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Signal processing methods to improve the Signal-to-noise ratio (SNR) in ultrasonic non-destructive testing of wind turbine blade

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Abstract

Ultrasonic non-destructive testing (NDT) methods are being used quite effectively nowadays, but the multilayered structure of composite materials results in the serious problem in the detection of defects/flaws. The resulting ultrasonic signal is often noisy and denoising of this signal is necessary in order to extract useful information so that faults can be detected, located and sized. Currently, there is a high demand for automatic ultrasonic signal processing techniques to not only remove the need for manual flaw detection and assessment, but also increase the accuracy, reliability and repeatability of the non-destructive evaluation. There are various signal processing techniques which can be used in ultrasonic measurements and selection of appropriate method is one of the major key factors in the field of ultrasonic testing of composite materials. In the presented work, the sample of wind turbine blade (WTB) manufactured using glass fiber reinforced plastic (GFRP) was investigated using ultrasonic NDT in order to estimate the artificially made disbond type defects of 15 mm and 25 mm diameter on the trailing edge. The transmitting and receiving transducers were fixed on movable panel at distance of 50 mm and guided waves (GW) were received at each one millimeter step along the scanning distance of 500 mm. The measurement is performed using low-frequency (LF) ultrasonic system which was developed by Ultrasound Institute of Kaunas University of Technology. Various signal processing techniques were applied to overcome the structural noise and/or extract the information about the defects. The three most promising signal processing techniques: cross-correlation methods, wavelet transform (WT) and Hilbert-Huang (HHT) transform were discussed and compared in the process of defects estimation.

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Keywords: Signal processing, wind turbine blade; ultrasonic NDT; composite; cross-correlation, wavelet transform; Hilbert-Huang transform

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1. Introduction

The WTB is manufactured from the composite materials but in comparison to the metals, composite materials have additional problems like high structural noise and acoustic attenuation in defect detection due to its multi-layered structure as explained by Katunin, Dragan and Dziendzikowski (2015) and Tiwari and Raisutis (2016). The ultrasonic testing process is quite complicated due to the non-homogeneous structure of composite materials makes the ultrasonic testing complicated and that is why high signal-to-noise ratio (SNR) is required to detect the defects and flaws highly grained material. Therefore, Signal processing methods are necessary for the effective ultrasonic non-destructive testing procedure of composite materials such as used in wind turbine blade (WTB). The objective of the signal processing is to extract information from the collected signal to detect flaws and defects. Once the signal has been denoised, proper parameter estimation methods can be used to extract the interested features of the signal for detecting flaws and their severity evaluation.

The aim of the current research is the investigation of a sample of WTB by guided waves (GW) using low-frequency ultrasonic transducers and the application of signal processing techniques to improve the SNR in order to estimate the defects. Section 2 demonstrates the challenges in the inspection of wind turbine blades and the need of signal processing techniques in ultrasonic NDT of wind turbine blades. Experimental analysis has been performed in Section 3 and signal processing techniques have been discussed in Section 4 followed by the conclusion in Section 7.

2. Challenges and complexity in the inspection of wind turbine blades (WTB)

Wind energy is the god-gifted renewable energy resources available in the world. The random nature of wind's force produces varying loads to the wind turbine and due to this, flaws, breakage and damages can exist in any component of WTB, Drewry and Georgiou (2007). Moreover, WTB is more sensitive due to very high stress which may easily lead the damages and defects. Hence, regular maintenance and inspection of the WTB are necessary to avoid any system failure as explained by Juengert and Grosse (2009), Schmidt et al. (2012) and Tippmann, Manohar and Lanza di Scalea (2012). There are a number of non-destructive testing methods which can be used to assess the quality of materials used in the manufacturing process of WTB (Amenabar et al., 2011). However, it is described by Lambert et al. (2012) that the dimension and complexity of WTB and limitation in applicability and accuracy of some methods makes them unsuitable for the on-site inspection of WTB. Although, the cold regions are the best installation sites for wind turbines due to greater air-density and higher wind speed, Parent and Ilinca (2011) but icing conditions in these regions create various problems such as failure due to ice loading on blades, problems in air-foil shape and undesired vibrations as explained by Virk, Homola and Nicklasson (2010).

