COMBINED ESAM AND DORT METHOD IN NONLINEAR ULTRASONIC SPECTROSCOPY

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Abstract Combination of ESAM (Excitation Symmetry Analysis Method) and DORT (Décomposition de l’Opérateur du Retournement Temporel) provides a powerful tool for detection and localization of defects by analysis of their nonlinear signature. Piezoelectric transducers are used for both excitation and data acquisition. Transmitters consequently emit the excitation signals and corresponding responses are measured by the array of receivers. The amplitude and phase of excitation signals is variable as to separate the nonlinear parts of the measured signal. ESAM signal pre-processing is used for nonlinear parts extraction. Separated signal records form linear and nonlinear multistatic data matrices. DORT method is applied on data matrices to separate echoes of defects in the tested medium. Data obtained from DORT method are used for evaluation of nonlinear parameters corresponding to separated defects and also for their localization. The procedure is completed by visualization of nonlinear signatures of detected defects which is referred to as pseudotomographic imaging.

Key words: nonlinear elastic wave spectroscopy (NEWS), ESAM, time reversal (TR), TR-NEWS imaging, DORT

Introduction

Methods based on elastic wave propagation provide a very effective tool in non-destructive testing (NDT) for detection and quantification of damage in various materials. The most recent trend is to link time reversal (TR) and nonlinear (NEWS = Nonlinear Elastic Wave Spectroscopy) approaches of ultrasonic signal processing [1][2]. On one hand, time reversal offers a bulk of advantages concerning signal-to-noise ratio enhancement, auto-focusing and heterogeneous medium compensation [3], on the other hand, nonlinear approach permits evaluation and quantification of nonlinear behavior typically generated by thin cracks and other defects like delamination or inhomogeneities [4], which are the major subject of interest of latest NDT, since they are hardly detectable by standard linear methods.

In this paper a new approach of TR-NEWS link will be presented. TR process is represented by DORT method (French acronym for Décomposition de l’Opérateur de Retournement Temporel, i.e. decomposition of time reversal operator), an approximative method which allows separation of invariants of time reversal process, i.e. the Green’s functions (pure echoes) corresponding to well-resolved scatterers present it the tested sample [5]. The nonlinear signalize of detected scatterers is evaluated by ESAM (Excitation Symmetry Analysis Method). ESAM is used to extract nonlinear terms from the
acoustic response. In order to obtain these terms, different excitations are used and corresponding responses are treated according to the properties of point group $C_3$ [6].

Combination of ESAM and DORT allows us to formulate quantified nonlinear parameters associated to different scatterers or zones of the tested sample. With regard to the sample geometry and positions of the transducers used for the data acquisition, the parameter values can be visualized to obtain an image of damaged zones.

1 ESAM signal pre-processing

Medium with tiny cracks generally shows an enhanced 3rd order nonlinearity which could be extracted with the ESAM signal processing approach using optimized excitations [6]. ESAM uses nonlinear signature coming from the direct acoustic response as a pre-processing tool for the extraction of nonlinear signature.

1.1 General principles

If scatterers’ responses are supposed to have cubic expansion in strain, the nonlinear response can be written as $y(t) = N_1x(t) + N_2x^2(t) + N_3x^3(t)$, where $N_1$, $N_2$ and $N_3$ are nonlinear parameters. With use of the properties of point group $C_3$ and its irreducible representation, ESAM permits extraction of these parameters. The responses $y_E$, $y_\epsilon$, $y_\epsilon^*$ to the excitations $x_E = x(t)$, $x_\epsilon = x(t)e^{\frac{2\pi}{3}}$, $x_\epsilon^* = x(t)e^{-\frac{2\pi}{3}}$ enable extraction of the cubic term $s_3(t) = N_3x^3(t)$ by

$$s_3(t) = N_3x^3(t) = \frac{y_E(t) + y_\epsilon(t) + y_\epsilon^*(t)}{3}, \quad (1)$$

