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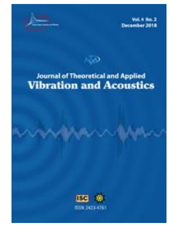

Experimental and numerical study of delamination detection in a WGF/epoxy composite plate using ultrasonic guided waves and signal processing tools

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ABSTRACT

Reliable damage detection is one of the most critical tasks in composite plate structures. Ultrasonic guided waves are acknowledged as an effective way of structural health monitoring (SHM). In this research, ABAQUS FE package is employed in order to develop a 3D finite element (FE) model to investigate the wave propagating features in a four-layer Woven Glass fiber (WGF) /epoxy composite plate. Dispersion curves have been extracted using semi-analytical finite element (SAFEM) in MATLAB. An experimental study has been done to obtain the sensitivity of the excitation frequency on the delamination detection problem. The Fast Fourier Transform (FFT), Butterworth filtering and the Continuous Wavelet Transform (CWT) signal processing methods have been utilized to extract a more accurate damage sensitive feature from experimental signals. Calculations of amplitude reduction ratio (ARR) for both raw and filtered signals shows that increasing the excitation frequency, which means decreasing the wavelength, leads to increase in the ARR in an approximately linear manner for raw signals, while using the filtered signals for ARR extraction yields higher ARR, peaked at the tuned Lamb mode, which is F=330 kHz in the study. The Butterworth filtering provides larger damage sensitive feature compared to CWT method. Consequently, the ARR is a reliable and enough sensitive feature for delamination detection in composite plates, especially when extracted from filtered signals.

1. Introduction

Regarding the beneficial parameters of composite materials properties, composite structures have been employed in many industries, especially in the high technology industries.[1]. However, these parts might be broken or out of service by different types of damages, some of which are

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matrix cracking, fiber breakage and delamination[2]. Meanwhile, As it is hard to detect most of these damages at early stages of initiation, it is crucial to detect them before happening of catastrophes[3, 4]. Non-Destructive Testing (NDT) methods are wildly recognized as one the most promising methods for evaluation and testing the healthiness of industrial systems.[5]
Structural Health Monitoring (SHM) has been utilized to evaluate integrity and safety of the structure being monitored since recent decades. Guided Ultrasonic Waves, GUW, as one of the most reliable tools for SHM has been employed widely, for several plate like structures inspection, including vessels, wings, pipes and other structures made from composite panels. There have been various numerical and analytical methods to capture and investigate the guided wave propagation in composite structures[6]. Knopoff (1964) developed the global matrix (GM) formulation in which the matrix has be composed of 4(n−1) equations, where n is the total number of layers.[7, 8] Lagasse (1973) introduced the Semi-Analytical Finite Element method (SAFE) to capture guided wave propagation. The guided wave cross section is discretized with finite elements and an analytical solution is assumed in the wave propagation direction[9]. Yu *et. al.* (2017) explored the possibility of employing ultrasonic Feature Guided Waves (FGW) for fast screening of an special type of 90^0 bends[2].
Mall in 2016 observed changes in the phase and group velocities of the fundamental anti-symmetric wave mode in a composite structure with linearly varying thickness[10]. Sohn et al.[11] detected a delamination in a specific composite plate using guided wave field image processing. Yelve et al. [12] also investigated a delamination in composite laminate based on a Lamb wave nonlinear method. Fucai Li et al. [13] implemented various optic sensors and excited guided waves in a composite laminate. In order to find a novel index for damage detection, a linear-phase finite impulse response (FIR) filter and Hilbert transform have been employed. Many authors [14-17] have focused on several aspects of ultrasonic guided waves inspection methods in composite materials in order to extract suitable features related to damages.

In this paper, an experimental as well as numerical study is carried out to detect a predefined delamination in a four layered WGF/epoxy composite plate followed by wavelet signals processing for proper feature extraction. A 3-dimension finite element model has been built to capture the GW propagating in an 8-layer composite plate in order to detect the dominant mode. Simulation results are utilized to verify result obtained in the experiment, which will be discussed further more.

