NONLINEAR DEFECT EXCITATION AND LOCALISATION USING RECIPROCAL TIME REVERSAL METHOD

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ABSTRACT

This paper proposes to use advanced signal processing methods to detect small defects in ultrasonic Non-Destructive Testing of carbon fibre composites by their nonlinear effects. The delayed Time Reversal – Nonlinear Elastic Wave Spectroscopy is used with Pulse Inversion and harmonic analysis in order to excite and detect the small defects using a single-channel ultrasonic testing setup. The study is conducted using 2D Finite Element simulations to accurately control and analyse the defect and its behaviour. It is found that the proposed advanced signal processing methods allow the simple testing setup to be used to detect small defects in complex materials.

KEYWORDS: Time Reversal, Ultrasonics, Non-Destructive Testing, Carbon Fibre Reinforced Polymer

1. INTRODUCTION

The use of Carbon Fibre Reinforced Polymer (CFRP) materials is steadily increasing in various safety-critical applications. However, its possible defects are difficult to detect using ultrasonic Non-Destructive Testing (NDT) methods. These include microcracking and delamination, which can be smaller than the ultrasonic wavelength. Therefore defect detection methods are required for the nonclassically nonlinear [1], [2] effects. In this work the reciprocal Time Reversal signal processing method with Nonlinear Elastic Wave Spectroscopy (TR – NEWS) [3], [4] is used. It has been developed for ultrasonic testing of complex materials and increases the signal-to-noise ratio by using the internal reflections of the medium as additional wave sources. Thus the wave energy can be focused in the medium using a long excitation from only a single channel (one transmitting and one receiving ultrasonic transducer). The focusing relies only on signal processing and requires no a priori knowledge of the geometry or physical properties of the test sample. It can be used with various NEWS methods to detect, excite and localise the sources of nonlinearity in the material. In this work, the Pulse Inversion (PI) method is used to excite the sources of nonlinearities [3] and the delayed TR – NEWS method [5] is used to excite the contacting defects in the materials by resonance. Finite Element Method (FEM) simulations [6] are used to study the proposed methods for conducting nonlinear NDT on CFRP to detect, excite and localise the defects. In numerical simulations, the defect size and shape can be controlled and its behaviour analysed precisely. A delamination defect modelled as a contacting gap between the plies of Carbon Fibre Reinforced Polymer (CFRP) is studied [2].

2. SIGNAL PROCESSING METHOD AND SIMULATIONS

The chirp-coded reciprocal Time Reversal (TR) method is used to focus ultrasonic energy in the test medium, using at minimum only a single-channel setup. Unlike conventional TR, the roles of the transducers are not switched, permitting the use of laser vibrometer for receiver, allowing to quickly scan the test specimen if needed. Firstly a broadband chirp excitation \( c(t) = A \cdot \sin(\psi(t)) \) is transmitted through the medium where \( \psi(t) \) is linearly changing instantaneous phase from 0.2 to 2 MHz. This first excitation fills the medium. Then the recorded signal (chirp-coded coda response \( y(t, T) \) with time duration \( T \) [7]) is cross-correlated with the sent chirp \( c(t) \) during time period \( \Delta t \) (time reversal window). This correlation is proportional to the impulse response of the medium \( \Gamma(t) \sim h(t) \) and therefore contains information about the wave propagation paths in the complex media, including reflections. Time reversed correlation \( \Gamma(-t) \) is used as a new input signal, so all of the internal reflections are played back in reverse, resulting in a focused signal under the receiving transducer. Transmitting it in the same configuration as the initial chirp results in a spatio-temporally focused signal \( y_{TR}(t, T) = \Gamma(T - t) \ast h(t) \sim \delta(t - T) \) under the receiving
transducer with focusing at time $T$. This second propagation is the focusing pass of the signal processing method. This is the basic chirp-coded reciprocal time reversal signal processing method that uses the internal reflections of the medium as additional virtual sources to spatio-temporally focus wave energy under the receiving transducer, increasing the signal-to-noise ratio.

