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Simulation of Detecting Contact Nonlinearity in Carbon Fibre Polymer Using Ultrasonic Nonlinear Delayed Time Reversal

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Summary

A finite element method simulation of a carbon fibre reinforced polymer block is used to analyse the nonlinearities arising from a contacting delamination gap inside the material. The ultrasonic signal is amplified and nonlinearities are analysed using delayed Time Reversal – Nonlinear Elastic Wave Spectroscopy signal processing method. This signal processing method allows to focus the wave energy onto the receiving transducer and to modify the focused wave shape, allowing to use several different methods, including pulse inversion, for detecting the nonlinear signature of the damage. It is found that the small crack with contacting acoustic nonlinearity produces a noticeable nonlinear signature when using pulse inversion signal processing, and even higher signature with delayed time reversal, without requiring any baseline information from an undamaged medium.

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1. Introduction

In the past, the use of carbon fibre reinforced polymer (CFRP) has been limited to non-structural parts of high-tech aeronautical products. In recent times, due to the effort of weight reduction and product lifetime enhancement, the application areas of CFRP have widened to the load-bearing parts of the aeronautical, automotive and civil engineering products. Due to the increased demands on the strength of the CFRP products and possible complex failure mechanisms, the Non-Destructive Testing (NDT) methods of CFRP have been an important applied and academic problem.

The complex failure mechanisms of CFRP include microcracking and delamination. Microcracking can occur at lower loads or due to aging and can be difficult to examine using ultrasonic NDT. With increased loading, the damage can evolve to delaminations, a very fine cracking between the layers of the CFRP. These damages are difficult to detect using ultrasonic methods due to their small thicknesses. The damage can exhibit itself as a contact acoustical nonlinearity (CAN) [1]. A statistical distribution of microcracks or delamination damage in the material could also be described by hysteresis in a continuum material model [2, 3, 4]. This can also be applicable for other materials than CFRP, for example biological tissues [5, 6].

Nonlinear ultrasonic methods known as Nonlinear Elastic Wave Spectroscopy (NEWS) methods, have been in development for detecting and localizing fatigue and micro-crack damage by their nonlinear effects [7, 8]. The detection of harmonic overtones is one of the simplest measures of nonlinearities [9]. Many nonlinear analysis methods not requiring filtering have been developed, for example scaling subtraction method [10, 11] or Pulse Inversion (PI) with its generalizations [12, 13], and applications of Time Reversal (TR) using scattering as new sources.

In this paper we demonstrate how to apply the delayed TR-NEWS signal processing method [14] for detecting the nonlinear signature of a single small crack in CFRP as CAN. In the Finite Element Method (FEM) simulation, the CFRP is modelled as anisotropic, layered medium. The ultrasonic signal is focused by TR-NEWS to the region of the material with the defect. The nonlinear signature of the crack is detected by PI and compared with the delayed TR-NEWS method, which allows to create arbitrary wave envelope at the focusing region of TR-NEWS. It is used here to create an interaction of waves near the damage. The signature of the damage appears as the nonlinear effect of the wave interaction on the contacting crack. This signal processing requires only one transmitting and one receiving transducer. The effectiveness of the delayed TR-

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NEWS method has been shown in the previous work by physical experiments and simulations in undamaged and linear materials [14]. In this paper, the FEM simulation model is advanced further by including absorbing boundary conditions and the contacting crack defect in the material.

2. Mathematical and simulation model

This section describes the simulation which is based on a physical experiment. It shows some important points about the mathematical model, the delayed TR-NEWS signal processing and the FEM simulation. Detailed information about the delayed TR-NEWS method is available at [14]. The derivation of mathematical and FEM model is discussed more in detail in [15], including the implementation of the absorbing boundary conditions, CAN and comparison of the FEM code used here with linear material code based on FEniCS library.

2.1. Mathematical model

The test object is a CFRP block consisting of 144 layers (Figure 1). It is composed of fabric woven from yarns of fibre and impregnated with epoxy. The cross-section of the yarns have elliptical shape (Figure 2) and the material has inclusions of pure epoxy, so a wave propagating through the material will encounter yarns (fibres with epoxy) and areas of pure epoxy.

The simulation is in time domain, since the TR-NEWS procedure relies on transient echoes and complex wave motion for the wave energy focusing process. Due to the heavy computational cost of time domain simulation, a simple laminate model is used where: i) the material consists of homogeneous layers, ii) each layer has its own elasticity properties, and iii) dispersion arises due to the periodical discontinuity of the material properties. It consists of CFRP layers with 90°/0° weave, 45°/45° weave and epoxy layer. The thicknesses of the layers are given by random variable functions which reflect the actual structure of the material. The random variable distribution, describing the CFRP structure, is measured from a close-up image of the CFRP test object [15]. This links the distribution of the microstructure inside the actual material with the thicknesses of the layers in the laminate model. It should enable a more realistic simulated material having dispersion effects due to discontinuities.