2. Guided wave in composite laminates

Based on Horace Lamb investigations, Lamb waves are known as the waves which can propagate in thin plates while there are free parallel boundaries [18]. Using the equation of motion, we will be able to study the Lamb wave behavior for an isotropic media. By considering the Helmholtz decomposition, there would be a separated symmetric (S) and anti-symmetric (A) Lamb wave equation as below [10]:

$$\frac{tan(qh)}{tan(ph)} = -\frac{4pqk^2}{(q^2-k^2)^2} \qquad \text{Symmetric Lamb wave} \tag{1}$$

$$\frac{tan(qh)}{tan(ph)} = -\frac{(q^2-k^2)^2}{4pqk^2} \qquad \text{Anti-Symmetric Lamb wave} \tag{2}$$

where $p^2 = \left(\frac{\omega}{C_L}\right)^2 - k^2$, $q^2 = \left(\frac{\omega}{C_T}\right)^2 - k^2$ and ω refers to angular frequency, K is the wave number and C_T, C_L are the transverse and longitudinal wave velocities[18].

It worth mentioning that the GM behavior depends on not only mentioned parameters but also their interface properties. SAFE method will be introduced to describe the way of extracting dispersion curves of a laminated composite. The algorithm of derivation has been done in MATLAB environment. An eigenvalue problem at a special frequency will be solved to find the wavenumbers along the propagation direction[19]. For the problem of guided wave propagation in a plate, a one-dimensional discretization across the plate thickness is sufficient. The coordinate system and the finite element discretization for the SAFE calculation are shown in (Fig 1), where ξ is the variable in the local coordinate system for the element itself. For a given point in the local coordinate described by ξ, the global coordinate of the point can be calculated from the global coordinates of the three nodes (Z1, Z2, and Z3). Combining the time harmonic assumption and the finite element discretization, one can write the particle displacements of any point in an element. Finally finding the eigenvalue of equation (3) leads to discover phase velocity in plate, where the expressions for M, K_{11} , K_{12} , K_{21} ,and $K_{22}$are expressed in [18]. Dispersion curves of the specific WGF/epoxy composite plate is shown in (Fig2). It must be noted that as the material properties are the same for 1 and 2 direction of composite lamina, dispersion curves are also the same.

$$\left(\begin{bmatrix} 0 & K_{11} - \omega^2 M \\ K_{11} - \omega^2 M & i(K_{12} - K_{21}) \end{bmatrix} - k\begin{bmatrix} K_{11} - \omega^2 M & 0 \\ 0 & -K_{22} \end{bmatrix}\right)\begin{bmatrix} U_0 \\ kU_0 \end{bmatrix} = 0 \tag{3}$$

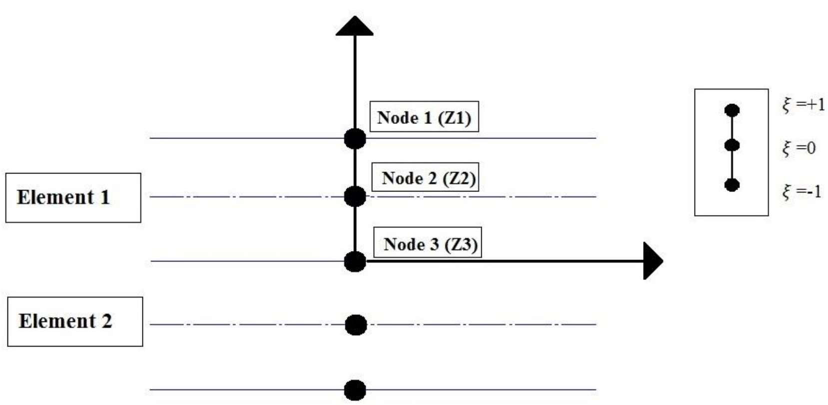

Fig 1:The coordinate system and the finite element discretization for the problem of wave propagation in plate