With use of similar procedure assuming only second order nonlinearity of the system, i.e. the acoustic response $y(t)$ as $y(t) = N_1x(t) + N_2x^2(t)$ and exploiting the point group $C_2$, we are able to extract also the 2nd order nonlinear term $s_2(t) = N_2x^2(t)$ and the linear term $s_1(t) = N_1x(t)$. Elements of $C_2$ are the identity $E$ and inversion $I = e^{i\pi}$. Similarly as before:

$$s_1(t) = N_1x(t) = \frac{y_E(t) - y_I(t)}{2}, \quad (2)$$

$$s_2(t) = N_2x^2(t) = \frac{y_E(t) + y_I(t)}{2}. \quad (3)$$

1.2 Nonlinear parameters extraction

Terms $s_1(t)$, $s_2(t)$ and $s_3(t)$ extracted by ESAM correspond to the nonlinear behavior of the system, but also they still depend on the original excitation $x(t)$ and its powers. Therefore, to obtain the unique coefficients $N_1$, $N_2$ and $N_3$, the excitation dependent parts must be eliminated. In order to realize it, energies related to the excitation, given by

$$E_{01} = \int_{-\infty}^{\infty} |x(t)|^2dt, \quad E_{02} = \int_{-\infty}^{\infty} |x^2(t)|^2dt, \quad E_{03} = \int_{-\infty}^{\infty} |x^3(t)|^2dt, \quad (4)$$
are included in a calibration process. Energies corresponding to the nonlinear terms extracted from the acoustic responses are then given by

\[ E_1 = \int_{-\infty}^{\infty} |s_1(t)|^2 dt = N_1^2 E_{01}, \]  
\[ E_2 = \int_{-\infty}^{\infty} |s_2(t)|^2 dt = N_2^2 E_{02}, \]  
\[ E_3 = \int_{-\infty}^{\infty} |s_3(t)|^2 dt = N_3^2 E_{03}. \]  

Hence the nonlinear coefficients can be obtained by:

\[ N_1 = \sqrt{\frac{E_1}{E_{01}}}, \quad N_2 = \sqrt{\frac{E_2}{E_{02}}}, \quad N_3 = \sqrt{\frac{E_3}{E_{03}}}. \]  

2 ESAM-DORT Analysis

To distinguish the different scatterers in the medium, DORT method is added to the preprocessing nonlinear analysis ESAM. DORT is an approximative method which substitutes the iterative time-reversal process. With use of this method, it is possible to extract echoes corresponding to well-separated defects present in the media (their Green’s functions), which can be used to focus on these defects [5]. Moreover, for each defect, information about its frequency dependent apparent reflectivity is obtained. This is associated to its nonlinear behavior extracted with ESAM.

2.1 DORT method

DORT can be implemented by transmit-receive scheme in a single array or transducers of between two different transducer arrays [7], where the number of transmitters does not necessarily have to be equal to the number of receivers. Let us consider \( K \) transmitters \( E_k, k \in \tilde{K} = \{1, 2, \ldots, K\} \), and \( M \) receivers \( R_m, m \in \tilde{M} = \{1, 2, \ldots, M\} \). Usually in the TR-NEWS experimental configurations, the number of receivers is equal or less than the number of transmitters (\( M \leq K \)). With use of these transducer arrays an inter-element \( K \times M \) matrix \( K(t) \) is constructed from the responses: matrix element \( K_{mk}(t) \) is the signal received on \( R_m \) after emission from \( E_k \). After Fourier transform (\( \mathcal{F} \)), the transfer matrix \( K(f) = \mathcal{F}[K(t)](f) \) is obtained, from which Time Reversal Operators \( T_{Tx}(f) \), \( T_{Rx}(f) \) are constructed according to the basis (transmit or receive) with

\[ T_{Tx}(f) = K^*(f)K(f) \in \mathbb{C}^{K,K}, \]  
\[ T_{Rx}(f) = K(f)K^*(f) \in \mathbb{C}^{M,M}. \]  