To focus the wave energy onto a nonlinear defect, a Pulse Inversion (PI) reciprocal TR–NEWS measurement is conducted by starting with two chirp transmissions in opposite phase ($c(t)$ and $-c(t)$). In linear and undamaged medium this will result in identical received output signals, however in case of nonlinearities from presence of defects, there is breaking of time reversal invariance [8] where a closed gap defect can act as a mechanical diode [9]. This results in difference between the two outputs $y_{\text{pos}}$ and $y_{\text{neg}}$. The output signals are summed, yielding the nonlinear signature. Upon cross-correlating the sent chirp $c(t)$ with the nonlinear signature $y_{\text{pos}} + y_{\text{neg}}$, we get the nonlinear impulse response of the medium $\Gamma_{\text{PI}}$. It is then time reversed for second propagation through the medium where it should excite mostly only the source(s) of the nonlinearity (by using internal reflections as virtual sources to focus the wave energy on the nonlinear defect). This can be then used to detect the defects and focus the wave energy onto them even when not near the transducers [3], [10], [11]. This procedure is hereafter denoted simply PI.

![Fig. 1 TR-NEWS focusing on the defect far from transducers. Displacement (m) in y direction](image)

The excitation can be fine-tuned further. Delayed TR–NEWS method uses the single focused excitation $y_{\text{TR}}$ as a new basis which can be scaled and delayed by modifying the correlation $\Gamma$ before the second transmission (focusing pass)

$$
\Gamma_s(T-t) = \sum_{i=0}^{n} a_i \Gamma(T - t + \tau_i) = \sum_{i=0}^{n} a_i \Gamma(T - t + i \Delta \tau),
$$

where $a_i$ is the i-th amplitude coefficient and $\tau_i$ the i-th time delay, or uniform time delay $\Delta \tau$. Upon propagating this $\Gamma_s(T-t)$ through the material, the correspondingly delayed and scaled focusing $y_{\text{TR}}$ appears on the receiving side. Among many possible applications [5], this method is here used to create a resonance at the defect.

2.1 SIMULATION MODEL

The proposed ultrasonic NDT signal processing method is studied by simulations. This enables to study not only the input and output signals normally obtained from physical measurements, but also the crack dynamics which is usually unavailable in physical ultrasonic NDT measurements. A CFRP plate is simulated by 2D FEM. The left and right boundaries have Lysmer-Kuhlemeyer absorbing boundary conditions to simulate the effect of an infinite plate [12]. If these boundaries would be reflecting, the reciprocal TR–NEWS would have a distinct advantage from the edge reflections, which then automatically contribute to increasing the signal focusing quality [13]. With absorbing boundary conditions the focusing quality is decreased for added realism. The simulation uses linear triangular elements. The model is a 3.24 mm thick plate that is 150 mm long, with the absorbing boundaries on short ends. Laminate model is used with epoxy and alternating 90° and 45° direction weave carbon fibre layers (22 pairs). The thicknesses of the layers are varied according to a model measured from a physical experimental CFRP sample [14]. Signal is input from an area near the top left side of the simulation model and received near the top right side with the defect being two-thirds of the way along, centered on 100 mm mark (Fig. 1). In the simulations the closed-gap defect spans either 10 mm, 5 mm or 1 mm. The shortest, 1 mm defect is sub-wavelength (minimum excitation wavelength is approx. 2 mm). Input signal is at 20° angle to fully excite the medium in all propagation modes (mixed in $x_1$ and $x_2$ directions i.e. displacements $u_1$ and $u_2$). All excitations are normalized to maximum 50 kPa amplitude. Only $u_2$ data is used in output.
3. RESULTS AND ANALYSIS

Firstly, the medium is illuminated with positive and negative chirps. For the three tested configurations (10 mm, 5 mm and 1 mm defect) the maximum \( u_2 \) deformation is shown in Figs 2–4. For 10 and 5 mm defects, it can be seen that the most of the chirp amplitude is near its transmission point while the PI signal has most of its energy near the defect area. The 1 mm defect seems too small to reliably detect from just looking at the maximum displacement matrix but the PI signal is still advantageous in reducing unneeded wave energy in undamaged regions of the material (Fig. 4).