The three different kind of layers have the following mechanical properties: i) isotropic pure epoxy: $E = 3.7$ GPa, $\nu = 0.4$, $\rho = 1200$ kg/m^3; ii) transversely isotropic composite with 0/90° weave: $E_1 = E_2 = 70$ GPa, $G_{12} = 5$ GPa, $\nu_{12} = 0.1$, $\rho = 1600$ kg/m^3; and iii) transversely isotropic composite with 45°/45° weave: $E_1 = E_2 = 20$ GPa, $G_{12} = 30$ GPa, $\nu_{12} = 0.74$, $\rho = 1600$ kg/m^3. For the simulation, a laminate model was constructed using 50 pairs of epoxy and carbon fibre layers, where carbon fibre weave direction alternated between each pair.

The model (Figure 3) includes Lysmer-Kuhlemeyer absorbing boundary conditions [16] so the wave energy

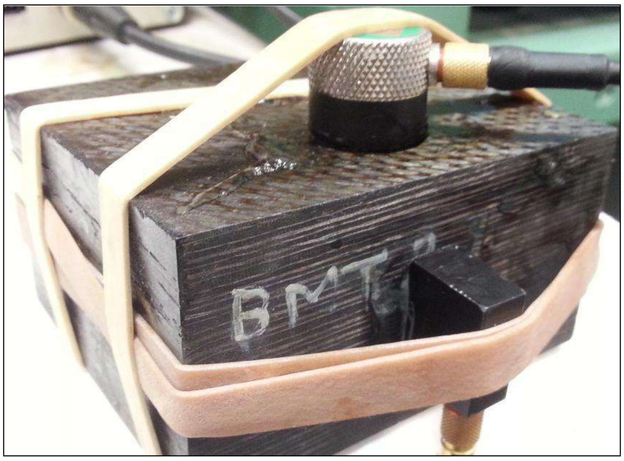

Figure 1. (Colour online) CFRP block in the test configuration with transmitting transducer on side and receiving on top.

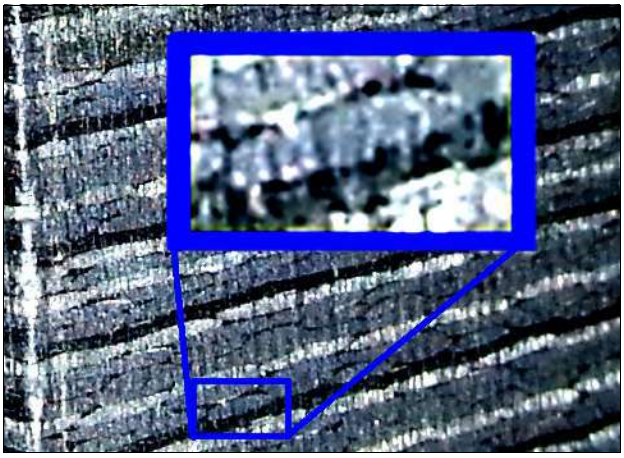

Figure 2. The layered structure of the CFRP with the fabric yarns in tight packing and epoxy in the voids.

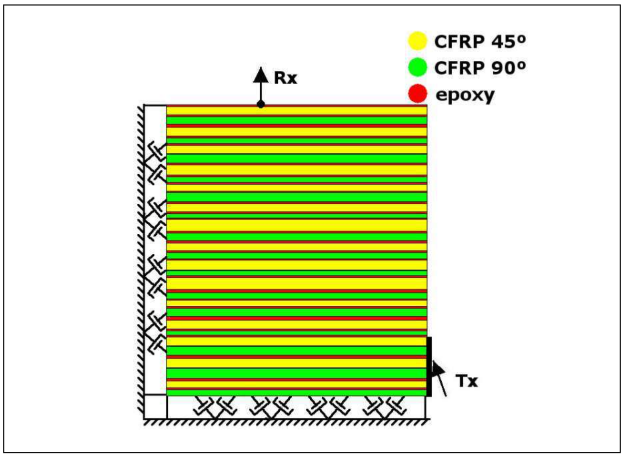

Figure 3. (Colour online) The laminate material model with layers of stochastic thicknesses and absorbing boundary conditions on bottom and left boundaries and four fixed degrees of freedom.

would pass through the simulation region. The absorbing boundary conditions model more closely the corresponding physical experiments, conducted on the corner of a CFRP block. Additionally, the absorbing boundary con-

