FLAW DETECTION IN HIGHLY SCATTERING POLYCRYSTALLINE MATERIAL: IMPROVEMENT OF THE PERFORMANCES BY THE USE OF PHASED ARRAY PROBES AND SMART FILTERING TECHNIQUE

F. Rupin, S. Shahjahan, B. Chassignole, EDF - R&D, France
A. Aubry, A. Derode, Institut Langevin, Université Paris Diderot, ESPCI, France

ABSTRACT

Flaw detection using ultrasonic non destructive testing on coarse grain steels commonly found in nuclear power plants is disturbed by a high backscattered noise. This leads to a decrease of the detection capabilities of common ultrasonic testing techniques, particularly at high frequencies and large depths for which multiple scattering dominates. Recent studies have shown that the contribution of single scattering could be extracted from multiple scattering in complex medium. These results were obtained on a model random medium made of parallel steel rods immersed in water. They showed that, when using a phased array probe, the ability to detect a target could be significantly increased using a smart filtering method, based on the application of the matrix theory on FMC (full matrix capture) acquisition, in supplement with the D.O.R.T. (French acronym for the decomposition of the time-reversal operator) method.

In this work, this new method is applied to an industrial material made of a nickel based alloy (Inconel600®) exhibiting a thermally-induced coarse grain structure. Experimental results on flaw detection of 2mm side drilled holes located at various depths in the mock-up are presented and compared to the classical detection techniques. Despite the existence of high structural noise when inspecting this material in the 2-5 MHz frequency range, a very significant improvement of the detection performances is observed. The advantages and limitations of the method are also discussed in this work.

Keywords: Ultrasound, Multiple Scattering, Noise, DORT Imaging, Array Processing, Flaw Detection

INTRODUCTION

Detection performances of ultrasonic techniques decrease for materials with a coarse grain structure. In particular, in the case where the characteristic grain size is comparable to the wavelength, scattering of ultrasonic waves at grain boundaries attenuates, distorts the wave and also generates a so-called “structural noise” which decreases detection capacities [1, 2].

Propagation of waves in a highly scattering medium has been the subject of many studies dealing with the development of theoretical backscattering models [3-6] or with the improvement of the signal-to-noise ratio [7-13]. From an experimental point of view, the development of phased array probes has also opened new perspectives for the UT characterization and inspection of heterogeneous materials. In particular, solutions to improve imaging in polycrystalline media using the advantages of phased array acquisitions emerge. Indeed, by means of the full matrix capture (FMC) [14, 15] and proper post-processing, it is possible to optimize target detection in homogeneous or weakly scattering media. For instance, the Total Focusing Method (TFM) allows creating an image as if the beam had been focused on every point of it. Consequently, it generally increases the signal-to-noise ratio compared to conventional imaging [16]. Time-reversal imaging is also possible by using a phased array to optimize target detection [11, 17, 18]. But both of these techniques are limited in presence of strong multiple scattering. Recent studies on the reduction of the multiple scattering contribution have been developed on synthetic model media (forests of steel rods immersed in water) in order to improve target detection in a scattering environment [19]. These studies, based on random matrix theory, discriminate single and multiple scattering contributions in the total backscattered signals. The technique relies on a particular property of single scattering: a deterministic coherence along the anti-diagonals of the response matrix.
The purpose of this paper is to apply this concept to an industrial metallic polycrystalline sample exhibiting strong ultrasonic scattering. Experiments were performed on a nickel-based alloy (Inconel600®) exhibiting a coarse grain microstructure in which four side-drilled holes (SDH) have been manufactured. First, the basic principles of the separation and detection method are described. Then the experimental results (particularly the detection rate and the signal-to-noise ratio) are presented and compared to the total focusing method (TFM). A significant improvement is demonstrated.

DENOISING OF THE ACOUSTIC SIGNAL

General principle
In highly diffusive material, the structural noise limits flaws detection and can create false alarms. A previous study has shown the possibility to separate the multiple scattering (noise) from the single scattering part of the signal. The details of the method have been published elsewhere [19, 20] but briefly, it is based on the acquisition of the transfer matrix of the material using a N-element linear array probe. A pulse is emitted from element i and the backscattered signal is recorded on the N elements of the array (Figure 1). The same operation is repeated with the N emitters. The response from transducer i to transducer j is then correlated with the emission signal to create $h_{ij}(t)$ impulse response of the couple (i,j). The N×N inter-element matrix $H$ is finally composed of all impulse responses $h_{ij}(t)$.