There are two key composite materials which are used to manufacture the wind turbine blade: Carbon fibre reinforced plastics (CFRP) and Glass fiber reinforced plastics (GFRP) and among the all available NDT testing methods, ultrasonic testing is extensively used for the inspection of these materials, Diamanti, Soutis and Hodgkinson (2005), Raišutis, Jasiuniene, and Zukauskas (2016), Rao (2007) and Lee et al. (2010). Ultrasonic NDT of GFRP with automatic 2D ultrasonic scanning system was also developed by Ye et al. (2014) for the purpose of in-situ wind turbine blades inspection. Even there is a limitation of noncontact ultrasonic methods as compared to the conventional ultrasound method due to the layered material and thick size, it can still be used in the testing and analysis of wind turbine blades to cover the large surface of the blade Steigmann et al. (2016). It was analysed by Gomez and Garcia (2016) that three MFCs glued on wind turbine blades are enough for the effective analysis of breakage. However, testing of WTB is still quite complex and challenging because of its composite and thick structure, one side access etc. Therefore, more innovation and research is required in this field. The accuracy of WTB testing depends on the various factors including the type of composite material, the sensitivity of the transducers, environmental noise, false signals due to impacts on the piece etc. and needs to be increased by applying appropriate signal processing techniques.

3. Experimental investigation of WTB

The ultrasonic GW testing of a sample of WTB is performed in order to analyse the disbond type defects of 25 mm and 15 mm diameter located on the trailing edge of the wind turbine blade. The first defect of 25 mm diameter was at the distance of 90 mm and the second defect of 15 mm diameter was at the distance of 445 mm from the tip end of blade sample. The main task is the exploitation of the GW properties but the complexity associated due to the multimodal effects of the propagating modes, it is difficult to extract the required signal. The interaction of A0 mode and some other modes with the structure along the path of propagating wave make it possible for the detection of defects. Two point type contact transducers are used as a transmitter and receiver respectively. The transmitting and receiving transducers were mounted on the same moving unit with a fixed distance of 50 mm and they were acoustically insulated from the housing as well in order to avoid any effect of acoustic cross-talk. Both point type transducers used in the experiment had 6 dB bandwidth up to 300 kHz and convex protectors were used on the active surface as explained and described by Vladišauskas et al. (2009), Vladišauskas et al. (2009a), Vladišauskas et al. (2009b). The schematic of contact type transducers and WTB sample is presented in Fig.1. The transmitter generates several GW modes and after propagating through the multilayered composite part of WTB, they are received by the receiver. The defects or inhomogeneities in the structure will alter the characteristics of some modes which in turn affects the waveform of received signal.

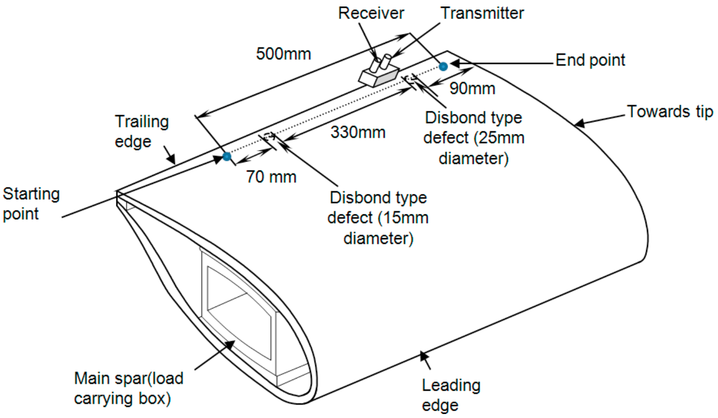
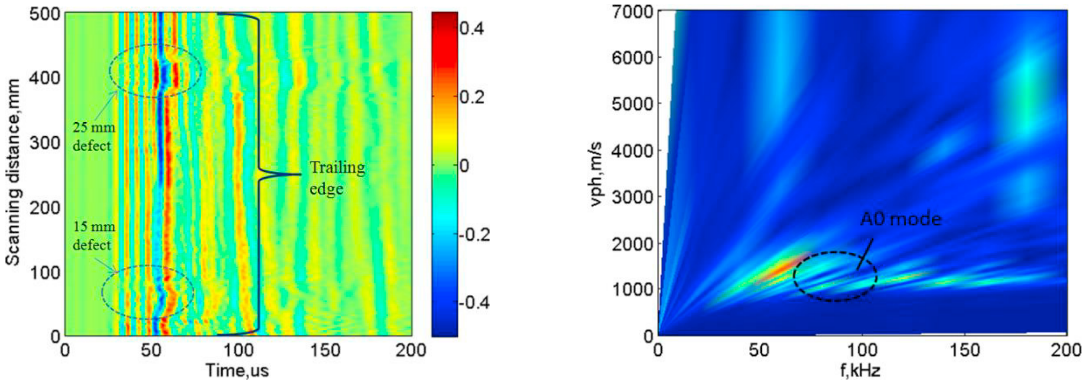