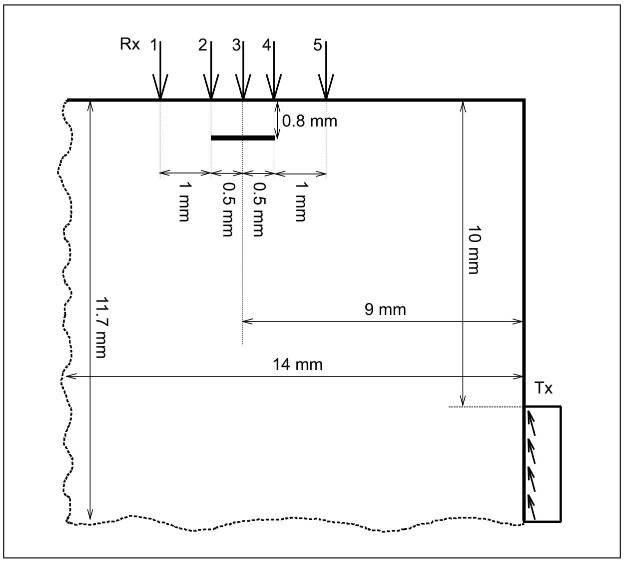

Figure 4. Schematic (not to scale) of the simulation geometry, location of crack, transmitter and receiver points without the layers.

ditions inhibit the TR-NEWS focusing, since it relies on the internal reflections. Four degrees of freedom are fixed, the rest are free. The simulation model includes a contacting delamination defect in the material near the receiving transducer (Figure 4). In the simulation, the transmitting shear wave transducer can send maximum 50 kPa pulse at 70° degree angle.

2.2. Signal processing

In the physical experiments, on which the simulation is based on, the CFRP block (Figure 1) was studied using TR-NEWS NDT equipment and signal processing methods [14]. The 2D FEM simulations here reflect it as closely as possible in terms of transducer placement, frequencies and signal processing. The linear chirp excitation ranges from 0 to 2 MHz during 30 µs, followed by 30 µs of silence.

The TR-NEWS signal processing method creates a TR focusing by using a reciprocial type of TR [17] in conjunction with linear chirp pulse compression, utilized widely in RADAR and SONAR technology. The reciprocial TR is a two-pass method where for both passes the signal is sent from the same source, enabling to use non-contact measurement equipment on the receiving side. The use of linear chirp as initial excitation and the pulse compression of signal in TR-NEWS results in amplification of the wave energy to a single focused impulse wave. In this sense, the "Time Reversal" used here relies on the internal reflections as virtual transducers for the focusing and describes the signal processing method, which accounts for them accordingly, to create the impulse signal focusing. In the course of the two-pass single TR-NEWS focusing, the *a priori* knowledge of the medium geometry is not needed and the transducer placement can be arbitrary since the signal processing method generates the impulse focusing without any additional information. However, the complete test configuration must remain fixed during both transmission passes of the TR-NEWS procedure.

In short, the TR-NEWS signal processing steps consist of firstly propagating a linear chirp signal $c(t)$ and receiving a response $y(t)$. Then the correlation between sent and received signals Γ is time reversed and re-propagated from the original source in the same configuration. The resulting response $y_{TR}(t)$ is an impulse-signal, which is focused spatio-temporally. The complete explanation of TR-NEWS steps is available in [14].

PI is an established method for detecting nonlinearities. It has been studied widely and is under constant development [12] and is used here as a comparison with delayed TR-NEWS. The procedure used here involves conducting TR-NEWS measurements with chirps $c(t)$ of positive and negative signs for amplitude (or 180° phase shift) and comparing the focused signals. Differences between the corresponding received TR-NEWS focused signals could indicate the presence of nonlinearities.

Delayed TR-NEWS signal processing is a further development of the TR-NEWS signal processing, which considers a single TR-NEWS focused impulse wave y_{TR} as a new basis which can be used to build arbitrary wave shapes at the focusing by assuming linear superposition principle. This is done by time-delaying and superimposing n time-reversed correlation $\Gamma(T-t)$ signals (Figure 5 left column),

$$\Gamma_s(T-t) = \sum_{i=0}^{n} a_i \Gamma(T-t+\tau_i) = \sum_{i=0}^{n} a_i \Gamma(T-t+i\Delta\tau), \quad (1)$$

where a_i is the i-th amplitude coefficient and τ_i the i-th time delay. In case of uniform time delay the $\Delta\tau$ is the time delay between samples. Upon propagating this $\Gamma_s(T-t)$ through the media according to the last step of TR-NEWS, a delayed and scaled shape of signal at the focusing point can be created. The delayed TR-NEWS signal processing optimization can be used for amplitude modulation, signal improvement and sidelobe reduction [14].

It is possible to predict what the delayed TR-NEWS focusing output would be in a linear material (Figure 5 right column),

$$y_{dTR}(t) = \left[\sum_i a_i \Gamma_c\left(T-t+\tau_i\right)\right] * h(t) \underset{\text{linearity}}{=} \sum_i a_i \Gamma_c\left(T-t+\tau_i\right) * h(t) = \sum_i a_i y_{TR}(t-\tau_i). \quad (2)$$

The purpose of the prediction is twofold. Firstly it can be used to figure out optimal delay and amplitude parameters a_i and τ_i beforehand for the delayed TR-NEWS experiment, using the original focusing peak y_{TR}. Secondly, it could be possible to analyse the differences between the measured delayed TR-NEWS result and its prediction, which acts as a baseline for comparison. The difference