Once $H(t)$ is acquired, a filtering method developed from the random matrix theory is used to reduce the multi-scattering part of the signal. The details of the method are explained in [19, 20]. Briefly, it is based on the fact that, in the Fourier domain, two typical behaviors of the inter-element matrix can be observed whether the Single Scattering (SS) or the Multiple Scattering (MS) dominates [21]. When MS dominates, the matrix was found to be similar to a classical random matrix, whereas when SS dominates it is similar to a Hankel matrix. As a consequence, it implies that whatever the medium, as long as there is only single scattering the elements of the matrix have a long-range deterministic coherence along their anti-diagonals. On the contrary, when multiple scattering dominates, there is no such coherence. This is the key to separate single and multiple scattering contributions. By and large, the idea consists in extracting from the total matrix the part that exhibits the particular form of coherence using a projection in an appropriate base.

Finally, the target detection is achieved by the DORT (French acronym for decomposition of the time reversal operator) method applied to the filtered matrix in order to detect more efficiently the manufactured defects [19, 20].

MATERIAL AND EXPERIMENTAL SET-UP

The inspected medium is a block of 90×90×280mm³ made of Inconel600® which is a nickel-based alloy commonly used in the nuclear industry. It contains four side-drilled holes (SDH) of radius 1mm, located at depths 10, 30, 50 and 70mm from one face and 20 to 80mm from the other face (Figure 2a). This block was harvested from a forged bar and underwent a specific heat treatment to induce a growth of the mean grain size. Metallographic and EBSD analyses performed on a 17×13mm² sample yield the mean grain size (750 µm), and the standard deviation around the mean

![Figure 1: Principle of the full matrix capture sequences, here the signal $h_{ij}(t)$ with i=3 and j∈[1;19] is illustrated.](image-url)
value is 400 µm. In Table 1, the characteristics of the two 128-element linear arrays used in the experiments are summarized.

The block is immersed in a water tank and the probes are in contact configuration (Figure 2a). The acquisitions of \( H(t) \) in presence of a defect are realized at 11 different probe positions recorded along the axis of each flaw (y axis in Figure 2b). The probe is centered on the flaw position along the x-axis.

**Table 1**: Array probes characteristics; \( r \) is the average wavelength / mean grain size ratio.

<table>
<thead>
<tr>
<th></th>
<th>Central Frequency</th>
<th>-6dB Bandwidth</th>
<th>Element size (mm²)</th>
<th>Pitch (mm)</th>
<th>Sampling (MHz)</th>
<th>( r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Array Probe 1</td>
<td>3 MHz</td>
<td>2.5 - 3.3 MHz</td>
<td>0.39×12</td>
<td>0.417</td>
<td>40</td>
<td>2.6</td>
</tr>
<tr>
<td>Array Probe 2</td>
<td>5 MHz</td>
<td>3.3 - 6.8 MHz</td>
<td>0.3×15</td>
<td>0.5</td>
<td>100</td>
<td>1.56</td>
</tr>
</tbody>
</table>

![Figure 2](image.png)

Figure 2: Illustration of the experimental set-up (a) and the acquisitions along the flaws (b).

**EXPERIMENTAL RESULTS ON VOLUMIC FLAW DETECTION**

**Total Focusing Method (TFM)**

Once the matrix \( H(t) \) is acquired, classical post-treatment can be realized by summation and time shift operations on the \( h_{ij}(t) \) signals in order to create a synthetic image of the medium [14, 22]. For example, adjacent elements responses can be added to create a plane wave or shifted and summed to steer the beam. Synthetic images can also be obtained using the total focusing method (TFM) [14, 22]. Signals from all the elements on the array are summed to synthesize a focus at every point \((x,z)\) of the inspected zone as Eq. (1).

\[
I(x, z = ct) = \sum_{i,j}^N h_{ij} \left( \frac{\sqrt{(x_i - x)^2 + z^2} + \sqrt{(x_j - x)^2 + z^2}}{c} \right). \tag{1}
\]

\( c \) is the longitudinal wave velocity, \( x_i \) and \( x_j \) are respectively the emitter and receiver positions. This amounts to focus the ultrasonic beam, in emission as well as in reception. The resulting image can be interpreted as a reflectivity map. As typical examples, Figure 3 shows TFM images obtained at different depths and frequencies. The structural noise level becomes so important that the flaws are hardly detectible beyond 70mm at 3 MHz (50mm at 5 MHz). For smaller depths, the flaws are correctly detected.
DORT method combined with multiple scattering filtering

DORT imaging was then applied before and after filtering obtained in the flaw’s area. An example of the images obtained for one of the deepest flaws (70mm) with the 5 MHz array is given in Figure 4. This corresponds to the worst configurations in terms of flaw detection. It undoubtedly shows the benefit of the MS Filtering (MSF) procedure, which is meant to eliminate multiple scattering. In Figure 4a and b, TFM and classical DORT images are too noisy and the defect is not detectable. On the contrary, the echo of the side drilled hole (SDH) is clearly visible once the “multiple scattering filter” is applied (Figure 4c). The MSF image also shows some spikes here and there (yet of much lower amplitude than the defect itself), which are false alarms.