Fig. 1. Showing the schematic of WTB sample with disbond type defects of 15 mm and 90 mm diameter and the contact type transducers (transmitter and a receiver)

The experiments were performed using a low-frequency ultrasonic measurement system and all components of the experiment set-up were developed at the Ultrasound Institute of Kaunas University of Technology, Lithuania. The transmitter was excited by a single pulse of 250 V, 150 kHz. The starting and end points of measurement process are at the distance of 530 mm and 30 mm respectively from the tip end of WTB. The scanning step was 1mm along the surface of the WTB sample, up to the distance of 500 mm. The glycerol was used as a coupling medium in order to obtain the uniform acoustic contact between the convex surfaces of the ultrasonic transducers and the WTB sample. At each scanning position, the received ultrasonic signals were averaged (number of averaging eight) and stored for further analysis. The B-scan along the scanning distance x (0 to 500 mm) *w.r.t.* time t (0 to 200 μs) is generated in MATLAB and shown in Fig. 2(a).

Both type of defects i.e. defects of 15 mm diameter and 25 mm diameter can be clearly observed in Fig.2 (a) as the alteration or scattering of signals occurred in those regions. In order to generate dispersion curve for the verification of phase velocity, the linear scanning of one of the contact type transducers (receiver) was performed while keeping the other transducer (transmitter) fixed at one point. During this experiment, the receiver was scanned away from the transmitter with a scanning step of 0.5mm along the surface of the sample, up to the distance of 200 mm. The transmitter was excited by a three period burst of 150 kHz. In order to generate the dispersion curve, the resulting B-scan is then processed using two-dimensional fast Fourier transform (2D FFT) as suggested by Su, Ye, and Lu (2006) and Alleyne and Cawley (1991). The dispersion curve is shown in Fig.2 (b) and the asymmetric A0 mode is clearly observed with the approximated phase velocity of 1000 m/s. Hence the approximated arrival time is 20 μ-secs which confirms that the raw B-scan shown in Fig. 2(a) depicts the dominant

A0 mode for the detection of defects. In the next chapter, the signal processing techniques will be used in order to improve the SNR which will lead to analyse the defects in more precise and accurate manner.



(a) (b)

Fig. 2. Raw B-scan image along the scanning distance of 500mm showing the internal artificially made disbond type defects, with the diameter of 15 mm and 25 mm (a), dispersion curve showing dominant A0 mode with the approximated phase velocity 1000 m/sec at 150 kHz.

4. Signal processing in ultrasonic NDT

The important tasks in the NDT of composites are the detection of reflected ultrasonic signal coming through defects and covered by structural noise, detection of scattered ultrasonic signals and determine the ways to improve the spatial resolution in case of multiple reflections. The various signal processing techniques are available to perform these tasks and to improve the accuracy of the defect estimation and characterization in NDT and SHM applications. These techniques are cross-correlation, Hilbert Transform (HT), autoregressive analysis, wavelet transform (WT) etc. The described ultrasonic signals processing methods are used in different areas of NDT of materials. There are some merits and limitations associated with each type of method. Hence, for the NDT of composite structures with structural noise, high attenuation and scattering of waves, it is necessary to choose the appropriate method or develop the new signal processing technique as per requirement.