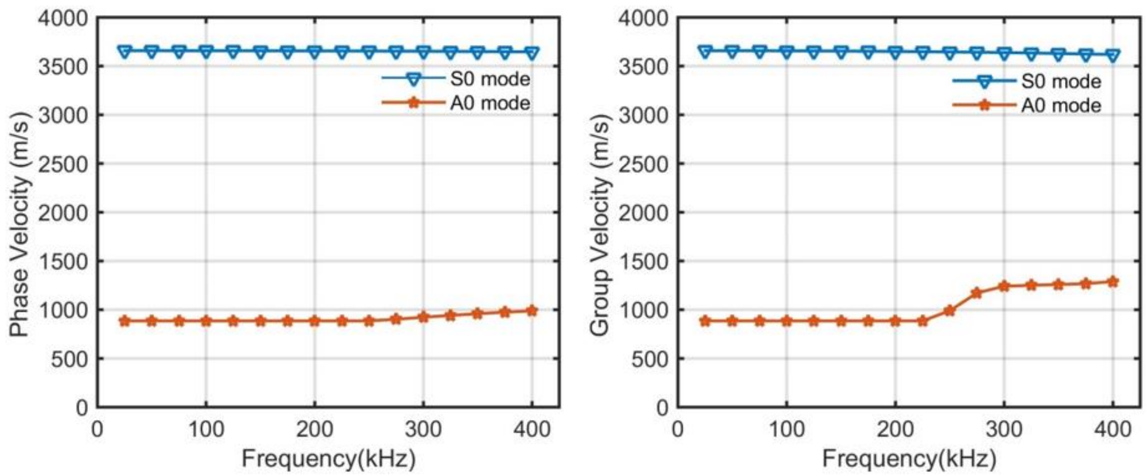

Fig2: Dispersion curves of the specific WGF/epoxy composite plate in 1 and 2 directions.

Table 1:Wavelength and Group Velocity of selected frequencies

Frequency (kHz)	240	270	300	330	370	400
Wavelength (mm)	13.402	13.285	12.175	11.234	10.428	9.729
Group Velocity (km/s)	3.654	3.653	3.652	3.651	3.649	3.646

The fundamental symmetric (S) and anti-symmetric (A) modes phase and group velocities are given in (Fig2). The curves indicate the non-dispersive area which is less than 400 kHz. Based on result of dispersion curve, the excitation frequency range has been selected from 240 kHz to 400 kHz, which is shown in (Table 1). It worth mentioning that selection of frequency from non-dispersive area ease the post processing.

3. Finite Element simulation

Because of unreachable theoretical solutions for Lamb wave tuning in composite plates, most of the recent researches recommend FE method to study Lamb wave propagating characteristics in composite laminates. The goal of such a simulation is to look for the dominant Lamb mode which is excited by the actuator. In this work, the FE simulation is conducted by using the commercial FE package, ABAQUS.

Table2:Elastic properties of the composite plate

Density (kg/m^3)	E_1=E_2 (GPa)	E_3 (GPa)	$\vartheta_{23} = \vartheta_{13}$	ϑ_{12}	$G_{12} = G_{13} = G_{23}$ (GPa)
2186	15.9	3	0.35	0.25	**1.1**

A four layer (0/90/0/90) WGF/epoxy composite laminate is modelled in ABAQUS. The geometry of the simulated plate including locations of delamination and actuator/sensors pair is shown in (Fig 3).

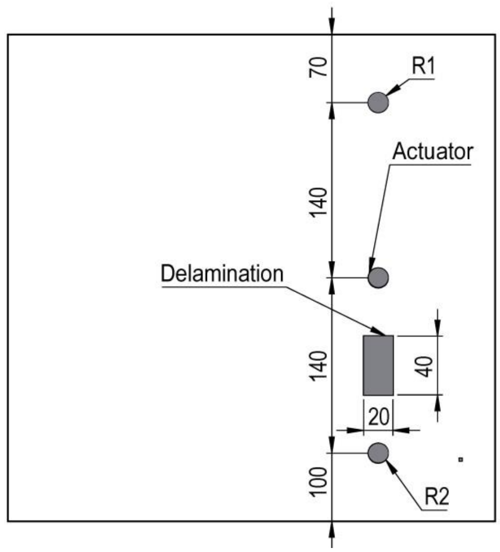

Fig 3: The geometry of the problem

The signal which is received by R1 is related to the healthy plate while R2 captures the damage related signal. The comparison of these two signals leads to detect the delamination in the plate. To simulate defect in composite plate, delamination is located between 2th and 3th layers by the seam feature of ABAQUS/CAE. The thickness of each layer is 0.2 mm and for 4-layer plate the total thickness is 0.8 mm. The layers are meshed with the 8-node hexahedral, C3D8R, element. In order to have accurate results, mesh size has been selected less than one tenth of the wavelength of the A0 mode [18]. A 5-cycle burst signal has been used as actuation signal. ABAQUS/Explicit is employed for simulation because it is more proper for wave propagation problems modeling[20]. As piezoelectric elements are not available in ABAQUS/Explicit, it is needed to apply an equal loading for actuation, and read a variable instead of the electric potential. A radial surface traction in polar coordinate with mentioned burst amplitude has been applied as the actuator effect on the plate.

