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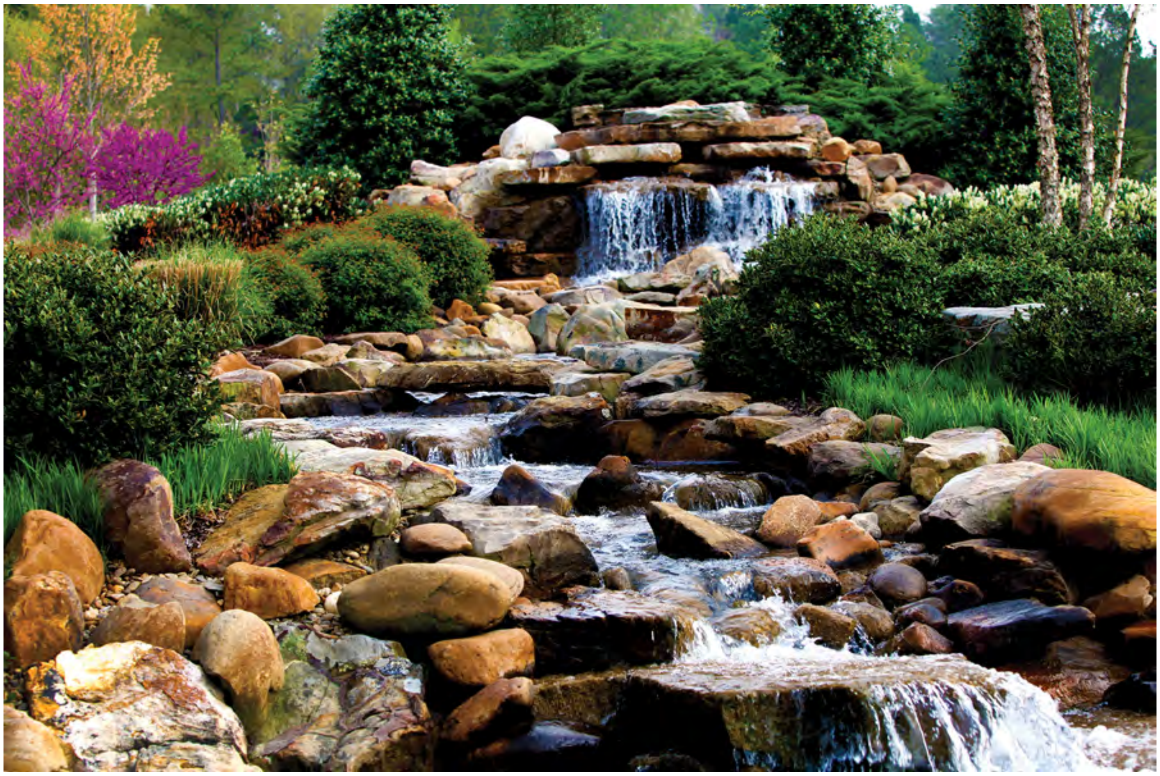
Ultrasonic Model Based Iterative Reconstruction of Experimental Concrete Specimens at EPRI



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January 2022

OAK RIDGE National Laboratory

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Nuclear Energy and Fuel Cycle Division
Electrification and Energy Infrastructure Division

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ABSTRACT

Concrete is a critical component of nuclear power plants (NPPs) for both safety and reliability issues. The original plant designers could not have anticipated the extended lifespan these facilities may reach. Continuous monitoring of the concrete for signs of degradation through nondestructive evaluation (NDE) may be applied to many levels of NPP infrastructure. To that end, ultrasonic measurements have been an industry standard for both surface and subsurface inspections. Oak Ridge National Laboratory is developing advanced image reconstruction algorithms to extend the limitations of ultrasonic NDE.

1 INTRODUCTION

Oak Ridge National Laboratory (ORNL) began research in nondestructive evaluation (NDE) of concrete in 2012 under the Light Water Reactor Sustainability (LWRS) program [1]. Since the initial studies, research has focused on the development of improved reconstruction algorithms to reduce artifacts and noise, as well as to increase precision. The synthetic aperture focusing technique (SAFT), a widely used and accepted reconstruction method that can be applied to ultrasonic data, was initially selected for NDE of concrete structures. Using the speed of sound and time-of-flight signal, SAFT compiles many A-scans into a specialized B-scan to generate a cross sectional image. The cross sectional image, or color-based map of the round-trip distance (or reflection), was a compilation of signal amplitudes between a transmitter (Tx) and receiver (Rx) pair and was calculated by converting the time traveled between Tx and Rx.