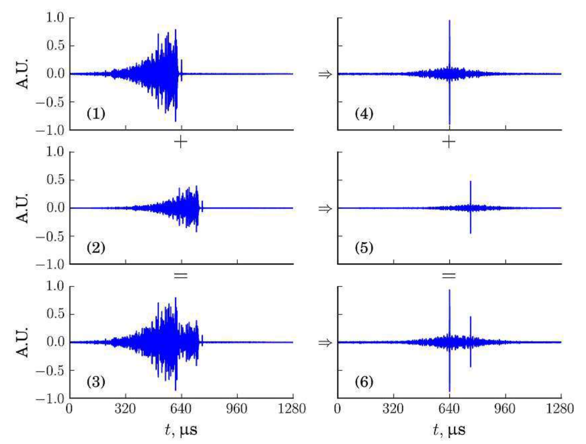

Figure 5. Delayed TR-NEWS signal processing steps starting from the cross-correlation step (left column) and prediction of linear superposition of waves (right column): (1) time reversed cross-correlation, (2) delayed and scaled cross-correlation, (3) linear superposition of two cross-correlations which becomes the new excitation, (4) TR-NEWS focused impulse, (5) delayed and scaled focusing, (6) linear superposition of the two impulse peaks.

could indicate the magnitude of nonlinearity, because the prediction relies on the applicability of linear superposition and is found to be accurate in experiments with linear material [14].

In this work, delayed TR-NEWS is used to create an interaction of focused waves under the receiving transducer. It is proposed that if it happens in a region with a defect or other nonlinearities, then there will be a difference between the recorded and predicted signals. This difference might be used as a new indicator for detecting nonlinear effects near the focusing region [14]. The goal of this work is to test this idea in simulations.

2.3. The FEM simulation model

The simulation program considers 2D wave propagation in a solid material with linear elasticity. The nonlinearity comes from an internal defect, a crack in the computational region (Figure 4) which can come into contact with itself. This contact nonlinearity has asymmetric stiffness and is therefore nonclassically nonlinear. Since the CFRP is a complex material, then in this work it is modelled as a laminate with anisotropic layers arranged in a periodic manner, described in Section 2.1. Because the physical experiment was conducted on the corner of a large CFRP block, the simulation is also in a semi-infinite quarter-space. The region has two free surfaces for reflection and two absorbing boundaries for the wave energy to escape, which should make the TR-NEWS focusing process more difficult, but realistic.

The constitutive equation of the material itself is linear (although anisotropic). The linear plane strain elastodynamics problem is solved

$$\rho\ddot{u}_i - \sigma_{ij,j} = b_i, \tag{3}$$

where ρ is material density, u_i is displacement component, σ_{ij} is stress component and, b_i is body force component [18]. Einstein summation convention is used and comma in index denotes spatial derivative. The constitutive equation in the variational formulation is

$$0 = \int_\Omega \left(\sigma_{ij}\delta\varepsilon_{ij} + \rho\ddot{u}_i\delta u_i\right) \mathrm{d}x\,\mathrm{d}y - \int_\Omega b_i\delta u_i\,\mathrm{d}x\,\mathrm{d}y - \int_\Gamma t_i\delta u_i\,\mathrm{d}s, \tag{4}$$

where ε_{ij} is strain and t_i is traction component on boundary. In our case the region Ω is a 2D space and boundary Γ surrounding it a 1D line. The body forces are zero in this simulation. Strain is assumed to be small.

The matrix formulation of the finite element model with damping is

$$M\ddot{\Delta} + C\dot{\Delta} + K\Delta = F, \tag{5}$$

where M is mass matrix, K is stiffness matrix, F is external forcing and Δ is displacement vector [15]. The damping matrix C contains the Lysmer-Kuhlemeyer absorbing boundary conditions [16] as a diagonal matrix, allowing to take advantage of the explicit solution scheme.

Equation (5) is solved for each timestep $\Delta t = 5\cdot 10^{-10}$ s by explicit central difference scheme

$$\left(\frac{M}{\Delta t^2} + \frac{C}{2\Delta t}\right) u_{n+1} = F_n - \left(K - \frac{2M}{\Delta t^2}\right) u_n - \left(\frac{M}{\Delta t^2} - \frac{C}{2\Delta t}\right) u_{n-1}. \tag{6}$$

Each simulation considers a 60 µs time window. This simulation code was developed in Fortran and Python using f2py [19] and scipy [20] packages. Full details of the FEM simulation model are available in [15].

2.3.1. Contact gap treatment

The goal of this work is to verify if delayed TR-NEWS is able to give information about nonlinear effects in material. For this, one simple CAN defect is introduced near the surface in the region where the TR-NEWS wave is focused (Figure 4). The crack is straight, with no preload or initial gap. This results in a simple localised nonclassical nonlinearity. Coulomb friction is also applied.