Fig 4) shows snapshots of Lamb wave propagation in the composite plate with delamination in several different times after the actuation. It is seen in Fig 4) that the amplitude of the wave field is not uniform in all directions as well as the group velocity, as expected due to orthotropic material behavior. The wave front travels faster in “X” and “Y” direction comparing to other directions like 45˚. Moreover, the S0 mode is excited in the plate, rather than the A0 mode. This is concluded from the group velocity calculation as below: the arrival time of the excited mode at R2 is about 62 μs, subtracting the center time of a 240 kHz 5-cycle burst, which is 10 μs, leads to a time of flight equals to 52 μs. Dividing 140mm to the TOF, the group velocity would be 2690 m/s which matches the group velocity of the S0 mode extracted from dispersion curve, shown in Fig2b). Thus the dominant excited mode by a radial piezoelectric disc is S0 which will be the basis for experimental data interpretations.

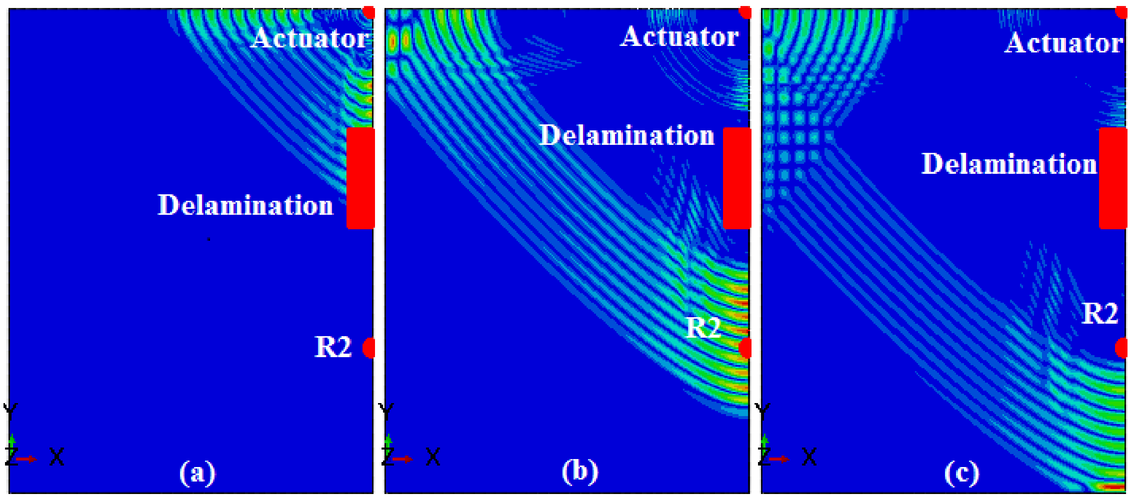

Fig 4: Fundamental symmetric wave propagation at frequency of 240 kHz after (a) 30 micro s (b) 60 micro s (c) 75 micro s

4. Experiments

A setup based on the geometry of the plate shown in Fig 3) has been prepared and equipped with three 7 mm diameter piezoelectric-discs as shown in Fig 5). A DIO LF 1000 pulser/receiver has been employed for actuating and receiving a 5-cycle tone burst signals got from piezoelectric-discs. The A-data signals have been transformed to a PC for further processing.

As the goal of the research is to investigate the sensitivity of the excitation frequency on the delamination detection problem, the actuator has been fired by several actuation frequencies. For each test, the damaged signal, which is gotten from R2, is divided by the peak to peak amplitude of the signal gotten from R1, which means all damaged signals are normalized with respect to their healthy state. These signals are shown in (Fig 6) a-f for F=240 kHz to 400 kHz.

