46th Annual Review of Progress
in Quantitative Nondestructive Evaluation
QNDE2019
July 14-19, 2019, Portland, OR, USA

QNDE2019-6778

# REVERSIBLE ULTRASONIC IMAGING FOR FAST SCATTERING MATRIX EXTRACTION

**Eduardo Lopez Villaverde[1], Anthony J. Croxford, Alexander Velichko**
University of Bristol
**Bristol, UK**

## ABSTRACT

*Ultrasonic phased-arrays are used in nondestructive evaluation for detection and characterization of defects. An image is produced by beamforming the array data, which is often enough for detection but not for characterization. More advanced post-processing approaches have been developed to characterize defects based on the scattering behavior. However, in some applications, the defect scattering information cannot be accessed accurately. This is the case in large grained structures where grains act as randomly distributed scatterers contaminating the target information. In this work, we present a fast method to extract an accurate scattering descriptor for a defined region of interest and compare it to other available techniques. This approach reduces the undesired contribution of nearby scatterers by applying spatial filtering to the array data.*

Keywords: inversible imaging, scattering, structural noise

## 1. INTRODUCTION

The use of ultrasonic phased-arrays in nondestructive evaluation is motivated by a desire to provide solutions for increasing the performance of detection and characterization of defects. Developments of imaging methods have facilitated the interpretation of images and then the characterization of critical defects [1], but these are generally limited to the wavelength scale. Subwavelength defects can be alternatively described by studying the scattering behavior using the full matrix capture (FMC) array data. These data contain the inter-element responses of the array. However, when other scatterers are close to the target, the time-responses overlap, contaminating the measured scattering descriptor of interest. This is not unusual, and happens, for example, when a defect is close to a structural feature, or while inspecting a coarse grained structure.

A conventional solution is the subarray approach [2] where sub-apertures are synthetized in order to increase the spatial selectivity. In this technique, an image is first produced to locate the target scatterer, then the subarray data is processed to estimate the scattering information. Nevertheless, the use of large sub-apertures impacts the reliability of the final estimation.

In this work, we present an approach to calculate efficiently the scattering field based on a reversible imaging concept. First, an image is produced using the forward imaging method. Then, the image is spatially filtered according to the region of interest. After that, the reverse imaging operation is performed in order to recover the temporal responses of interest. Finally, the scattering information is retrieved accurately.

This study aims to evaluate the performance of the method in terms of accuracy and computation time compared to existing approaches. The final scattering information is compared to that estimated using the subarray approach.

## 2. MATERIALS AND METHODS

The presented imaging method is the reversible back-propagation approach which is described in [3]. This algorithm is considered as an operator $B$ that transforms the full transmit-receive array data $h(x_{\mathrm{T}}, x_{\mathrm{R}}, t)$ into a generalized image:

$$g(x_{\mathrm{T}}, x_{\mathrm{R}}, z) = B[h(x_{\mathrm{T}}, x_{\mathrm{R}}, t)], \tag{1}$$

where $x_{\mathrm{T}}$ and $x_{\mathrm{R}}$ are the abscissas of the transmitter and receiver elements. This generalized image contains the necessary information for the inverse operation $B^{-1}$, i.e., to recover the array data from the image.

The back-propagation operator is defined as a series of Fourier transforms:

$$B = F_{D_2}^{-1} M F_{D_1}, \tag{2}$$

where $F$ and $F^{-1}$ are the multidimensional direct and inverse Fourier transforms with respect to the spatial coordinates $x_{\mathrm{T}}$ and $x_{\mathrm{R}}$ in their respective domain $D$, and $M$ is the mapping from the temporal frequencies of the array data to the wavenumbers of the generalized image.

[1] Contact author: eduardo.lopezvillaverde@bristol.ac.uk

 

Spatial filtering is performed on the generalized image $g(x_{\mathrm{T}}, x_{\mathrm{R}}, z)$ in order to isolate the spatial information of the scatterers in a region of interest.

