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Investigation of Diffuse Lamb Wave Sensitivity to the Through-Thickness Notch in Structural Health Monitoring of Composite Objects

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***Abstract*—Modern engineering constructions are made from various kinds of multi-layered composites. Due to safety and economic reasons such objects should be monitored in order to detect the originating defects. Ultrasonic guided waves are very powerful inspection technique, due to ability to propagate long distances and sensitivity to the non-homogeneities. However due to multimodal, dispersive and environmental sensitive character the detection of defects using guided waves is complicated and requires advanced signal processing techniques. In this paper two signal processing techniques for detection of the originating defects with diffused Lamb waves was proposed and experimentally verified detecting the through-thickness notch type defects in GRFP plate.**

***Index Terms*—Composite materials, condition monitoring, Lamb waves, non-destructive testing, numerical simulation.**

I. INTRODUCTION

Various composite materials are widely used in aerospace, renewable energy sector and other modern engineering constructions, due to good mechanical properties. However daily operational conditions, fatigue, leads to the risk of failure, so the key components of such constructions should be monitored permanently or periodically. The Lamb waves are one of the most powerful tools for condition monitoring of engineering constructions, because of its ability to propagate long distances and sensitivity both to the internal and the surface defects [1]. One of the major advantages of the Lamb waves is that they enable to inspect large structures from single transducer position, so various kinds of defects can be detected even in the inaccessible areas [2].

On the other hand the Lamb waves possess multimodal, dispersive and environmental sensitive character, so defect detection is often confusing and requires understanding of the wave's propagation phenomenon. The plenty of researchers are investigating Lamb wave interaction with holes [3], [4], delaminations [5], [6] and notches [7]–[9]. However, most of the studies are concerned about the interaction between the fundamental Lamb wave modes and various discontinuities, whereas the effect of the defects on diffuse Lamb waves [10] have not been widely investigated. The excitation of the one particular Lamb wave mode in real environment seems to be challenging task. Typically, the ultrasonic transducers, such as macro-fiber composites (MFC) [10], excites several guided wave modes in particular frequency domain, which after propagation together with reflected and mode converted waves creates diffuse ultrasonic field. The key question is whether the originating defects can be reliably detected by measurement of the diffuse ultrasonic waves or not. In addition, there are also many works devoted to detection of defects using the transducer arrays, which provides a good spatial coverage and sensitivity [12]–[14], however how the diffuse Lamb waves are sensitive to various defects using small number of sensors is the question still to be answered.

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Therefore, the purpose of this paper is to analyse how the diffuse Lamb waves are influenced by various sizes of through-thickness notch type defects and to investigate the defect detection capabilities using small number of sensors.

II. EXPERIMENTAL INVESTIGATION

A. *Object under Investigation*

To investigate how the through-thickness notch type defect affects the diffuse Lamb waves, a complex shape 8-ply $[0/90]_{2s}$ glass-fiber reinforced plastic (GFRP) laminate with dimensions of (775 mm × 70 mm × 4 mm) was selected. The graphical representation of the object under investigation is presented in Fig. 1.

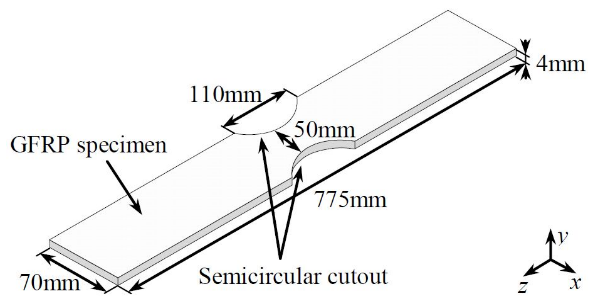

Fig. 1. Schematic view of the GFRP plate under investigation.