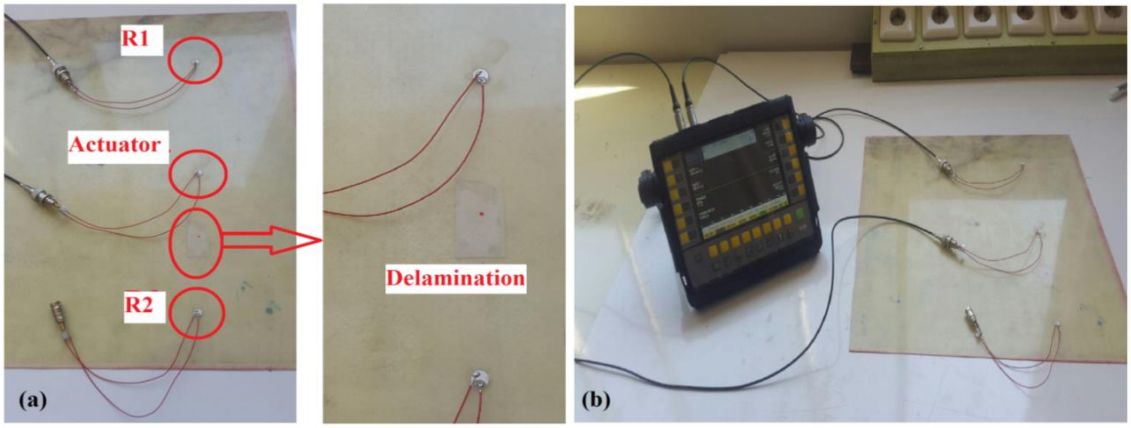

Fig 5: Experimental setup

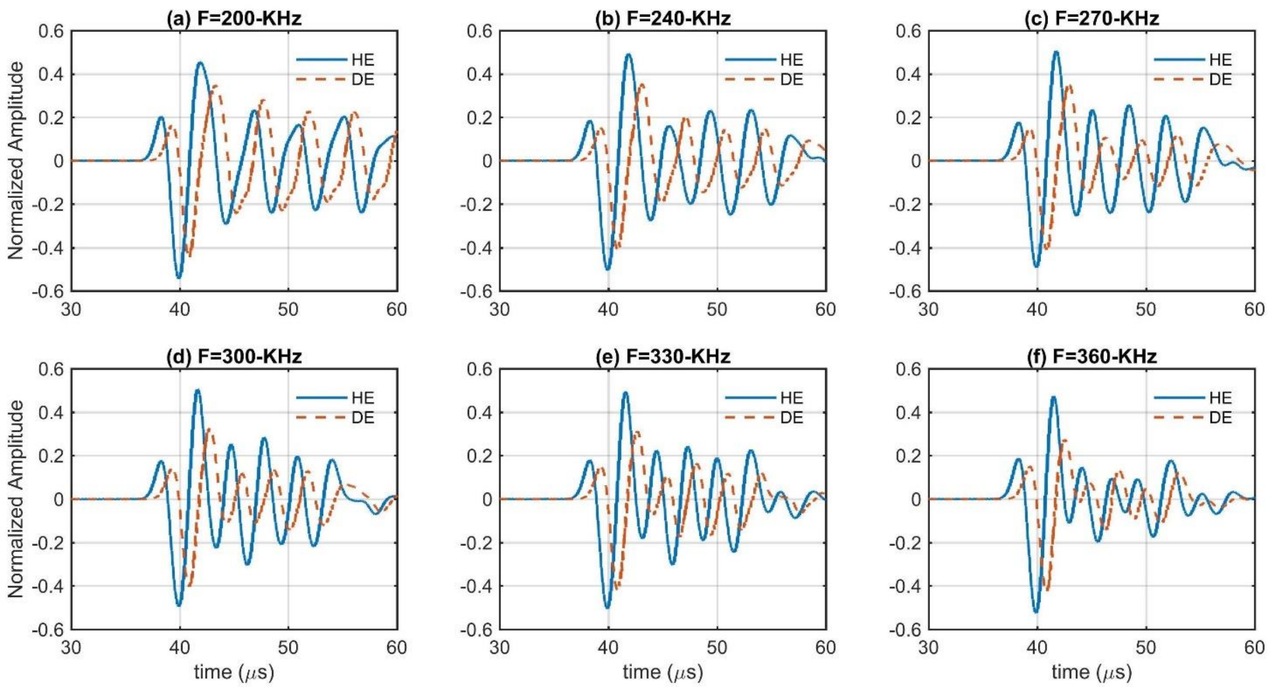

Fig 6: Normalized signals got from experimental tests for different frequencies (HE: healthy plate DE: defected plate)

As it is seen in Fig 6a-f), for all excitation frequencies, the amplitude of the damage related signal is less than the healthy signal, which means the existence of the delamination causes the transmitted signal energy to be decreased. This is because of the fact that part of the incident wave will reflected and consequently transmitted wave would not have the same power with the excited one.

In order to quantify this phenomenon, the amount of decrease in the transmitted wave amplitude is calculated from equation (4). This introduced parameter is called Amplitude Reduction Ratio (ARR).

P2PA refers to the peak to peak amplitude of healthy (HE) and damaged (DE) received signals. F_i shows the selected frequency.

$$\mathrm{ARR}(\mathrm{F_i}) = \frac{\mathrm{P2PA}(\mathrm{HE}(\mathrm{F_i})) - \mathrm{P2PA}(\mathrm{DE}(\mathrm{F_i}))}{\mathrm{P2PA}(\mathrm{HE}(\mathrm{F_i}))} \qquad i=1,2,3,4,5,6 \tag{5}$$

As one of the main features of Lamb wave propagation in thin walled structures is the dispersion phenomena, the bandwidth of the excitation signal and the dynamic of the transducers would cause a spectrum of frequencies appears in the received signals. Therefore, the received signals have been processed using some signals processing tool, wavelets and Fourier transform, to study the effect of signal processing tools on the extracted ARR.