Generally, \( T_{Tx}(f) \) and \( T_{Rx}(f) \) are different, but both have the same rank, equal to the rank of \( K(f) \) (\( \text{rank}(K) = D \)), with the same number of non-zero eigenvalues. Since they are both hermitian positives, they can be diagonalized. In practice, the diagonalization of \( T_{Tx}(f) \) and \( T_{Rx}(f) \) is not used, since it is mathematically equivalent to singular value decomposition

\[ K(f) = U(f)S(f)V^*(f), \]  

\[ \mathcal{F}[K(t)](f) = U(f)S(f)\mathcal{F}[K(t)](f) = U(f)S(f)\mathcal{F}[K^*(t)](f) = U(f)S(f)\mathcal{F}[K(t)](f). \]
where $U(f)$ is a $M \times M$ unitary matrix ($U^* = U^{-1}$), $V(f)$ is a $K \times K$ unitary matrix and $\Sigma(f)$ is a $M \times K$ diagonal positive semidefinite matrix. Columns of $U(f)$ are the eigenvectors of $T_{Rx}(f) = K(f)K^*(f)$ (the TRO in receive basis), columns of $V(f)$ are the eigenvectors of $T_{Tx}(f) = K^*(f)K(f)$ (the TRO in transmit basis). The singular values $\sigma_d(f) = \Sigma_{dd}(f) \neq 0$, $d \in D$, corresponding to the transfer matrix $K(f)$ are the square roots of the TRO eigenvalues $\lambda_d(f)$, same in transmit and receive basis. Thus, the apparent reflectivity of the scatterers where their corresponding Green’s functions $g(f)$ are given by the TRO eigenvectors\(^5\). For each frequency component $f_0$ and scatterer $S_d$, a monochromatic Green’s function $g_d(f_0)$ is obtained in transmit $g_d^{(T)}(f_0)$ and receive $g_d^{(R)}(f_0)$ basis together with singular value $\sigma_d(f_0)$:

\[
g_d^{(R)}(f_0) = U_{\bullet d}(f_0) \in \mathbb{C}^M, \tag{12}
\]
\[
g_d^{(T)}(f_0) = V_{\bullet d}(f_0) \in \mathbb{C}^K, \tag{13}
\]
\[
\sigma_d(f_0) = \Sigma_{dd}(f_0) \in \mathbb{R} - \{0\}, \tag{14}
\]

where $U_{\bullet d}$ denotes the $d^{th}$ column of matrix $U$ and $V_{\bullet d}$ denotes the $d^{th}$ column of matrix $V$. For nonlinear parameters evaluation it is necessary to reconstruct the spectrum of broadband Green’s function $g(f)$ and link together singular values $\sigma(f)$ corresponding to given scatterer \[^7\][^8].

### 2.2 Nonlinear parameters of different scatterers

#### 2.2.1 Construction of multistatic data matrices

For the extraction of nonlinear parameters corresponding to the scatterers, DORT is applied on the separated nonlinear terms of direct responses provided by ESAM. This procedure requires measurement of inter-element responses for each excitation necessary for ESAM application. From these responses the nonlinear terms $s_{1, mk}(t)$, $s_{2, mk}(t)$, $s_{3, mk}(t)$ corresponding to the trajectory $|T_kR_m|$ are extracted and finally multistatic data matrices $K^{(1)}(t)$, $K^{(2)}(t)$ and $K^{(3)}(t)$ corresponding to the extracted linear and nonlinear terms are constructed according to

\[
K_{mk}^{(i)}(t) = s_{i, mk}(t), \quad i \in \hat{3}. \tag{15}
\]

#### 2.2.2 Implementation of DORT method

DORT method is applied on each of multistatic data matrices $K^{(i)}(t)$ ($i \in \hat{3}$), as described previously in subsection 2.1. Finally broadband Green’s functions $g_d^{(i)}(f)$ and corresponding singular values $\sigma_d^{(i)}(f)$ are obtained for each matrix $K^{(i)}$ and each separated scatterer $S_d$.