In order to determine the regularities of Lamb waves propagation in GFRP plate, the phase and group velocity dispersion curves were calculated using semi analytical finite element (SAFE) technique, described in [15], [16]. The dispersion curves were calculated for a 4mm thickness infinite GFRP plate. The cuts were not taken into account.

The calculated phase and group velocity dispersion curves are presented in Fig. 2.

The simulation results (Fig. 2) demonstrated that all fundamental modes propagate in rectangular GFRP plate in the frequency band up to about 30 kHz. The results also showed that above the 30 kHz frequency, the higher order S_{10} mode can propagate. The two indices here correspond to distribution of particle displacement in the propagating waves along *x* and *y* axis respectively. In this case the S_{10} mode along *x* axis has particle displacement distribution similar to S_1 mode and along *y* axis – similar to S_0 mode. From the results it follows that the optimal excitation frequency in such plate should be nearly 80 kHz, where the character of all modes is almost non-dispersive (Fig. 2).

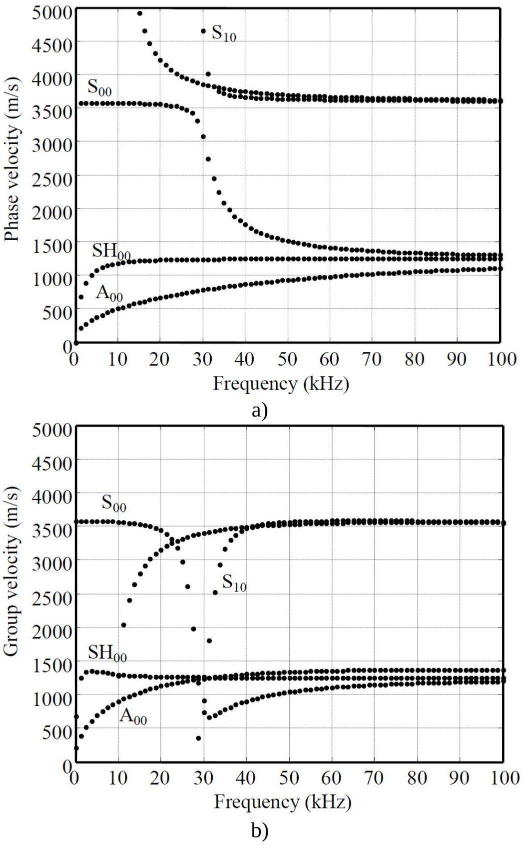

Fig. 2. Theoretically obtained phase (a) and group (b) velocity dispersion curves on the 8-ply $[0/90]_{2s}$ GFRP laminate sample.

B. Experimental Set-up

Two independent experiments were carried out to investigate interaction of the diffuse Lamb waves with through-thickness notch type defect in GFRP plate. For both experiments, the same GFRP plates, described in previous section were used. Each of the experiment was carried in the following order:

– *Case #1.* In the first experiment the through-thickness notch of width 0.5 mm was cut across the side edge of the plate at the distance to 130 mm from the transmitter (Fig. 3). The length of the notch was ranging from 1 mm to 30 mm with step 1 mm. At each notch increment the signals were recorded.

– *Case #2.* The second experiment retained the same set-up, except that the through-thickness notch was introduced 70 mm behind the receiver (Fig. 3). The key question in this case was to find out whether the notch outside the line between transmitter and receiver can be detected or not.

The experimental investigation was performed using low frequency ultrasonic measurement system "*Ultralab*", developed at Ultrasound Institute, Kaunas University of Technology. The pair of the MFC transducers was bonded to specimen using a thin wax layer at the positions shown in Fig. 3. In both cases only two transducers (one transmitter and one receiver) were used, to investigate spatial coverage and sensitivity to defects. The transmitting transducer was driven with a 1 cycle, 20 V tone burst with central frequency of 80 kHz. The waveforms were recorded using 25 MHz sampling frequency. The duration of the each recorded signal was 1 ms. To ensure better signal to noise ratio the averaging of 8 times was used. The signal recorded on the plate without the notch was used as reference in comparisons. The duration of the experiments was relatively short, so the influence of temperature was neglected.