![Fig.2 Maximum amplitude matrix of 10 mm defect simulation, chirp and PI focusing](image1)

![Fig.3 Maximum amplitude matrix of 5 mm defect simulation, chirp and PI focusing](image2)

Although the TR—NEWS using PI is suitable for containing most of the acoustic energy near the defect, its benefits in case of 1 mm defect (smaller than wavelength) must still be determined.
3.1 SPECTRAL ANALYSIS OF THE CRACK DYNAMICS

The analysis of the nonlinear defect excitation is straightforward in simulations, as we have the crack surface data to analyse. In physical experiments we only have the output signal data (in case of the simple single-channel TR-NEWS experiment). The goal is to be able to analyse the output data in order to create a resonance at the defect using delayed TR-NEWS excitation at the resonance frequency. This involves using Eq. (1) with uniform time delay $\Delta \tau$ corresponding to the defect resonance period to construct a $I_1(T - \tau)$ excitation. The idea is to excite the crack using PI focused signals at precise time intervals, which are determined from the spectral analysis.

The received output signals of the chirp and PI excitations, and the motion of the defect surfaces itself can be analysed spectrally. However, in case of physical experiments, one would only have the output signals available. To ascertain which frequency component is enhanced by the defect, it is possible to compare the output signals of the chirp (which excites the medium fully) and PI output (which has focused the excitation more to the defect region). Figure 5 shows the spectral densities of the output signals in case of various defect sizes. The PI increases 45 kHz frequency in 10 mm crack, 137 kHz in 5 mm crack and 427 kHz frequency in 1 mm crack. Next, the delayed TR-NEWS simulation can be conducted to excite these corresponding frequencies using the $I_1(T - \tau)$ based on the transmitted signal used during the PI simulation.

![Fig.5 Spectral densities of the output signals in case of chirp and PI excitations](image-url)
Since in the simulations we also have the data of the crack surfaces, we can analyse its spectrum to further investigate the "clapping" dynamics of the closed crack defect. Let \( g_n = n_x^n - n_y^n \) be the vertical contact gap between the master and slave surfaces at node \( n \). During the course of the 120 \( \mu \)s simulation, the coordinates of the crack are saved during 1998 time steps. The spectral analysis of the contact area gap \( g_n \) can confirm the resonance frequency in the simulation. Spectral densities are calculated by

\[
S_k(k, t) = \begin{cases} 
\frac{2|U(k,t)|^2}{N}, & k = 1, 2, 3, \ldots, \frac{N}{2} - 1, \\
\frac{|U(k,t)|^2}{N}, & k = \frac{N}{2},
\end{cases}
\]  

where \( |U(k,t)| \) is the value of the \( k \)-th wavenumber of discrete Fourier transform result at time \( t \). This characterises the energy distribution over wave numbers [15]. We can analyse the frequency of the "clapping" motion of the crack by studying the dynamics of the energy distribution. However, as the energy is added into the defect area during the course of the simulation, the spectral densities need to be normalized for comparison:

\[
S_{\text{norm}}(k, t) = S_k(k, t) / S_{\text{sum}}(t), \text{ where } S_{\text{sum}}(t) = \sum S(k, t).
\]  

From normalized spectral densities of the crack dynamics, it is straightforward to find the "clapping" frequency by either studying the time gap between high-frequency excitations or analysing the spectrum of some higher mode energy partition. Normalized spectral densities of the contact gap are plotted in Figs. 6–8, where the contact period of the defect can be seen and measured temporally.

Fig.6 Normalized spectral density matrix of the 10 mm defect dynamics
To study the resonance frequency of the contact gap more precisely, we can use cumulative spectral densities [15], which are calculated by

$$S_c(m, t) = \sum S_{\text{norm}}(k, t), \text{ where } m = 1, 2, 3, \ldots N/2.$$ (4)

The cumulative spectrum sums the energies from the wavenumbers of higher frequency than some determined cutoff wavenumber \(m\) (Fig. 9). It can be useful for analysing the „clapping” here by identifying the dynamics of the spectral content. Instead of identifying the period, the cumulative spectrum can be analysed spectrally to arrive at frequency content of the contact gap motion. We can choose a suitable cumulative spectrum wavenumber for spectral analysis, for example \(m=2, 3\) or \(4\) and analyse from \(t=26\) \(\mu\)s onwards to cut off the initial wave arrival peak.