Frictional contact problems can be sensitive to timestep length and loading path [23]. Therefore an explicit solution scheme (Equation 6) is used, which enables to keep timestep and applied contacting forces small [24]. This enables to have a simple contact gap treatment logic. A more precise solution could be expected from an implicit scheme, but that requires also further development of the contact gap treatment and is left for the future. Future refinements could also include thermoelastic contribution to the constitutive equation at the frictional contact gap [3].

Node-to-node contact model is used in FEM analysis [25]. It was chosen because of its simplicity, since we assume small deformations. Moreover, the choice of master and slave surfaces is unimportant for this scheme, unlike the more complex node-to-surface method. Since the defect is horizontal and fully known in advance, the calculation of normal and tangential gap between the nodes is simple. If the position of a node on a slave (lower) surface is (n_x^s, n_y^s) and on master (higher) (n_x^m, n_y^m), then the normal contact gap is $g_N = n_y^s - n_y^m$ and the tangential gap (offset) is $g_T = n_x^s - n_x^m$. In case of normal penetration of one surface into another, then $g_N > 0$. If there is no penetration, then $g_N \leq 0$. The coefficient of friction is $\mu = 0.6$. The contact gap treatment has to satisfy the Kuhn-Tucker conditions on the crack surface,

$$\begin{cases} g_N \leq 0, \\ \lambda_N = \sigma \cdot n \leq 0, \\ g_N \cdot \lambda_N = 0, \end{cases} \tag{7}$$

where λ_N is the normal force on crack, σ is stress and n is the normal vector of the surface. The normal contact conditions are satisfied using the penalty plus Lagrange multiplier method [26] for the normal forcing. A simpler penalty method is used to satisfy Coulomb friction, which is activated from the second timestep since the beginning of non-slip contact [15]

The contact logic for the node pairs can be summarized by following steps.

- The initial contact forces are zeroed: normal $\lambda_N = 0$ and tangential $\lambda_T = 0$.
- System in Equation (6) is solved.
- Vector gap functions are found: $g_N = n_y^s - n_y^m$ and $g_T = n_x^s - n_x^m$.
- Normal forcing is updated $\lambda_N = \lambda_N + g_N b$ where b is some big penalty value and $\lambda_N \geq 0$.
- Logic diverges to 3 paths:
  No force is applied in case of no contact.
  Only normal force is applied if preceding step had no contact or had contact with tangential slip.
  Normal and tangential forces are applied if previous iteration had non-slip contact.
- The normal contact condition is verified by setting the penetration value $g_P = g_N$ where $g_N \geq 0$. Then the L^2-norm of penetration is evaluated $\langle g_P | g_P \rangle < \varepsilon$ where ε is the limiting value for the error due to contact penetration. If the condition is not fulfilled, the iteration is repeated, otherwise new timestep is taken.

3. Results

The signal analysis of the time domain simulation results of the damaged and undamaged medium are compared, describing some analysis measures which could allow to detect the presence of damage as nonlinearity. The simulation follows ultrasonic TR-NEWS NDT procedures where the transducer data is available as time-series, measured at some specific location. The signals are low-pass filtered to keep only the ultrasonic component. Five measurement points are analysed at various distances from the 1 mm crack damage and transmitting transducer (Figure 4). This

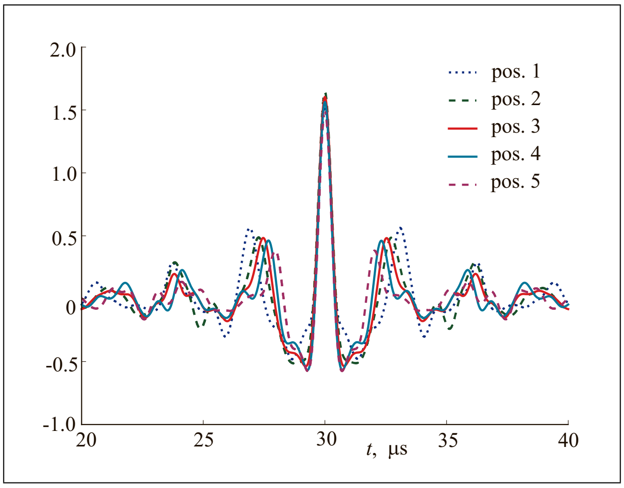

Figure 6. (Colour online) Unnormalized TR-NEWS focusing in simulation of undamaged CFRP.

simulates an ultrasonic NDT when searching for a nonlinear defect with both PI and delayed TR-NEWS. A video of the displacement fields for TR-NEWS focusing to point 3 in cracked medium is available at [27]. The simulations were also ran for a range of defect sizes from 1 mm downwards. The measurement point 3 was utilized (near the middle of the crack). These simulations compare the sensitivity of PI and delayed TR-NEWS in case of smaller crack sizes.