5. Processing of experimental signals

In order to study the effect of signal filtering in ARR, a Fast Fourier Transform (FFT) has been applied to raw signals in order to extract the frequency spectrum of the received signals; results are shown in Fig 7). As it is seen, the bandwidth of received signals is rather wide, which means other frequencies have been also fired by the piezoelectric actuator and received by the sensor. Both frequency domain and time-frequency domain signal processing tools have been employed for filtering the signals in order to help better understanding of the underlying phenomena.

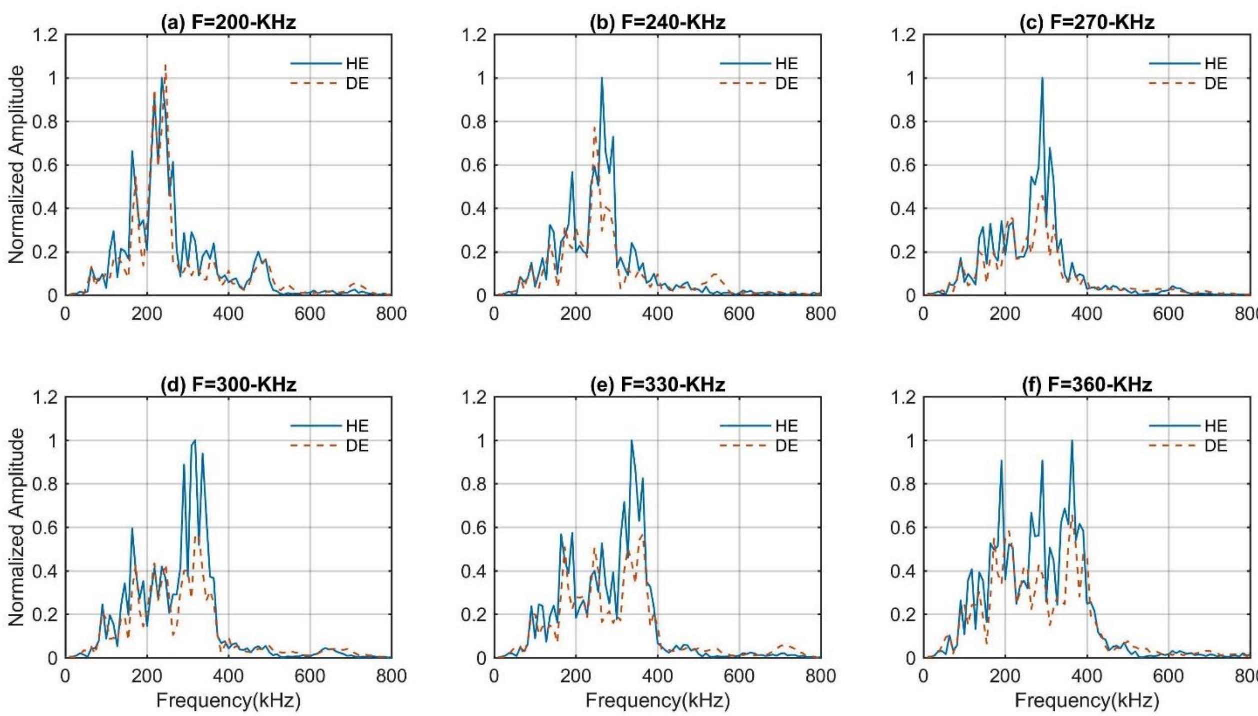

Fig 7: Frequency contents of filtered experimental signals

The Continuous Wavelet Transform (CWT), has been employed as one the most powerful time-frequency domain signal processing tools as well as simple Butterworth band-pass filtering. The "Morlet" wavelet has been selected as the desired wavelet, and the time-frequency distribution of wavelet coefficients have been extracted for both healthy and damaged signals at each frequency.

Then the wavelet coefficients at the excited frequency have been used to reconstruct the sensor signal. A sample of the process results is shown in Fig 8), for the case F=330 kHz. The bandwidth of the Butterworth filter has set to 20% of the central frequency.