#### 2.2.3 Parameters evaluation

For nonlinear parameters evaluation it is necessary to reconstruct echo associated to every separated scatterer $S_d$ and trajectory $|T_kR_m|$. First extracted singular values $\sigma_d^{(i)}(f)$ undergo
a normalization by corresponding Green’s functions in transmit array \( (g^{(T,i)}_d(f) \in \mathbb{C}^K) \) and in receive array \( (g^{(R,i)}_d(f) \in \mathbb{C}^M) \):

\[
\tilde{\sigma}_{d,km}^{(i)}(f) = \sigma_{d}^{(i)}(f) \cdot g_{d,k}^{(T,i)}(f) \cdot g_{d,m}^{(R,i)}(f),
\]

where \( g_{d,k}^{(T,i)}(f) \) is the \( k \)th element of \( g^{(T,i)}_d(f) \). This normalization introduces trajectory dependence (indices \( k \) and \( m \) correspond to trajectory \( \vert T_kR_m \vert \)) into the nonlinear parameters. Fourier transform of normalized singular values \( \tilde{\sigma}_{d,km}^{(i)}(f) \) give the desired echo \( e_{d,km}^{(i)}(t) \):

\[
e_{d,km}^{(i)}(t) = F^{-1} \left[ \tilde{\sigma}_{d,km}^{(i)}(f) \right].
\]

The corresponding energy \( E_{i}^{(d,km)} \) is given by

\[
E_{i}^{(d,km)} = \int_{-\infty}^{\infty} \left| e_{d,km}^{(i)}(t) \right|^2 dt,
\]

and the nonlinear parameters \( N_{i}^{(d)} \) are finally evaluated for each trajectory \( \vert T_kR_m \vert \):

\[
N_{i}^{(d,km)} = \sqrt{\frac{E_{i}^{(d,km)}}{E_{0i}}} \quad i \in \hat{3},
\]

where \( E_{0i} \) are given by Eq (4).

3 Simulations

The previous theoretical results were tested by simulations (performed in MATLAB) of elastic wave propagation excited by monochromatic signal \( x(t) \) of the frequency \( f_0 = 500\text{kHz} \) in a lossless medium (Figure 1) with celerity \( c = 4500\text{m/s} \).
3.1 Single scatterer identification

First simulation considered presence of a single scatterer ($S_1$), transducers $T_1 - T_4$ as emitters and transducer $R_1$ as receiver. The responses at the receiver $R_1$ were calculated according to the time delays resulting from the propagation distances between the transmitters and the receiver. Each response received on $R_1$ is constructed with a part from direct trajectory, thus an intact excitation signal with appropriate delay and also a contribution from the scatterer $S_1$, also with appropriate delay, in form $y(t) = N_1 x(t) + N_2 x^2(t) + N_3 x^3(t)$, where

$$N_1 = 0.2; \quad N_2 = 0.02; \quad N_3 = 0.002.$$  \quad (20)

The responses were calculated for every excitation necessary for separation of nonlinear parts (subsection 1.1). Parameters $N_1$, $N_2$ and $N_3$ were calculated by Eq. (8) according to previous procedure (subsubsection 2.2.3). The calculated parameters parameters $N_2$ and $N_3$ were equal to prior given values, Eq. (20), same for each trajectory $|T_k R_1|$, $k \in \hat{4}$. As ESAM takes into account all parts of the response, the values of parameter $N_1$ reach almost $1.2 \approx N_1 + 1$, where +1 represents the contribution of direct trajectory (Table 1).

| Table 1: Evaluated parameter $N_1$ versus the corresponding distance ($\Delta S$) and phase ($\Delta \varphi$) differences |
|---|---|---|---|
| eval. $N_1$ | $T_1$ | $T_2$ | $T_3$ | $T_4$ |
| $\Delta S$ [mm] | 0.0479 | 0.2438 | 0.5841 | 1.0291 |
| $\Delta \varphi$ [rad] | 0.0106$\pi$ | 0.0542$\pi$ | 0.1298$\pi$ | 0.2287$\pi$ |

Parameter $N_1$ also shows a variation with regard to the propagation path. This is caused by the position of the defect, i.e. the distance difference $\Delta S$ between the direct trajectory $|T_k R_1|$ and the trajectory via the scatterer ($|T_k S_1| + |S_1 R_1|$) (Table 1). Higher difference may cause a destructive superposition of contributions in Eq. ?? formulated through the phase shift $\Delta \varphi = \frac{2\pi f_0 \Delta S}{c}$ and indeed, the evaluated parameter decreases as distance difference increases.

