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Noise filtering in the Synthetic Transmit Aperture imaging by Decomposition of the Time Reversal Operator: Application to flaw detection in coarse-grained stainless steels

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Abstract

In the present work, the Synthetic Transmit Aperture (STA) imaging is applied on coarse grained steels using a contact phased-array probe. In order to reduce the noise introduced by the heterogeneous structure, as well as artifacts due to surface guided waves, the Decomposition of the Time Reversal Operator method is performed before calculating STA images.

Keywords: non-destructive testing; ultrasonic imaging; phased-array; heterogeneous materials; noise filtering

1. Introduction

The Synthetic Transmit Aperture (STA) imaging [1], also called Total Focusing Method (TFM) [2], is a delay-and-sum algorithm that provides optimized images in Non-Destructive Testing (NDT). However, this method leads to a poor Signal-to-Noise Ratio (SNR) in the case of noisy materials, such as coarse grained austenitic-ferritic steels of the nuclear industry. The highly heterogeneous structure of these materials yields a strong coherent noise that hides the defect echo and complicates its detection, even at relatively low frequencies. In the present paper, we propose to apply the Decomposition of the Time Reversal Operator (DORT is the French acronym) method in order to improve the detection in such noisy materials.

The DORT method consists of the analysis, in the frequency domain, of the singular values and singular vectors of the full array transfer matrix $\hat{K}(f)$ [3]. The noise filtering is obtained by separating the signal subspace from the noise subspace for each frequency in the transducer bandwidth. The signal subspace identification is based on cross-correlations of the singular vectors with a reference one (e.g., the singular vector at the central frequency or a theoretical one). Then, a filtered matrix $\hat{K}'(f)$ is redefined and an inverse Fourier transform is applied to return to
the time domain. Finally, the STA algorithm is applied to the filtered matrix \( \mathbf{K}'(t) \) to form an image with a reduced structural noise.

2. Theoretical background

2.1. The STA imaging

The STA algorithm is applied to the full array matrix \( \mathbf{K}(t) \). For a \( N \)-element array, \( \mathbf{K}(t) \) contains \( N \times N \) signals. The component \( K_{nm}(t) \) of \( \mathbf{K}(t) \) is the impulse response recorded by the element \( n \) when the transmitter element \( m \) is excited by an electric pulse. The STA image is calculated by summing at every point all the analytical signals \( S_{nm}(t) \), defined as \( S_{nm}(t) = K_{nm}(t) + j\mathcal{H}(K_{nm}(t)) \), where \( \mathcal{H}(K_{nm}(t)) \) denotes the Hilbert transform of \( K_{nm}(t) \). The coherent summation of the analytical signals may be written in the form:

\[
I(r) = \left| \sum_{n=1}^{N} \sum_{m=1}^{N} S_{nm}(t_m(r) + t_n(r)) \right|, 
\]

where \( r \) is the position vector of the focusing point. In imaging with direct modes, \( t_m(r) \) is the direct time of flight between the \( m \)-th transmitter element (represented by the position vector \( r_m \)) and the focusing point:

\[
t_m(r) = \frac{|r - r_m|}{c}.
\]

2.2. The DORT method

The DORT method consists of a singular value decomposition of the full array transfer matrix \( \mathbf{\hat{K}}(f) \) at each frequency in the transducer bandwidth, which may be written as:

\[
\mathbf{\hat{K}}(f) = \mathbf{U}(f)\Sigma(f)\mathbf{V}^\dagger(f),
\]

where the columns of \( \mathbf{U}(f) \) and \( \mathbf{V}(f) \) are the singular vectors of \( \mathbf{\hat{K}}(f) \), and \( \Sigma(f) \) is a diagonal matrix containing the singular values of \( \mathbf{\hat{K}}(f) \) listed in descending order. The analysis of the singular values distribution of \( \mathbf{\hat{K}}(f) \) allows to identify the subspace characterizing the defects for noise filtering operations. In the ideal case of a point-like defect with a low-level structural noise, \( \mathbf{\hat{K}}(f) \) can be expressed as the sum of the two matrices:

\[
\mathbf{\hat{K}}(f) = \sigma_1(f)\mathbf{u}_1(f)\mathbf{v}_1^\dagger(f) + \sum_{q=2}^{N} \sigma_q(f)\mathbf{u}_q(f)\mathbf{v}_q^\dagger(f),
\]

where \( \sigma_q(f) \) is the \( q \)-th singular value, \( \mathbf{u}_q(f) \) and \( \mathbf{v}_q(f) \) are the received and transmitted singular vectors, respectively. The first term in Eq. (4) is the matrix that contains the spectral information of the defect, whereas the second term is a matrix associated with the noise. In practice, for materials with higher structural noise, the precedent assumption is not valid because the singular value associated with the defect is not the dominant one for all the frequencies. The index \( p \) of the singular value associated with the defect varies with the frequency and Eq. (4) becomes:

\[
\mathbf{\hat{K}}(f) = \sigma_{p(f)}(f)\mathbf{u}_{p(f)}(f)\mathbf{v}_{p(f)}^\dagger(f) + \sum_{q \neq p(f)} \sigma_q(f)\mathbf{u}_q(f)\mathbf{v}_q^\dagger(f).
\]