3.1. TR-NEWS with pulse inversion

Figure 6 shows the TR-NEWS focusing in undamaged CFRP for the receiver positions 1 to 5 (Figure 4). It is an ordinary TR-NEWS focusing where at the middle of the signal ($t = 30$ µs) is the focusing, surrounded by the sidelobes. There are two aspects to note about this figure. Firstly, the sidelobes shift toward the main focusing and comparatively decrease in amplitude as the receiving transducer position shifts toward the transmitting transducer (from position 1 to position 5), indicating lower noise as the signal gets stronger. Secondly, the sidelobes are symmetrical with respect to the main lobe. This does not happen in nonlinear (damaged) material. The PI results indicate zero nonlinearity and are not shown here.

Figure 7 shows the TR-NEWS results of the cracked CFRP simulation for the receiving transducer positions 1 to 5 (Figure 4). Here the PI signal processing shows the nonlinearity as difference between TR-NEWS results from initial chirp signals with positive and negative sign. This nonlinear simulation with 1 mm crack exhibits nonlinearity particularly strongly in receiving position 3 (near the middle of the defect). Also, the sidelobes are unsymmetrical with respect to the main lobe. The comparison between left and right side of TR-NEWS focusing has been successfully applied since 2006 [5, 28, 29] to localize sources of nonlinearities.

Figure 8 shows the envelopes of the PI measure of nonlinearity across the five measuring points. The nonlinearity magnitude depends on the measuring point location with

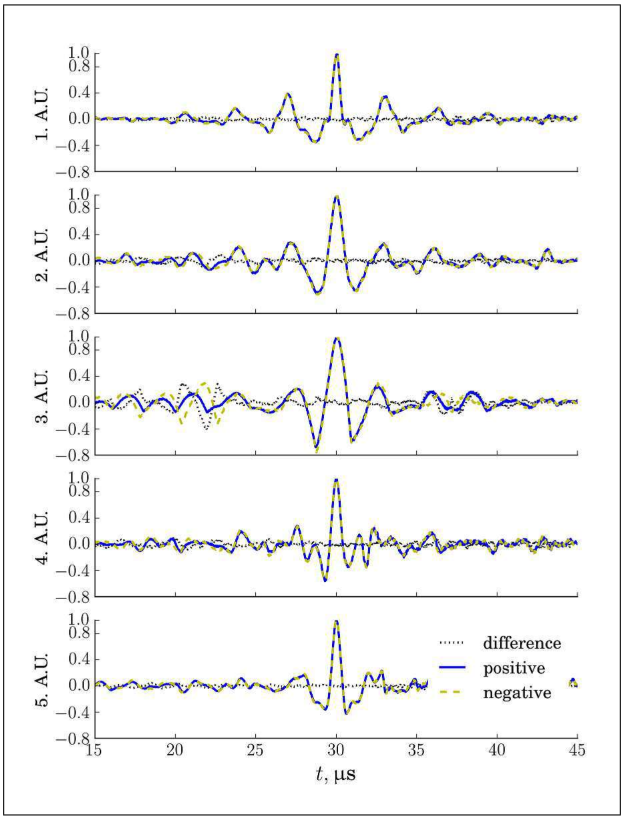

Figure 7. (Colour online) Normalized TR-NEWS focusing of damaged CFRP simulation with PI applied to detect nonlinearities as difference between negative and positive excitations.

respect to the crack: point 3 near the middle of the crack shows strongest nonlinearity, points 2 and 4 show less, and points 1 and 5 show the least.

Figure 9 shows the unnormalized focusing signal for the damaged medium, which can be compared with corresponding undamaged result in Figure 6. The focused signals have some interesting properties:

1. The highest signal amplitude comes from the receiver position closest to the crack midpoint (pos. 3), not from the position closest to the transmitter (pos. 5).
2. Comparing the amplitudes of the positions 2 and 4, at far and near side of the crack end respective to transmitter: the farther position has larger focusing amplitude than the nearer position. Since the simulation region has two absorbing boundaries, the wave propagation is mostly in one direction, therefore the defect between pos. 2 and 4 must be capturing the wave energy and the TR-NEWS signal processing is using that energy as a new "virtual transducer" for the pos. 2 focusing. This could be further analysed in future works from the correlation signal which should indicate the contribution from additional reflections.
3. Amplitudes from the measurement positions 1 and 5 are "right way" around: the nearer measurement point has larger focusing amplitude than the farther.
4. Comparing just the TR-NEWS focusing amplitudes of undamaged (Figure 6) and damaged (Figure 9) CFRP, we see that indeed the additional reflection from the defect aids in amplifying the focused signal, increasing the focused wave amplitude. This is a known property of the reciprocial TR-NEWS signal processing.