In Fig 8-a), the normalized raw, CWT filtered and Butterworth filtered signals are shown. As stated before, the wavelet coefficients distribution in time-frequency domain has been extracted, which is shown in Fig 8-b). As it is seen in this figure, there are other frequencies in receiver signal. The white line in Fig 8-b) corresponds to F=330 kHz. Wavelet coefficients on this line have been considered as the filtered signal and are shown in Fig 8-a) by the dashed line. The phase shift of the Butterworth filtered signal is considerable comparing to CWT filtered signal.

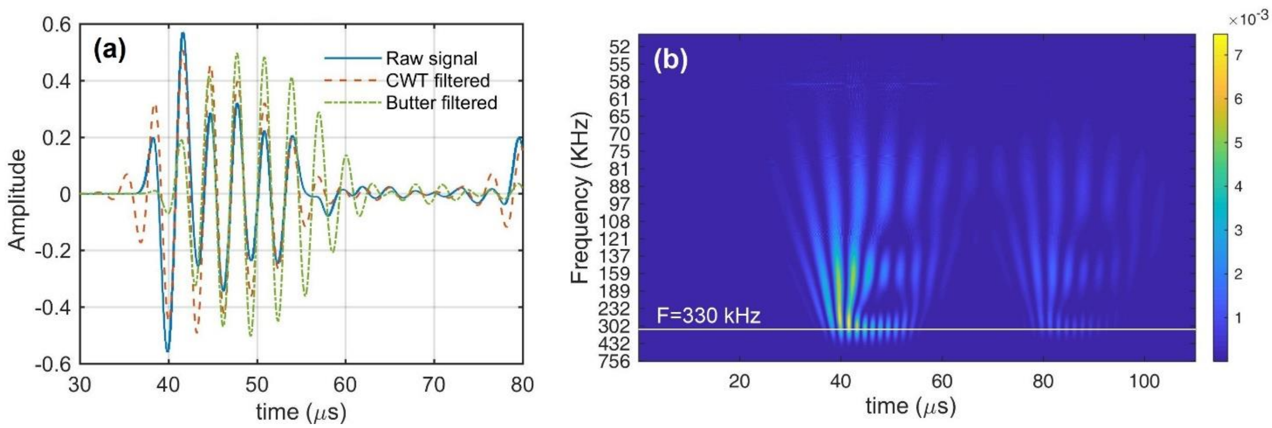

Fig 8:Results for F=330 kHz (a) time domain signals (b) CWT of raw signal

Having done the CWT and Butterworth filtering, the Fourier transform of filtered and unfiltered signals are shown in Fig 9). As it is seen, the bandwidth of the filtered signals decreases and low frequency content of the signals has been removed, comparing to unfiltered signals. The bandwidth of the Butterworth filtered signal is narrower that the CWT filtered, but not in a considerable manner.

The same processing technique have been applied to both healthy and damaged signals for all frequencies in mentioned range, and ARR has been extracted for filtered and unfiltered cases.