The filtering method consists of the tracking of the index \( p(f) \) for each frequency in the transducer bandwidth.

2.3. Noise filtering with the DORT method

In order to track the index \( p(f) \) of the singular value associated with the defect, the first singular vector \( \mathbf{v}_{\text{ref}} \) at the center frequency \( f_c \) of the transducer is considered as reference \( \mathbf{v}_{\text{ref}} = \mathbf{v}_1(f_c) \). In general, the reference vector \( \mathbf{v}_{\text{ref}} \) contains the delay law \( \tau_{\text{ref}} \) to focus on the defect. This delay law can be extracted from the phase of \( \mathbf{v}_{\text{ref}} \) as follows:
\[ \tau_{\text{ref}} = \frac{\max(\arg(v_{\text{ref}})) - \arg(v_{\text{ref}})}{2\pi f_c}. \]  

(6)

Then, the index \( p(f) \) is determined through the cross-correlation between the delay laws \( \tau_q(f) \) extracted from the vectors \( v_q(f) \) and the reference \( \tau_{\text{ref}} \), which may be expressed as:

\[ p(f) = \arg \max_q \left( \frac{\tau_q^\dagger(f)\tau_{\text{ref}}}{\|\tau_q(f)\| \|\tau_{\text{ref}}\|} \right). \]  

(7)

After identification of the index \( p(f) \) in the whole bandwidth, we can redefine a new matrix:

\[ \hat{K}'(f) = \sigma_{p(f)}(f)u_{p(f)}(f)v_{p(f)}^\dagger(f). \]  

(8)

Only the spectral content of the defect is contained in \( \hat{K}'(f) \) and, in the time-domain, the associated full array matrix \( K'(t) \) contains only information about the defect. The application of the STA algorithm to \( K'(t) \) provides an image with reduced structural noise.

3. Examples of STA images after DORT filtering

In order to evaluate the DORT filtering, experiments have been performed on a coarse grained steel specimen (70 mm thickness). Three side-drilled holes of 2-mm diameter are located at 40, 50 and 60 mm depths. The probe is a contact linear phased-array composed of 32 elements with a center frequency of 1.1 MHz, and a pitch of 1.4 mm. The STA algorithm has been applied to \( K(t) \) and \( K'(t) \) to image the three defects. In each case, the image area is centered on the defect and its dimensions are 40 × 45 mm². The image amplitudes are expressed in dB, with a dynamic range of 30 dB. In Figs. 1(a), 2(a), and 3(a), the singular value distributions present significant values around 0.8 MHz that are not associated with the defect. These values are grouped by pairs, and a theoretical study of the invariants of the time reversal operator in the presence of guided surface waves has shown that these values are associated with leaky Rayleigh waves propagating in opposed directions. Another peak observed around 0.5 MHz is due to the cross-coupling between the adjacent elements.

Fig. 1. Defect at 40 mm depth: (a) Singular value spectrum; (b) STA image without filtering; (c) new image with DORT filtering.

In the STA images of Figs. 1(b), 1(c), 2(b), 2(c), 3(b), and 3(c), we note that the DORT filtering reduces significantly the structural noise. Table 1 gives the quantified SNR of the images for the three cases. The DORT filtering combined with the STA imaging exhibits an improvement of at least 12 dB in comparison with the STA images without filtering.

4. Conclusion

The DORT method has been used to improve the STA imaging in a noisy material. Through the singular value decomposition of the transfer matrix, one is able to select the spectral content useful to describe a defect echo.
In the three cases presented, this approach selects correctly the spectral content associated with each defect, even if they are located in a deep position. The final images, calculated from the filtered matrix, present a significant reduction of the noise and a SNR of at least 30 dB.

As perspective, a coded excitation will be coupled in order to increase the transmitted energy. Another future work will study the case of crack-type defects, to which the DORT filtering will be performed, in order to apply the STA algorithm using the principle of multi-modal imaging.

References