- transducers are widely used to as a actuator and sensor of guided lamb modes (e.g. the asymmetric A0 and symmetric S0 mode). The scanning step and sampling frequency was used as 0.5 mm and 100 MHz respectively. The contact-type receiver was wideband with 6 dB bandwidth up to 300 kHz (Vladišauskas et al. (2010)). A conical protection layer with a diameter less than 0.25 mm was provided to the surface of receiving transducer and glycerol was used to make a good acoustic contact. In this paper, only the experimental scanning on 51 mm defect is presented. The initial distance between the center of MFC transmitter and the contact-type receiver was 229 mm. The initial end-to-end distance between 51 mm defect and receiver was 125 mm.



a) (b) (c) (d)

Fig. 1. (a) Schematic of WTB; (b) Photo of defects with 15 mm and 25 mm diameters on trailing edge of WTB segment; (c) Photo of defects with 81 mm and 25 mm diameters on main spar of WTB segment; (d) Photo of defect with 51 mm diameter on main spar of WTB segment



(a) (b) (c)

Fig. 2. (a) Schematic showing the placement of transducers and location of 51 mm defect; (b) B-scan acquired from experimental linear scanning; (c) Phase velocity dispersion curve with the application of 2D-FFT

The variations, scattering or reflections of waves in some part of B-scan (Fig. 2(b)) implies the defect or misalignment in the composite structure. The time of arrival and amplitude variations can also be observed in the defect-free and defective regions. As receiver operates in a thickness mode interested mode for analysis is A0 mode (*out-of-plane*). The two-dimensional fast Fourier transform (2D-FFT) was used to observe the dispersive characteristics (Fig. 2(c)) of the propagating UGW. However, due to mode-mixing or another wave phenomenon, the interested A0 mode is not clear in Fig. 2(c). Hence, the velocity and time of arrival of the A0 wave mode could not be determined. Moreover, the detection of defect was possible from Fig. 2(a) but the location, size, time of arrival and velocity of UGW in the defective and defect-free region cannot be estimated.

2.2. Experimental analysis using Air-coupled transducer pair

The air-couple transducer system (a pair of transmitter-receiver) developed by Ultrasound Institute of Kaunas University of Technology was used to analyze the 15 mm, 25 mm and 81 mm diameter defects in a non-contact manner (Jasinien et al. (2009)). The schematic of experiment is shown in Fig. 3. Both transducers had transduction losses of -66 dB in the air, the centre frequency of 290 kHz, -6 dB bandwidth up to 150 kHz and operated in pitch-catch mode. The transmitter was excited by 700 V, 8-period signal and 200 UGW signals at each 1 mm scanning step were acquired along the distance of 200 mm. Results of this experiment are not presented.

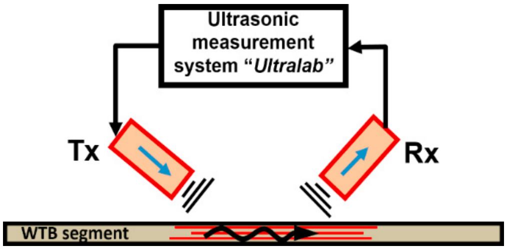
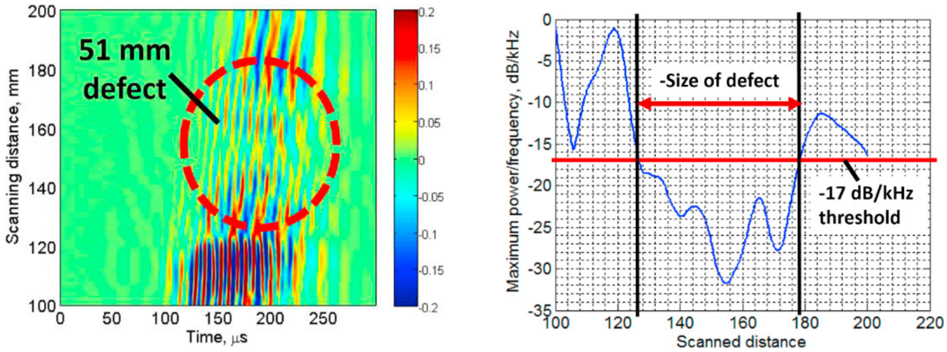


Fig. 3. Schematic of experimental investigation using a pair of air-coupled transducers

4. Results after signal refinement

The determination of size and location of the defect can be possible by removing the structural and coherent noise, mode-mixing and attenuation due to traveled distance. The DWT is applied to remove the structural and non-stationary noise from the experimental B-scan. The DWT-denoised B-scan is presented in Fig. 4(a).



(a) (b)

Fig. 4. (a) Denoised B-scan after DWT; (b) Estimation of size and location of 51 mm defect by comparing maximum power spectral density after compensating the attenuation

The cross-correlation and amplitude detection are very common methods to locate and size the defect. But, it was not possible in our case due to increase in signal attenuation along the distance. Therefore, an alternative approach is proposed for the defect estimation. First the power spectral density of each A-scan signal from denoised B-scan is calculated. Later on, the attenuation coefficient (dB/length) is estimated and multiplied to each A-scan signal depending on the distance. In this way, the problem related to signal attenuation was solved. The variation in maximum power spectral density along the distance is shown in Fig. 4(b). After applying a threshold (-17 dB/kHz) the size of 51 mm was estimated as 54 mm with an error less than 6 %. The location of defect was measured as 126.5 mm with an error less than 1% from the initial position of the receiver.

4. Conclusions

The disbond-type defects with different sizes ranging from 15 mm to 81 mm, located on a segment of WTB, are estimated with contact and air-coupled transducers. The signal processing techniques are combined to improve the accuracy of results. The DWT is used to de-noise each A-scan signal from B-scan after windowing. The signal attenuation is compensated by calculating the attenuation coefficient. The comparison of power spectral density then leads to estimate the size and location of the defect. The characteristics of defects such as time of arrival, phase velocity and variations in instantaneous amplitudes and frequencies are also calculated but the results for the estimation of size and location of only 51 mm defect is presented.

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