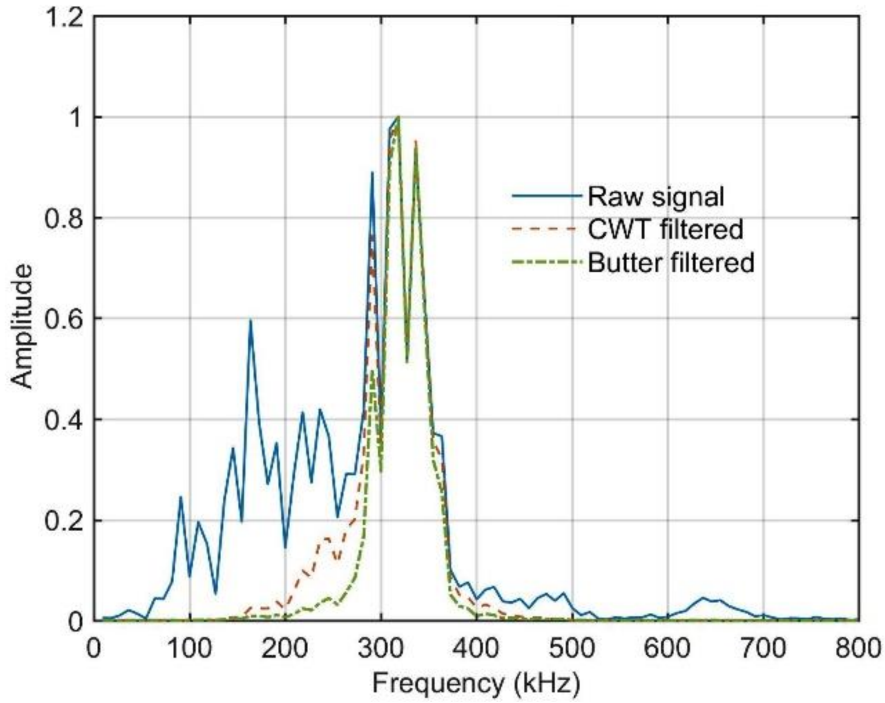

Fig 9: Fourier transform of raw and filtered signals

6. Results and discussion

The amount of ARR has been calculated for raw, CWT and Butterworth filtered signals which are shown in Fig10). Increasing frequency from 240 kHz to 400 kHz, which means reducing the wavelength from 10.10 mm to 4.83 mm, leads the ARR increases from 21% to 30% for unfiltered signals. This could be a result of having more wave packets interacting the delamination and consequently more wave energy loss due to friction.

The results for ARR extracted from filtered signals stand higher than raw signals and it peaked at F=330 kHz and then decreases. It can be concluded that filtering the signals causes the tuned Lamb mode amplitude to increase and the damage effect on the signal become more visible. The Butterworth filtering leads to more sensitive feature rather than CWT filtering, while causes larger error in arrival time estimation due to larger phase shift in the filtered signal. Finally it is shown that ARR is a sensitive feature for delamination detection and can be used for defect sizing in future works.

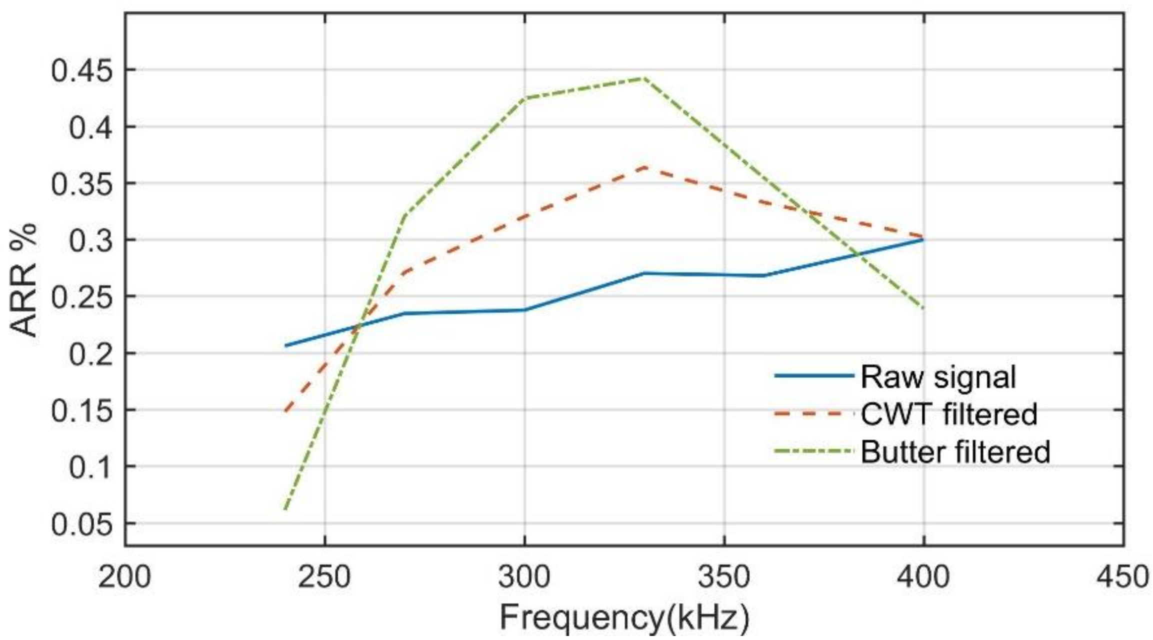

Fig10: ARR amplitude for mentioned range of frequencies

7. Conclusion

In this paper both numerical and experimental investigations have been occurred to find sensitive frequency for delamination detection in a four layer WGF/epoxy composite plate by using ultrasonic guided waves. SAFE method has been used for dispersion curves calculation. A numerical model has been built up in ABAQUS for mode excitation and group velocity verification. The amount of decrease in the fundamental symmetric Lamb mode, S0, has been considered as the sensitive feature to delamination, and quantified through a feature called Amplitude Reduction Ratio (ARR). ARR has been calculated with both raw and filtered signals and it has been shown that removing low frequency content of received signals via Butterworth and CWT filtering, yields more sensitive feature to delamination in composite plate, especially in the tuned Lamb mode and frequency.

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