However, SAFT is known to contain artifacts and scatter noise, and it has a limited ability to reconstruct objects or defects behind solid objects such as rebar. Because a large portion of concrete infrastructure contains reinforced rebar, this poses an issue for structural health monitoring in larger concrete specimens. To improve and leverage the extensive knowledge base, a frequency-banded SAFT (FB-SAFT) technique was developed, which was a modification of the SAFT workflow through division of the time-series data into frequency bands. The FB-SAFT is based on wavelet packet decomposition or the wavelet node containing the nominal center frequency of the ultrasonic instrument [2], [3], [4].

Recognizing the need for an even more comprehensive reconstruction technique, an ultrasonic model–based iterative reconstruction (U-MBIR) technique was developed. This was motivated by image reconstruction methods applied to large 6–7 ft (2 m) thick concrete. It was observed that there was a lack of back-wall reflections, suggesting that ultrasonic energy was being absorbed or dissipated without reflecting back to the receivers [5]. The U-MBIR method is novel because it does not process individual scans separately and then stitch the results together; instead, the model accounts for all measurements made from the entire scan, thereby reducing stitching artifacts. The application of U-MBIR to forward-model one-sided ultrasonic measurements applies the maximum posteriori probability (MAP) estimation using the minimization problem (i.e., minimizing cost function with data fidelity and regularization):

$$\begin{aligned} x_{MAP} &= \underset{x}{\operatorname{argmax}} \left\{ -\log p\left(y \mid x\right) - \log p\left(x\right) \right\} \\ &= \underset{x \geq 0,\, g,\, \sigma^2}{\operatorname{argmax}} \left\{ \frac{1}{2\sigma^2} \|y - Ax - Dg\|^2 + \frac{MK}{2} \log\left(\sigma^2\right) + \sum_{\{s,r\} \in C} b_{s,r}\, \rho\left(x_s - x_r\, \sigma_{g_{s,r}}\right) + \sum_{s \in S} \frac{x_s}{\sigma_{e_s}} \right\}, \end{aligned} \tag{1}$$

where x is the ultrasound image *to be* reconstruction, y is the raw data from the instrument, x_{MAP} is the ultrasound reconstructed image, $p\left(y \mid x\right)$ is the forward model and probability distribution of y given x, and

$p(x)$ is the prior model and the probability distribution of x [6]. A represents the linear propagation matrix, D is a matrix representing the direct arrival signal, g is a scaling for the direct arrival signal, σ is the standard deviation of the measurement noise, $b_{s,r}$ is a set of weights between neighboring voxels, *rho*(.) is an MRF-based penalty applied to the difference between neighboring voxels, and σ_g and σ_e are smoothing parameters [7], [8].

A linear forward model was developed that accounts for

- direct arrival of the ultrasound signal,
- delay in received signal due to reflections in the concrete,
- attenuation effects in the sample,
- Gaussian measurement noise present, and
- shape of the ultrasound beam.

All of the previously discussed algorithms require extensive and diverse datasets to improve the reconstruction techniques. Computer-generated scenarios were initially used in the development of FB-SAFT and U-MBIR. Based on these scenarios, several concrete specimens were created to support NDE studies [9], [10], [11]. Additionally, the Electric Power Research Institute (EPRI) provided data from a blind study of four large concrete specimens that are being used to for additional improvement of the U-MBIR algorithm.