3.2 Multiple scatterer analysis

Simulation with two scatterers $S_1$ and $S_2$ was performed. Transducers $T_1 - T_5$ were used as emitters and transducers $R_1$ and $R_2$ as receivers (Figure 1). The responses corresponding to the trajectories between the transducers $|T_k R_m|$ were evaluated by similar procedure - each response contains a direct echo of the excitation signal and contributions of the two scatterers with appropriate delays. The parameters of the scatterers $S_1$ and $S_2$ were set to following values:

$$N_1^{(1)} = 0.2; \quad N_2^{(1)} = 0.02; \quad N_3^{(1)} = 0.002, \quad (21)$$

$$N_1^{(2)} = 0.5; \quad N_2^{(2)} = 0.05; \quad N_3^{(2)} = 0.005. \quad (22)$$
Multistatic data matrices $K^{(i)}$, $i \in \hat{3}$, were constructed and each matrix underwent singular value decomposition. The obtained non-normalized singular values $\sigma_1^{(i)}(f)$ and $\sigma_2^{(i)}(f)$ for each matrix $K^{(i)}(f)$, $i \in \hat{3}$, are on Figure 2. From the difference between $\sigma_1^{(i)}(f)$ and $\sigma_2^{(i)}(f)$, it can be assumed that the values of nonlinear parameters were not evaluated properly according to the given values. This assumption is confirmed after nonlinear parameters evaluation which is summarized in Table 2.

### Figure 2: Singular values of matrices $K^{(i)}(f)$ ($i \in \hat{3}$) obtained from simulation with scatterers $S_1$ and $S_2$

### Table 2: Parameters $N_i^{(d)}$ evaluated after application of DORT in simulation with two scatterers

<table>
<thead>
<tr>
<th>$N_1^{(1)}$</th>
<th>$T_1$</th>
<th>$T_2$</th>
<th>$T_3$</th>
<th>$T_4$</th>
<th>$T_5$</th>
<th>$N_1^{(2)}$</th>
<th>$T_1$</th>
<th>$T_2$</th>
<th>$T_3$</th>
<th>$T_4$</th>
<th>$T_5$</th>
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<tbody>
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<td>$R_1$</td>
<td>1.6881</td>
<td>1.6545</td>
<td>1.6432</td>
<td>1.5525</td>
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<td>0.0287</td>
<td>0.0517</td>
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</table>

<table>
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<tr>
<th>$N_1^{(2)}$</th>
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<th>$T_5$</th>
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<th>$T_3$</th>
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<tr>
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<td>0.0055</td>
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<td>0.0686</td>
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<td>$R_2$</td>
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<td>0.0107</td>
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<tr>
<th>$N_1^{(3)}$</th>
<th>$T_1$</th>
<th>$T_2$</th>
<th>$T_3$</th>
<th>$T_4$</th>
<th>$T_5$</th>
<th>$N_1^{(4)}$</th>
<th>$T_1$</th>
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<tr>
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<td>0.0070</td>
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<td>0.0058</td>
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<td>$R_1$</td>
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<td>0.0003</td>
<td>0.0007</td>
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<td>0.0003</td>
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However, it can be observed that maxima of parameters $N_i^{(1)}$ are reached for trajectory $|T_1R_1|$ and for parameters $N_i^{(2)}$ on trajectories $|T_4R_3|$. According to the simulation layout (Figure 1), the scatterers’ positions are near these trajectories. Thus, from the variation of the parameters values, the positions of the scatterers (or the pseudotomographic image) may be assumed. They are most likely to be present near the trajectories corresponding to the maximal values of the parameters $N_i^{(d)}$ (Figure 3).

The reason why the real values of the parameters were not evaluated precisely may be in the implementation of the simplified simulation. The only difference between application of DORT in linear media and the application proposed in this paper is in the signals used to construct the transfer matrix $K(f)$. In linear case this matrix is built from direct responses, in the ESAM-DORT approach the three multi-static matrices $K^{(i)}(f)$ are built from the separated nonlinear terms. Thus at least for the linear term the method should be equivalent. This shows that the failure of DORT method to distinguish the real value of the parameters was caused by the simulation implementation.
Figure 3: Visualization of the trajectories with maximal values of the parameters - the scatterers $S_1$ and $S_2$ lie near these trajectories.