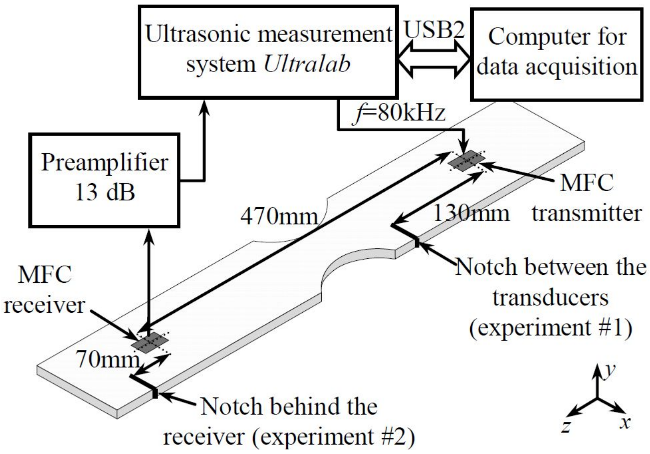

Fig. 3. Layout of the experimental system for investigation of diffuse Lamb waves sensitivity to the through-thickness notch type defect.

III. Proposed Methods for the Detection of the Originating Defects

In order to detect defects in structural health monitoring systems, the reference signal is usually subtracted from the current signal and the residual amplitude is evaluated. Ideally such subtraction enables to eliminate the direct and reflected signals from the structural features, so the residual signal contains the information about the changes caused by the defects. However in this case to detect the defects reliably, the amplitude of the residual signal should be not less than –40 dB in comparison to the amplitude of the first arrival [17]. To ensure better sensitivity two different techniques were proposed. Let's assume that there are two waveforms $u_R(t)$ and $u_D(t)$, which describes the undamaged and damaged state respectively. The first technique is based on the calculation of the maximum of the cross-correlation function in short time window:

$$x(\tau_C) = \frac{\sum_{t=-\Delta\tau}^{\Delta\tau} u_{RL}(t) \cdot u_{DL}(\tau_C - t)}{\sqrt{k_1 \cdot k_2}}, \tag{1}$$

$$k_1 = \sum_t u_{RL}(t) \cdot u_{RL}(t), \tag{2}$$

$$k_2 = \sum_t u_{DL}(t) \cdot u_{DL}(t), \qquad (3)$$

where $u_{RL}(t) = u_R(t) \cdot u_L(t - \tau)$, $u_{DL}(t) = u_D(t) \cdot u_L(t - \tau)$ describes windowed waveforms obtained from undamaged and damaged state respectively, $\tau = 0 \div (t_m - \Delta\tau)$ is the shift of the time window, t_m is the total duration of the analysed signal, $\Delta\tau$ is the width of the time window, $u_L(t)$ is the window function. This technique enables to indicate the changes of the waveforms over the time; however it is not sensitive to the changes in the amplitudes of the signals and small shifts in time domain. In order to detect the variations of the amplitudes, it was proposed to calculate the ratio of cross-correlation normalization coefficients: $y(\tau_C) = k_2/k_1$.

IV. Results and Discussion

The Fig. 4 and Fig. 5 shows plots obtained using both techniques for the case #1 and case #2 of the experiments. Due to large amount of data the results are presented for the notches with length 10 mm and 30 mm only.The sensitivity to the defects in the case of first technique strongly depends on the width of the selected time window, so the optimal parameters should be considered regarding to the obtained results. In this case the width of the time window was set equal to 5 periods of the excitation signal (80 kHz, the duration of the cycle is 12.5 µs).