The most common signal processing methods based on the literature, experiments and research work are discussed by Varghese et al. (1996), Abbate et al. (1997), Shankar et al. (1989), Mallett et al. (2007), Bouden et al. (2009), Iyer et al. (2012) and Raišutis et al. (2008). Due to the availability of these techniques, it is possible to analyze the signals in time domain, frequency domain or in both.

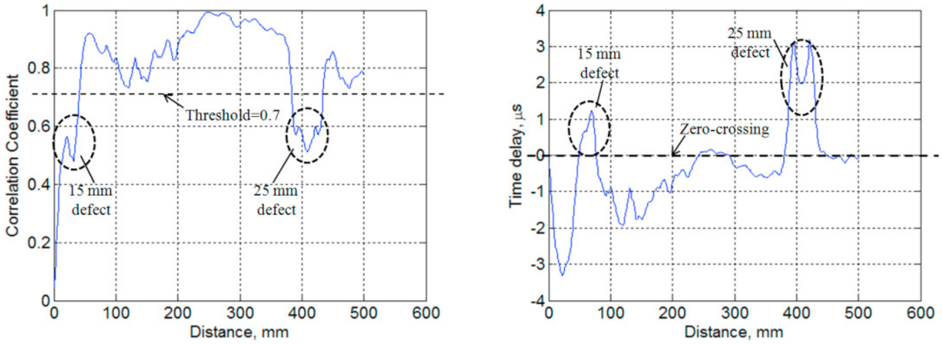
4.1. Analysis of defects using cross-correlation

The cross-correlation of two signals depicts the degree of similarity between them. If the two signals show the greatest similarity, the output of the cross-correlation operation will be maximum corresponds to that point and the *vice-versa*. This technique could be used to compare the received signal with the reference signal in long range ultrasonic testing (LRUT) and could possibly extract the information from dispersive wave modes or the change in signal waveform due to delay and scattering. If $x_1[n]$ and $x_2[n]$ are the two discrete signals, the cross-correlation function will be defined by Oppenheim, and Schafer (1989):

$$y[n] = \sum_{k=-\infty}^{\infty} x_1[k] \cdot x_2[k+n] \tag{1}$$

- In the first step of the analysis, normalised cross-correlation coefficients were estimated by applying the cross-correlation between the reference signal acquired at defect-free region and all signals up to the full scan length of 500 mm. The defect-free A-scan signal is calculated by taking the average value of B-scan in the region between 200 mm and 300 mm. In order to remove the noise and distortion, the 10-point moving average filter is applied to the resulting signal and shown in Fig. 3(a). A simple threshold can be applied to the resulting signal in order to detect the defects. A choice of detection threshold is chosen as a balance between false calls and missed defects. The value of the threshold is chosen here is 0.7 and both defects having the correlation coefficient below the threshold can be clearly observed in Fig. 3(a).

- During the second step, the cross-correlation along with 10-point moving average filter is used in order to estimate the delay time between times of flights between the defect-free A-scan signal to the all averaged A-scans along the scanning distance as shown in Fig.3(b). Considering the zero-crossing as a reference, defected region is showing more delay. The maximum delay in 15 mm and 25 mm defected region was observed as 1.1 µs and 3.1 µs respectively.