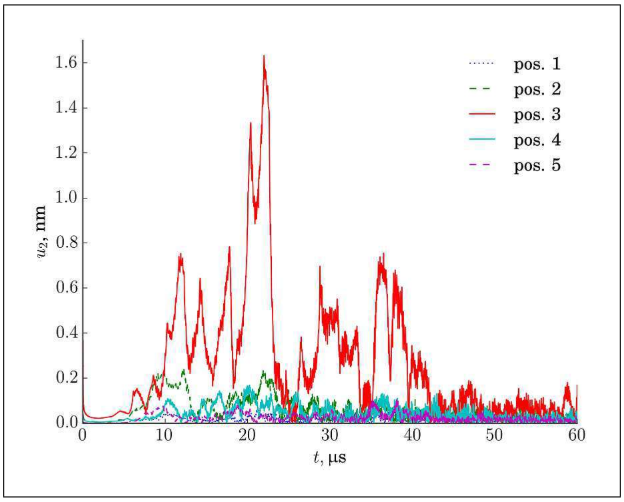

Figure 8. (Colour online) Nonlinearity magnitudes of PI signal processing from different measuring locations of 1 mm defect.

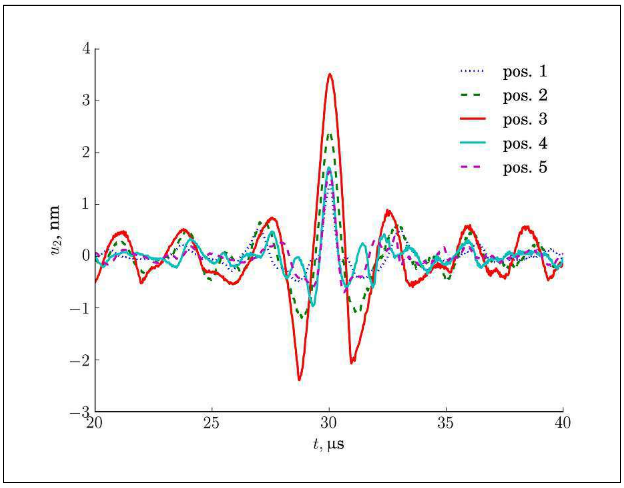

Figure 9. (Colour online) TR-NEWS focused wave in different measuring locations of damaged CFRP defect.

Figure 10 shows a snapshot of the simulation u_2 displacement at a time moment $t = 32.6$ µs, just after the focusing. The defect in the material is acting as a source of new excitation after TR-NEWS focusing. Wave energy is captured between the damage and outside wall of the material and emitted as a wave. This behaviour is not visible in simulation with undamaged medium.

3.2. Delayed TR-NEWS analysis

The main point of this work is testing the nonlinearity measure of delayed TR-NEWS in simulation of CFRP with a CAN type of nonlinearity. Section 2.2 describes the delayed TR-NEWS signal processing method which allows to create arbitrary envelope wave at the focusing (Equation (1)), instead of the simple peak of the TR-NEWS. Equation (2) shows that in linear material, the

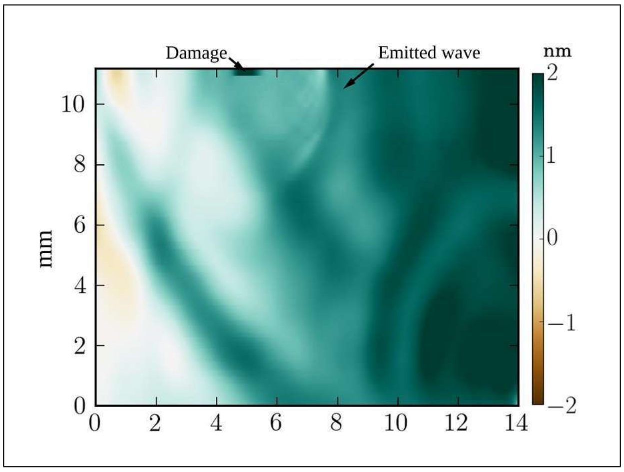

Figure 10. (Colour online) TR-NEWS focusing to pos. 3 at time $t = 32.6$ µs, showing displacement u_2 wave emission coming from the damaged region. Video available at [27].

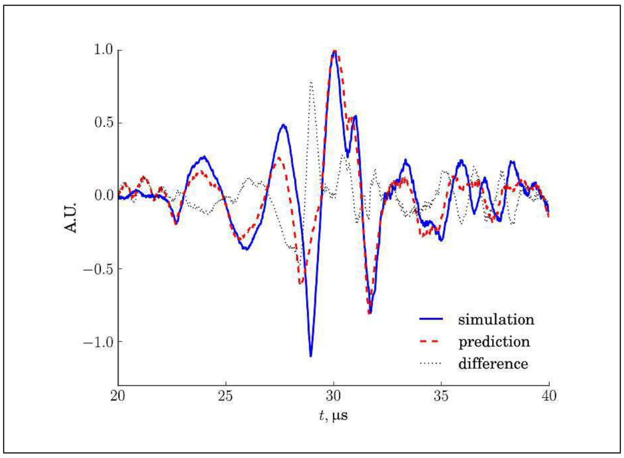

Figure 11. (Colour online) Delayed TR-NEWS nonlinearity measure between predicted and simulated values from position 3 on 1 mm damage with delayed peak amplitude $a_i = 1$ and delay value $\tau = 1$ µs (Equation 2).

outcome of the delayed TR-NEWS process can be predicted. Since the prediction works very well in physical NDT measurements of linear materials [14], it is now tested in simulation with the nonlinearity, supposing that the difference between the simulation result and the linear prediction (Equation 2) is due to nonlinear interaction of waves in the presence of nonlinearities or damage. Figure 11 shows the comparison between the linear superposition prediction and the simulation result of a simple delayed TR-NEWS process where two focusing peaks are at superposition with 1 µs time delay. The difference between the prediction and the simulation is large and obvious, indicating the presence of nonlinearity. This measure of nonlinearity seems to be at least as strong as the measure calculated from PI (Figure 7, pos. 3), so it is now investigated further.