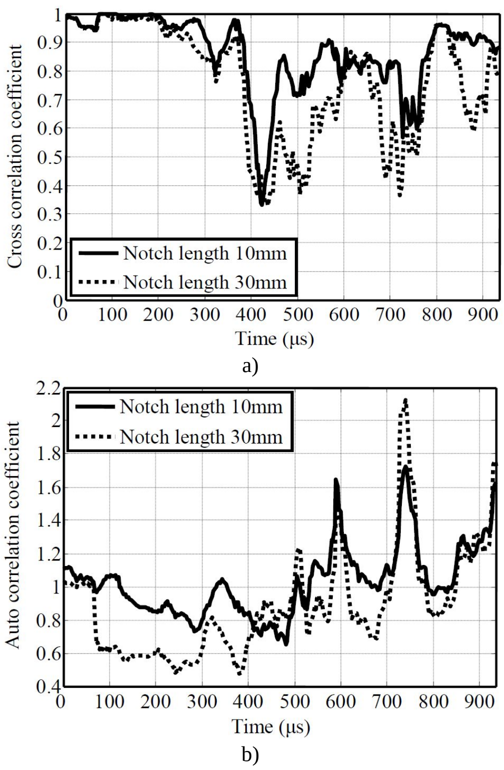

Fig. 4. The cross-correlation (a) and the auto-correlation (b) distribution over time in the case #1 experiment (the notch is between the transducers).

In the case of absence of the defects these methods should give the values equal to 1. If there are changes in the signal caused by the originating defect this value should be reduced due to reduction of correlation between the signals.

From the results (Fig. 4 and Fig. 5) follows that the time interval in the waveform which is mostly affected by the defect depends on the location of the notch. In the case #1 experiment, the major changes of the waveform can be observed at earlier time instances in comparison to the case #2 experiments when the notch is behind the receiver.

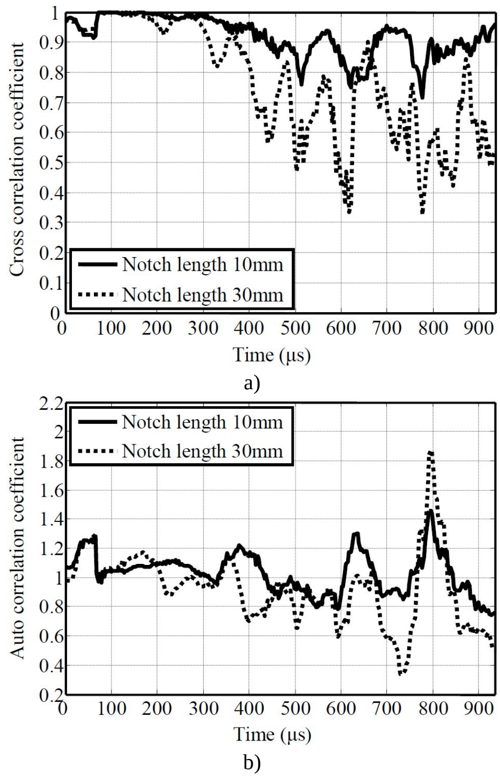

Fig. 5. The cross-correlation (a) and the auto-correlation (b) distribution over time in the case #2 experiment (the notch is behind the receiver).