For 10 mm defect, it can be seen from Fig 10 that the Fourier transform of the cumulative spectrum numbers \(m=2..4\) indicate a resonance at 42 kHz, while the spectrum number \(m=1\) indicates 65 kHz resonance. At 112 kHz there is a peak for \(m=1..4\) which could be a second harmonic of a 56 kHz main harmonic. The PI output signal previously indicated a resonance at 45 kHz, so we choose 42 kHz for delayed TR-NEWS excitation frequency in an to increase the excitation at the defect. The spectral densities of 5 mm defect cumulative spectrum can be seen in Fig. 11, indicating resonance at 132 kHz. In case of 1 mm defect, the only clear signal comes from spectral analysis of the cumulative spectrum signals and indicates resonance at 425 kHz (Fig. 12). These values confirm the estimates from spectral analysis of the output signals (in Fig. 5).
Fig. 9 Cumulative spectrum of 5 mm defect motion showing the resonance of the crack

Fig. 10 Spectral densities of the cumulative spectrum of 10 mm defect gap motion

Fig. 11 Spectral densities of the cumulative spectrum of 5 mm defect gap motion
3.2 DELAYED TR—NEWS EXCITATION OF DEFECT RESONANCE

Having found the resonance frequencies from the PI output signal (42 kHz for 10 mm, 132 kHz for 5 mm and 425 kHz for 1 mm defect) and confirmed it with the spectral analysis of the contact gap motion, the delayed TR-NEWS procedure is now used to modify the signal sent in PI experiment. This was the signal which created increased spatio-temporal focusing at the defect location. Modification is done by Eq. (1) by choosing the resonance period as the delay period $\Delta \tau$.

![Fig.12 Spectral densities of the cumulative spectrum of 1 mm defect gap motion](image)

![Fig.13 Received signal comparison between PI and delayed TR—NEWS](image)
Figure 14 shows that for 10 mm crack, the delayed TR—NEWS is effective in increasing the defect gap amplitude the most during the last 10 μs of the simulation, which is not enough for the signal to reach output. For 5 mm defect, the absolute difference between delayed TR—NEWS and PI excitation amplitude is not as notable. The delayed TR—NEWS creates a stronger signal near the initial arrival of the pulse. This can mean that we need a longer TR time window (excitations of longer length). Conducting simulations in a finite plate with good ergodic qualities could also enhance both the focusing qualities of TR—NEWS with PI and delayed TR—NEWS. The simulation results published here were unsuccessful in creating a resonance in 1 mm defect, but it remains as a further research objective. It cannot be ruled out that it could be caused by either small defect size relative to node spacing length, too large mesh size or non-optimal tuning of the contact gap parameters for the complex nonlinear simulation.

4. CONCLUSION

The 2D FEM simulations are conducted in a laminate CFRP model with a single small horizontal contacting gap defect. This kind of defect is inherently nonlinear and can be detected by its nonlinear signature. Simulations are conducted for defect sizes of 10 mm, 5 mm and 1 mm. The simulation results indicate that the reciprocal TR method with broadband chirp coded excitation is suitable for focusing the wave energy in the medium. The presence of defects can be detected by TR—NEWS signal processing method where the nonlinear signature of the defect is detected by PI. Moreover, it is possible to focus the wave energy onto the defect which is far from the either transducer and analyse the nonlinear harmonics of the defects. Thereafter, the delayed TR—NEWS can be employed to excite the resonance of the defect. Unlike physical experiments, the simulations offer additional analysis of the crack surface dynamics to confirm the resonance frequency and analyse the effect of the signal processing methods on the defect excitation strength. Best results in creating resonance by delayed TR—NEWS are for 10 and 5 mm defects. For 1 mm defect the results are inconclusive but will be undertaken in future with finer mesh and longer time reversal excitation length with fine-tuned contact condition parameters. Alternatively, multiple input method could be devised to further increase the ultrasonic power at defect region. Future goal is to create resonance with this signal processing method in a defect that is smaller than wavelength.
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