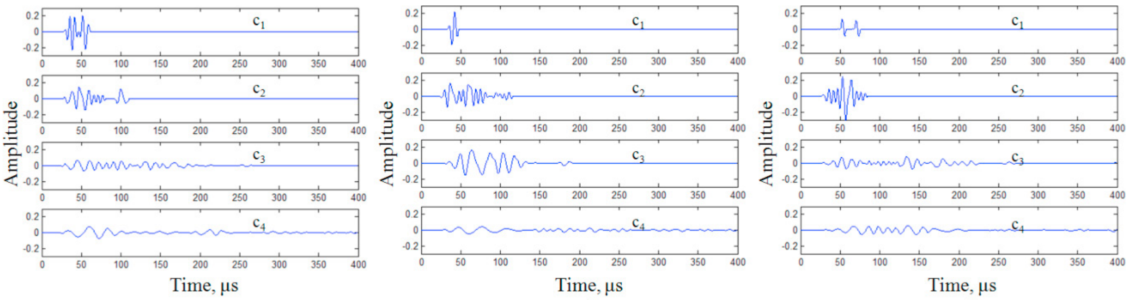


(a) (b)

Fig. 3. Defect estimation using cross-correlation: showing correlation coefficient along the scanning distance of 500 mm (a), Time delay of all signals along the scanning distance of 500mm *w.r.t.* defect-free signal (b)

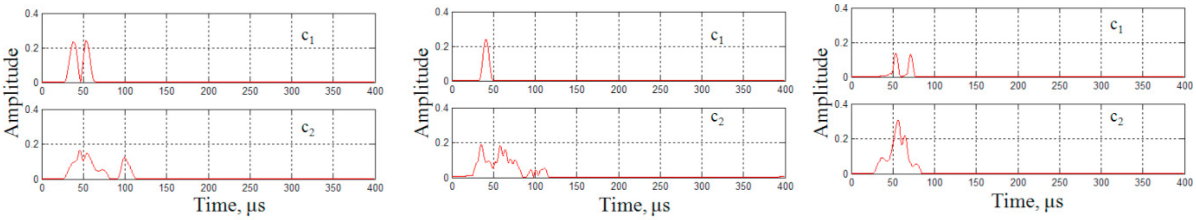
4.2. Analysis of defects using Hilbert Haung Transform(HHT)

The HHT proposed by Huang et al. (1998) is the combination of two signal processing techniques: Hilbert transform (HT) and empirical mode decomposition (EMD).First, the EMD decomposes the analysed signal into the various intrinsic mode functions (IMFs) and then individual frequencies are calculated using HT. The decomposed ultrasonic signal can be represented as the local energy or amplitude distribution in the time-frequency plane. This distribution differs for the defect-free and defected regions which in turn enable to extract the information about the defects for the further processing. As compared to the Fourier transform (FT) and wavelet transform (WT), the HHT is adaptive and can be used for non-linear and transient signals. The various research analysis by Kazys, Tumsys and Pagodinas (2008), Li, Wang and Xi (2013), Liu et al. (2015) and Haung and Wang (2016) suggests that HHT is among the best signal processing methods in NDT testing. The defect-free and defective regions are chosen from the B-scan (Fig. 2(a)) and after averaging; the A-scans of defect-free, 15 mm defective region and 25 mm defective regions are generated. The next step is the decomposition of each A-scan into Hilbert-Huang IMFs. The first four IMFs (c_1 to c_4) for defect-free and defective regions are shown in Fig.4. The analysis of first four IMFs confirms that first two IMFs have a higher amplitude as compared to others and defect information in time –domain is concentrated in these two modes only which also contains less noise and dispersion. The instantaneous amplitudes of first two modes for defect-free and defective regions are estimated using Hilbert transform and shown in Fig. 5. The defects are clearly visible in Fig.5 (b) and 5(c) as received signal differs as compared to Fig.5 (a). Also the approximate time of arrival of first IMF of the defect-free signal, 15mm defective signal and 25 mm defective signals are 27 µs, 33 µs and 41 µs respectively. By plotting the Hilbert-Huang spectrum of the sum of two IMFs in the 3D plot can give the more clear view of defect size and estimation.