Secondly, the effect of the crack size on the strength of the measured nonlinear effect is analysed. Simulations were ran with PI and delayed TR-NEWS nonlinearity

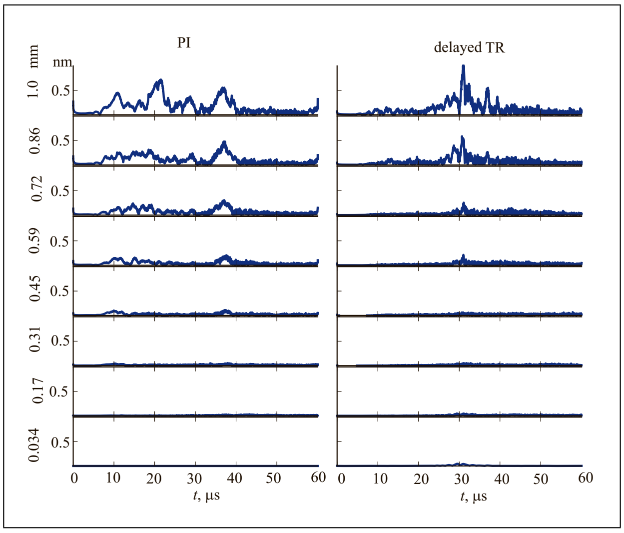

Figure 12. Comparison of the PI and delayed TR-NEWS nonlinearity measure envelopes (deformation u_2 difference in nm) depending on the size of the defect (in mm).

analysis on medium with defect size between 0 and 1 mm. These are sub-wavelength for the used signal. The spatial focusing region was in the centre of the defect, in *Rx* position 3 in Figure 4. Figure 12 shows the comparison of the envelopes of the nonlinearity measures. It can be seen that the nonlinearity measure of the delayed TR-NEWS is easily locatable in the temporal focusing region (near $t = 30$ µs), conversely the PI nonlinearity is located in the sidelobe region, potentially making it more difficult to analyse in applications. The magnitudes of the two nonlinearity measures are comparable. With 1 mm defect, the delayed TR-NEWS nonlinearity measure has larger maximum amplitude than PI but in case of smaller defects the advantage disappears. The PI seems to work slightly better at smaller defect sizes, but the delay $\tau = 1$ µs in delayed TR-NEWS could be optimized further. Both methods work well for detecting sub-wavelength defects at the focusing region in the damaged material.

The delayed TR-NEWS signal processing could also be used for activating the contacting gap as the energy pocket. This could be done by creating a new focusing wave envelope which would have the resonant frequency of the defect, permitting higher amplitude waves near the damaged region, which would enhance the extraction of the nonlinear signature. This study is left for the future.

4. Conclusion

This paper investigated nonlinear NDT by using a simple FEM simulation model for a crack nonlinearity in CFRP. In the laminate model, the damage is a simple horizontal contacting crack near the receiving transducer. The signal processing uses TR-NEWS method for focusing the available wave energy near the receiving transducer. The magnitude of nonlinearity due to the damage is measured firstly with PI, secondly with the proposed delayed TR-NEWS signal processing procedure and compared. Both measures have comparable magnitude, with difference being that for PI it is mostly in the sidelobe region, but in delayed TR-NEWS in the focusing peak region.

The advantage of the delayed TR-NEWS nonlinearity analysis, compared to the established PI method, is that it only requires three wave transmissions (chirp transmission, TR-NEWS focusing, delayed TR-NEWS focusing), not four like PI. This can be important in applications where the measurement time needs to be minimized. The disadvantage is that it requires specifying at least the time delay parameter τ to create an interaction of waves, while in PI no such parameter needs to be specified. This makes PI more robust and easy to apply, but delayed TR-NEWS more flexible (for example in activating a defect resonance). Neither method requires any *a priori* baseline measurement knowledge.

Since the delayed TR-NEWS procedure allows to generate a wave at the focusing with arbitrary envelope, it could be used in the future to excite the crack damage by its resonance frequencies, using the damage as an energy pocket. Other perspectives include a more detailed simulation model for the CFRP in order to take more of its microstructure geometry into account to have stronger focusing. Additionally, the damage could be modelled either by a collection of various cracks at various angles or by hysteresis. Moreover, heating from the frictional forces at the damage could be in future considered for a more precise simulation model.

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