The reverse back-propagation operator $B^{-1}$ is then applied to the filtered generalized image. The recovered array data contain only the responses of the scatterers located inside the defined region.

The filtered data set $h'(x_{\mathrm{T}}, x_{\mathrm{R}}, t)$ is finally processed to calculate the scattering field of interest. The accessible behavior for a wave mode is represented by the scattering matrix as a function of the transmitter angle $\theta_{\mathrm{T}}$ and the receiver angle $\theta_{\mathrm{R}}$ [4]:

$$S(\theta_{\mathrm{T}}, \theta_{\mathrm{R}}, f) = h'(x_{\mathrm{T}}, x_{\mathrm{R}}, f) A(\mathbf{r} - \mathbf{r}_{\mathrm{T}}, \mathbf{r} - \mathbf{r}_{\mathrm{R}}, f), \qquad (3)$$

where the function $A$ is a correction term according to the geometry of the array elements and the position $\mathbf{r}$ of the target.

Two implementations of the presented method are developed. The first uses 3D fast Fourier transforms. In the second implementation, the back-propagation is performed using a delay-and-sum approach [5]. Direct and inverse imaging operations are implemented in parallel on a graphics processing unit (GPU).

A numerical study in a grained structure is carried out to compare the performance of the proposed algorithms against the subarray approach. Complexity, memory cost, computation time, and accuracy of the extracted scattering matrices in different scenarios, including experimental data, are evaluated.

## 3. RESULTS AND DISCUSSION

The subarray approach is a low-cost manner to understand the scattering behavior. This operation is based on temporal transmit-receive responses which are initially frequency filtered around the frequency of interest. Moreover, in order to obtain the scattering information at different frequencies, the subarray method needs to be performed for each frequency separately. Also, the size of the subarray is an important parameter for the scattering matrix extraction which is chosen arbitrarily.

The reversible back-propagation is a more complex method, yet computed relatively fast. For example, the image formation can be run in real-time, and it is possible to extract about 10 scattering matrices per second. This is very useful when many positions of the image need to be analyzed, or for the creation of large databases. Unlike the subarray approach, this procedure provides the whole frequency spectrum of the scattering matrix, preserves phase information and is more readily suited to minimizing the effects of multiple scattering. It is shown that the two suggested implementations of the back-propagation algorithm extract scattering coefficients with the similar accuracy. However, the processing based on 3D Fourier transforms demands significant hardware memory. For large volumes of data, the delay-and-sum approach may be preferred.

## 4. CONCLUSION

The reversibility of the back-propagation is here used to isolate the responses of a defect or a feature in a region of interest. The filtered data set is exploited to extract the frequency-dependent scattering information of the target from the raw transmit-receive array data. A parallelized implementation of this procedure is suitable for real-time characterization. The high rate of the method allows thousands of scattering matrices to be extracted in a few minutes.

## REFERENCES

[1] Zhang, Jie, Drinkwater, Bruce W. and Wilcox, Paul D. “The use of ultrasonic arrays to characterize crack-like defects.” *Journal of Nondestructive Evaluation* Vol. 29 No. 10 (2010): pp. 222-232.

[2] Zhang, Jie, Drinkwater, Bruce W. and Wilcox, Paul D. “Defect characterization using an ultrasonic array to measure the scattering coefficient matrix.” *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* Vol. 55 No. 10 (2008): pp. 2254-2265.

[3] Velichko, Alexander and Wilcox, Paul D. “Reversible back-propagation imaging algorithm for postprocessing of ultrasonic array data.” *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* Vol. 56 No. 11 (2009): pp. 2492-2503.

[4] Schmerr Jr., Lester W. *Fundamentals of Ultrasonic Nondestructive Evaluation: A Modeling Approach*. Springer, New York (2016).

[5] Karaman, Mustafa, Li, Pai-Chi and O’Donnell, Matthew. “Synthetic aperture imaging for small scale systems.” *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* Vol. 42 No. 3 (1995): pp. 429-442.

 