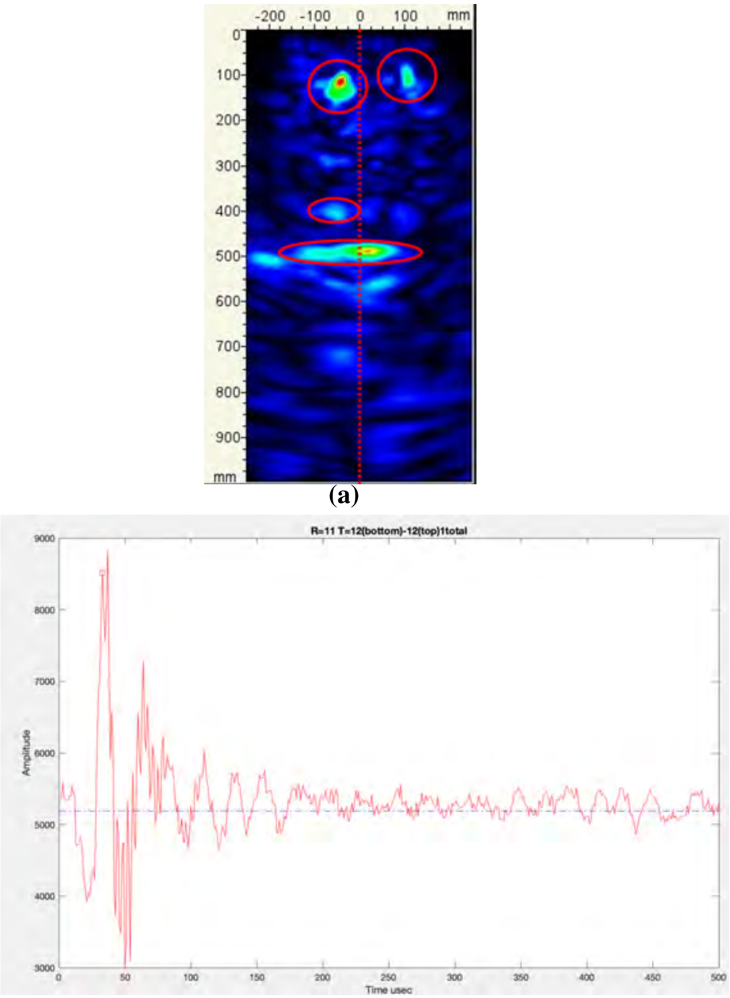
2 EXPERIMENT DESCRIPTION

The LWRS program has supported ORNL's collaboration with EPRI since 2012 toward the development of a roadmap to serve as guidance for the NDE community focused on concrete degradation within nuclear power plants. EPRI is a well-known leader in training, development, and implementation of NDE techniques. For these reasons, EPRI is one of many possible users of the U-MBIR technique. Image reconstruction of their most recent blind study experiment continues to build upon that collaboration.

In 2017, EPRI conducted a blind international study enabling the NDE community to perform measurements to validate and test with instrumentation and reconstructions algorithms. Four concrete measurement datasets containing varying defects were fabricated and designated: Alpha, Bravo, Charlie, and Delta. Specimen thicknesses and defect locations were different for each measurement. Since this is a blind study, the defect, location, and other impediments were not provided to NDE collaborators. However, since ORNL was post-processing the data, limited information was provided to help with the validation of algorithm processing, as seen in Fig. 1a. The MIRA instrument generates a fast image reconstruction using SAFT. A visual is displayed on the handheld instrument and saves the A-scan and B-scan data locally. This data is then transferred to a computer for more in-depth analysis. The MIRA reconstruction displays possible rebar at the top of the image and defects around 400 mm and 500 mm.

Note the high levels of noise in the background.

EPRI used a MIRA ultrasonic system containing 48 transceivers in a 12 column by 4 row topology. Sequentially, during each measurement (single dataset), 4 rows transmit simultaneously and the adjacent 4 rows receive, resulting in a complete file containing 66 signals. The sensor rows are spaced approximately



(a)

(b)

Figure 1. (a) MIRA reconstruction produced by EPRI for ORNL reconstruction evaluation and (b) A-scan between Tx-1 and Rx-2 transceiver pair.

30 mm apart with a thickness measurement range of 50–600 mm. Measurements were acquired on a 10 cm by 10 cm grid format with overlapping files in the x-direction (see previous discussion on overlapping data files). An A-scan between Tx-1 and Rx-2 transceiver pair from a single measurement of Alpha concrete specimen is shown in Fig. 1b.