(a) (b) (c)

Fig. 4. Intrinsic modes by decomposition: showing four intrinsic modes (c_1 to c_4) of defect-free signal (a), 15 mm defective signal (b) and 25 mm defective signal (c)

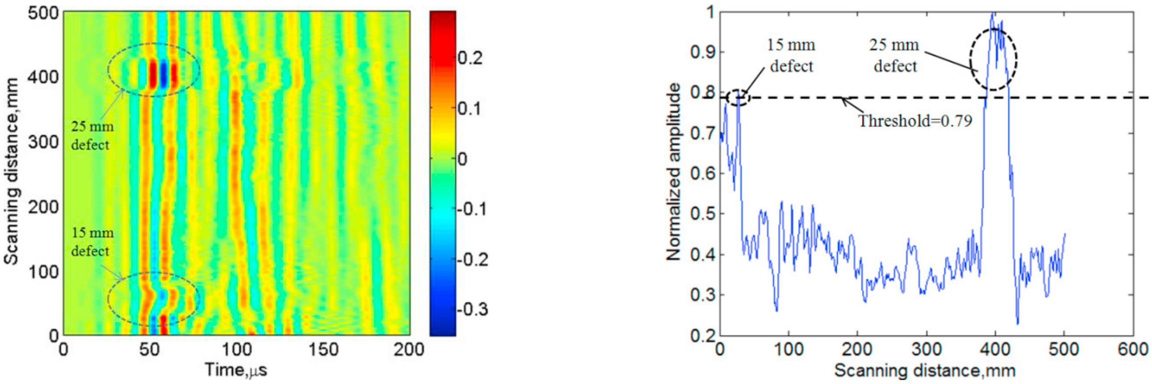


(a) (b) (c)

Fig. 5. Instantaneous amplitudes of first two IMFs (c1 and c2) using Hilbert transform: defect-free signal (a), 15 mm defective signal (b) and 25 mm defective signal (c)

4.3. Analysis of defects using wavelet transform(WT)

One of the most widely used methods for the noise suppression from the signals in order to improve the accuracy of defect estimation is the discrete wavelet transform (WT) as explained by Rodríguez et al. (2004), Vermaak, Nsengiyumva and Luwes (2016) and Yu and Wang (2016). The basic principle is the decomposition of signals into the elementary signals which are called as wavelets and each wavelet coefficient contains signal and noise in the time-frequency domain.



(a) (b)

Fig. 6. Signal processing using DWT: Processed B-scan image of detailed signal at level 8 using Daubechies wavelet (db16) (a), showing the marginal detection of 15 mm and full detection of 25 mm defect using amplitude detection by considering the threshold value of 0.79

By manipulating the wavelet coefficients, the noise effect can be reduced and the most promising way for selecting and discarding the wavelet coefficients is by using the soft or hard threshold method, Mallat (1989) and Lazaro et.al. (2002).But this way is not efficient in the case of correlated noise. We propose to use the discrete wavelet transform (DWT) using the Daubechies wavelet (db16) to decompose the each A-scan signal into the 8 levels. After analysis, it is found that detailed signals of each A-scan at level 8 contain the minimum noise. Finally, the B-scan is regenerated by considering all the detailed signals at level-8 as shown in Fig. 6 (a). It can be clearly observed that processed B-scan has minimum noise effects as compared to the raw B-scan shown in Fig. 2(a). After setting the threshold value of 0.7 in amplitude detection method, the 25 mm defect can be easily detected but 15 mm defect is marginally detected as shown in Fig. 6(b).

5. Conclusions

The defect detection in the composite materials by ultrasonic GW testing has become a tedious task in the presence of structural noise, and due to dispersion, reflection and scattering of signals. In this paper, three signal processing techniques namely Cross-correlation, Hilbert Haung transform and wavelet transform have been studied in order to improve the detection of disbond type defects in wind turbine blades.

Cross-correlation is the easiest way of signal processing but it is not an efficient in order to reduce the noise. As the noise or signal may be of same amplitude in the same frequency range and it would be impossible to distinguish between them. The Hilbert Haung transform considers the selection of intrinsic modes and application of Hilbert-transform to these modes. Most of the information is contained in the first few modes. The HHT is an efficient method but it is limited by the selection of intrinsic modes as the selection depends on the signals to be analysed. The wavelet transform improves the signal to noise ratio in our case and 25 mm defect is detected completely but 15 mm defect is only marginally detected. In order to improve the detection in the presence of correlated noise, the hybrid method which may combine the different signal processing, is recommended.

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