Detection rate and SNR

Since we deal with a random structure, the spectacular result of Figure 4 might be just a lucky strike. In order to compare the results of all three techniques, a systematic study was achieved for 11 realizations of each SDH (Figure 2b). Two indicators are used to furnish quantitative evaluation of the performances of the techniques. The first indicator is a signal-to-noise ratio (SNR) defined as:

$$SNR^X = 20 \log \frac{A_{max}^X}{N_{max}^X}$$  \hspace{1cm} (2)

The superscript X represents the technique used (TFM, DORT, MSF DORT). It is computed, for each realization, as the ratio of $A_{max}$ (the maximum amplitude in the flaw area) to $N_{max}$ (the maximum noise amplitude for the same realization in a time window corresponding to depths between ±10mm around the flaw, see Figure 5).
The second indicator is a detection rate: as often in NDT, the flaw is considered to be detectible if SNR≥3dB.

Table 2 summarizes the detection rates (evaluated on the ensemble of 11 positions along the same defect as illustrated in Figure 2b) and the mean SNR on the detected cases. First, these results show that for all three techniques, detection is more difficult at 5 MHz, which is not surprising since attenuation and structural noise increase with frequency in the stochastic domain. Second, a clear improvement of the detection rate is observed at large depths by using the combination of DORT method and MS filtering, particularly for the 5 MHz array. The mean SNR is also significantly increased which lets one expect that for less echogenic flaws than SDH, this technique might give interesting results.

Table 2: Experimental results: comparison of detection rates and means SNR for all three techniques.

<table>
<thead>
<tr>
<th>Imaging technique</th>
<th>Frequency of 3MHz</th>
<th>Frequency of 5MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDH 30</td>
<td>100% 100% 100%</td>
<td>8.9±1.9 17.0±2.4 15.5±3.6</td>
</tr>
<tr>
<td>SDH 40</td>
<td>100% 100% 100%</td>
<td>14.1±1.5 17.9±2.5 20.4±7.6</td>
</tr>
<tr>
<td>SDH 50</td>
<td>100% 100% 100%</td>
<td>16.2±5.2 16.9±4.5</td>
</tr>
<tr>
<td>SDH 60</td>
<td>100% 100% 100%</td>
<td>16.0±6.6 14.2±5.8</td>
</tr>
<tr>
<td>SDH 70</td>
<td>64.5% 12.8% 92%</td>
<td>13.8±8.2 16.6±9.2</td>
</tr>
<tr>
<td>SDH 80</td>
<td>0% 27.3% 9%</td>
<td>7.2±7.2 9.53</td>
</tr>
</tbody>
</table>

Detection rate (%)  Mean signal to noise ratio (dB)

**FIRST RESULT ON A PLANE DEFECT**

An additional flaw was introduced inside block B4: an emerging notch of 20mm height perpendicular to the backwall face (Figure 6). The same experiment than for the SDHs was carried out with a 128-element linear array of 2 MHz. The results when applying the three post-processing techniques (TFM, DORT, MS DORT) are given Figure 7. With the TFM, a discontinuity of the back-wall echo is observed due to the shadowing of the notch but the defect itself is not detected. Similarly, the classical DORT method fails though it shows strange artifact at higher depth. On the contrary, the MSF DORT reveals clearly an echogenic signature, roughly corresponding to the notch extension. However, it has to be noted that it is just a first attempt on one inspection configuration, so it is difficult to draw general conclusions but the potential of the MSF DORT is enhanced.
CONCLUSIONS AND PROSPECTS

Experimental results regarding flaw detection on a nickel-based alloy block exhibiting a coarse-grain structure were presented. A novel imaging technique, the DORT method combined with the MS filtering, was compared to the Total Focusing Method. At large depths and higher frequencies, classical imaging techniques are clearly not adapted to detect flaws in such scattering microstructures. However the improvement of flaw detection by reducing the multiple scattering contribution is spectacular. Yet the method proposed here is naturally not perfect and, for instance, some false alarms were produced. The present experimental results must be completed e.g., by a study of the influence of the microstructure (grain size, etc.), on the SNR, the detection rates and the persistence of false alarms. New experimental results on more complex structures and defects are currently on hand, as well as numerical simulations on various microstructures, in order to challenge the robustness of this promising technique.

ACKNOWLEDGEMENTS

A. Derode is grateful for funding provided by the Agence Nationale de la Recherche (ANR-11-BS09-007-01, Research Project DiAMAN 2011-1015). EDF R&D (Électricité de France – Recherche & Développement) is grateful for funding provided by the Association Nationale de la Recherche et de la Technologie (ANRT).
REFERENCES