To sum up, even though in used simulation implementation the expected values of parameters $N_1^{(1)}$ and $N_1^{(2)}$ were not obtained exactly, from the variation of those parameters, the pseudotomographic image of scatterers $S_1$ and $S_2$ was obtained: their position is most likely to be near the trajectories, on which the maxima of the parameters $N_1^{(1)}$ and $N_1^{(2)}$ were obtained.

4 Experimental tests

4.1 Practical aspects of ESAM implementation

In practice implementation of ESAM may be difficult, particularly because of the measurement devices, which are not capable to handle complex signals. Therefore some modifications have to be adopted. One possibility is to use amplitude variation of the excitation signals. Amplitude variation of excitations used in our experiments is based on the real and imaginary parts of the original complex excitations (section 1.1), i.e.

$$x_E(t) = x(t), \quad x_A(t) = -\frac{1}{2}x(t), \quad x_{B_1}(t) = \frac{\sqrt{3}}{2}x(t), \quad x_{B_2}(t) = -\frac{\sqrt{3}}{2}x(t)y_{B_2}. \quad (23)$$

According to the hypothesis that $y(t) = N_1x(t) + N_2x^2(t) + N_3x^3(t)$ the nonlinear terms are coming from:

$$s_3(t) = N_3x^3(t) = \frac{4}{3}\left[y_E(t) + 2y_A(t) - y_{B_1}(t) - y_{B_2}(t)\right], \quad (24)$$

$$s_2(t) = N_2x^2(t) = \frac{2}{3}\left[y_{B_1}(t) + y_{B_2}(t)\right], \quad (25)$$

$$s_1(t) = N_1x(t) = y_E(t) - s_2(t) - s_3(t). \quad (26)$$
4.2 Experiment

Experiments were carried out with a steel cuboid containing a relatively large and complex crack. Emitting array consisted of transducers $T_6$, $T_8$, $T_9$, $T_{10}$ and $T_{12}$ of a 16-elements Vermon NDT probe whereas single receiver was used (Figure 4).

Gaussian modulated sine wave of frequency $f_0 = 300kHz$ was chosen as basic excitation signal $x(t)$ with sampling frequency 10MHz. The direct ESAM and ESAM-DORT procedure were carried out and both allowed $N_1$, $N_2$ and $N_3$ extraction as summarized in Table 3.

<table>
<thead>
<tr>
<th></th>
<th>$T_6$</th>
<th>$T_8$</th>
<th>$T_9$</th>
<th>$T_{10}$</th>
<th>$T_{12}$</th>
</tr>
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<tbody>
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<td>$N_1$</td>
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<td>$N_2$</td>
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<td>0.87E-05</td>
<td>0.83E-05</td>
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<tr>
<td>$N_3$</td>
<td>2.04E-08</td>
<td>2.33E-08</td>
<td>1.97E-08</td>
<td>1.69E-08</td>
<td>1.67E-08</td>
</tr>
</tbody>
</table>

Figure 5: Evaluated parameters $N_1$, $N_2$ and $N_3$ versus the trajectories $|T_iR|$, $i \in \{6, 8, 9, 10, 12\}$

The parameters $N_1$, $N_2$ and $N_3$ show a variation with respect to the transducer array $T_6 \ldots T_{12}$. The maximum for parameter $N_1$ is obtained for transducers $T_8$ and $T_9$ (Figure 5) which are affected by the most reflective part of the crack (Figure 4). Parameters $N_2$ and $N_3$ reach maximum for transducer $T_8$. This variation should be explained by the crack characteristics along the propagation paths on these trajectories.
The parameters evaluated from the first preliminary experimental data give the expected information about the presence of a nonlinear signature coming from the crack.

Conclusion

The link between ESAM pre-processing and DORT was established. Simulations and experiments were carried out in order to test the ESAM-DORT performance. Nonlinear parameters evaluation corresponding to different wave paths (trajectories) show a coherence between the variation of the parameters values and the position of the scatterers. The pseudo-tomographic image which could be proposed would be given by the evaluated parameters along different wave-paths. Using ESAM-DORT improves the efficiency of the local TR-NEWS methods applied to the tomography of structural defects.

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