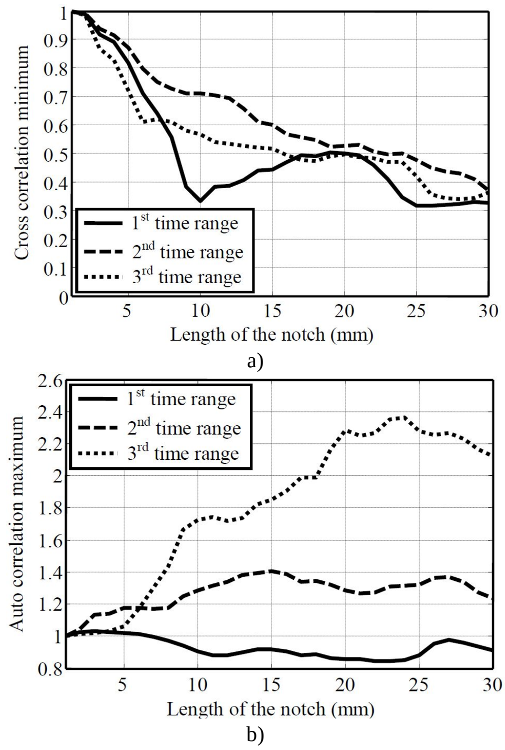

Fig. 6. Relationship between the cross-correlation minimum (a), the auto-correlation maximum (b) and the length of the notch in the case #1 experiment (the notch is between the transducers).

However, in both cases the major changes are noticeable at later time instances so the sensitivity to the development of the defects seems to be increasing when larger time domain of the signal containing multiple reflections is analysed. The comparison of the amplitude demonstrated that the diffuse Lamb waves are slightly more sensitive to the notch in the direct path, however the similar character was obtained for both defect locations.

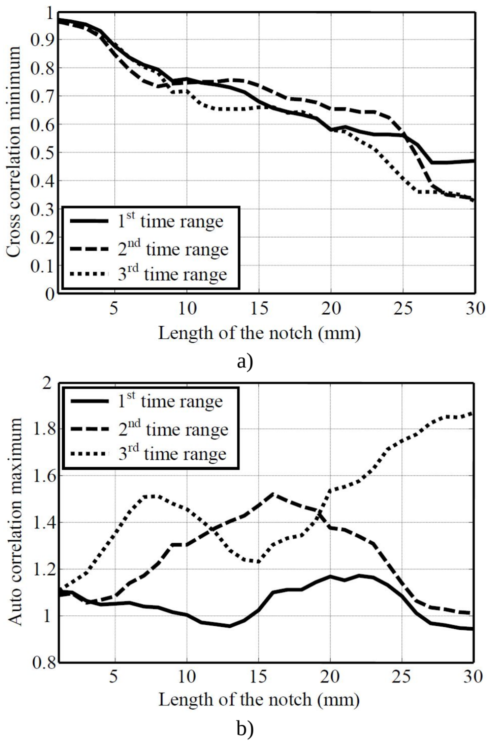

Fig. 7. Relationship between the cross-correlation minimum (a), the auto-correlation maximum (b) and the length of the notch in the case #2 experiment (the notch is behind the receiver).

In Fig. 4 and Fig. 5, the extremums of functions $x(\tau_C)$ and $y(\tau_C)$ are in the time intervals at which waveforms are mostly affected by the defects. So, the most reasonable is to monitor the time intervals that are most sensitive to the structural changes. Therefore the extremum values of functions $x(\tau_C)$ and $y(\tau_C)$ corresponding to several time intervals were selected for each case of the defect size and the obtained dependencies are presented in Fig. 6 and Fig. 7.

As can be seen in the case #1 experiment the mismatch of the shape drops to –6 dB and amplitude increases up to 6 dB when the length of the notch reaches 8 mm. In the case #2 experiment the similar regularities are obtained at the notch length of 15 mm. It can be observed that proposed methods enable to detect defects of the size comparable to the wavelength of S_{00} and A_{00} modes (λ_{S00} = 16.7 mm, λ_{A0} = 13.13 mm) and half wavelength of the fastest mode (λ_{S10} = 45.2 mm).

V. CONCLUSIONS

The investigations demonstrated that the influence of the small originating defects on reflected and transmitted signals is not strong and detection of it requires quite sensitive signal processing techniques. Two signal processing techniques for detection of originating defects was proposed. It was demonstrated that using the proposed methods, the defects which are comparable to half wavelength of the fastest mode (8 mm ÷ 15 mm) can be reliably detected. It was observed also that sensitivity to the development of the defects increases when larger time domain of the signal containing multiple reflections is analysed.

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