3 RESULTS

The data were reconstructed by the ORNL team from the Alpha sample using the first row that contains nine scans. The input signal to generate the A matrix for the U-MBIR method was performed by assuming three cycles of a 50 kHz signal modulated by a Gaussian envelope. Prior knowledge required for this reconstruction method includes the following:

- The speed of sound was set to 2625 m/s and the dispersion coefficient was set to $30 \times 10^{-6} Hz^{-1}$.
- The same signal was used to determine the direct arrival matrix D in the MBIR method.
- The first 30 time samples at each receiver were zeroed out to eliminate errors caused by potential synchronization issues.
- The regularization parameters were set to obtain a reconstruction of reasonable visual quality.

Fig. 3 shows a single reconstructed cross section from the EPRI system and the U-MBIR method. Notice that the MBIR algorithm significantly suppresses the background noise while delineating features of interest. Note that the resolution of the features are lower in MBIR. We believe this can be improved with better knowledge of the transmitted signal, speed of sound, and other system-dependent parameters for the MIRA system. Fig. 2 shows the reconstruction of all nine cross sections from the Alpha $1 - x$ data set. The reconstructions show various features in the sample, including the back-wall at the expected location. ORNL plans to compare these to the reconstructions from the EPRI-MIRA system in the future.

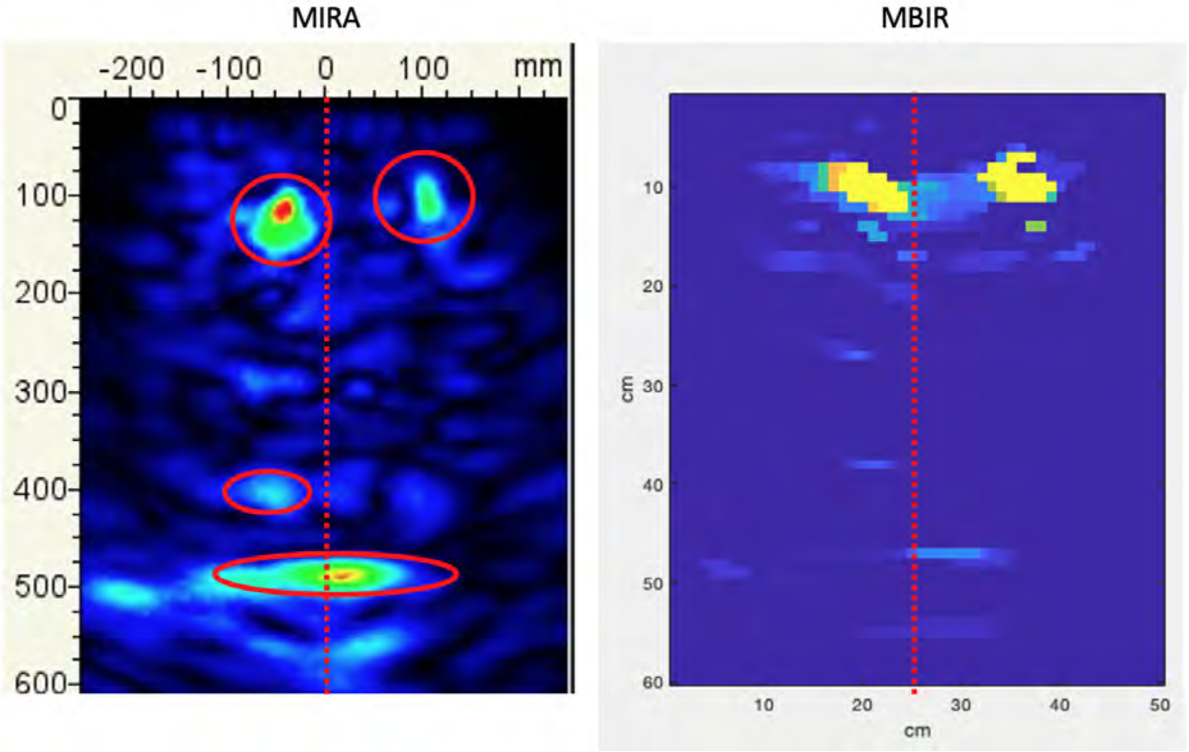


Figure 2. MIRA reconstruction produced by EPRI and MBIR reconstruction of Alpha 1-1 cross section.

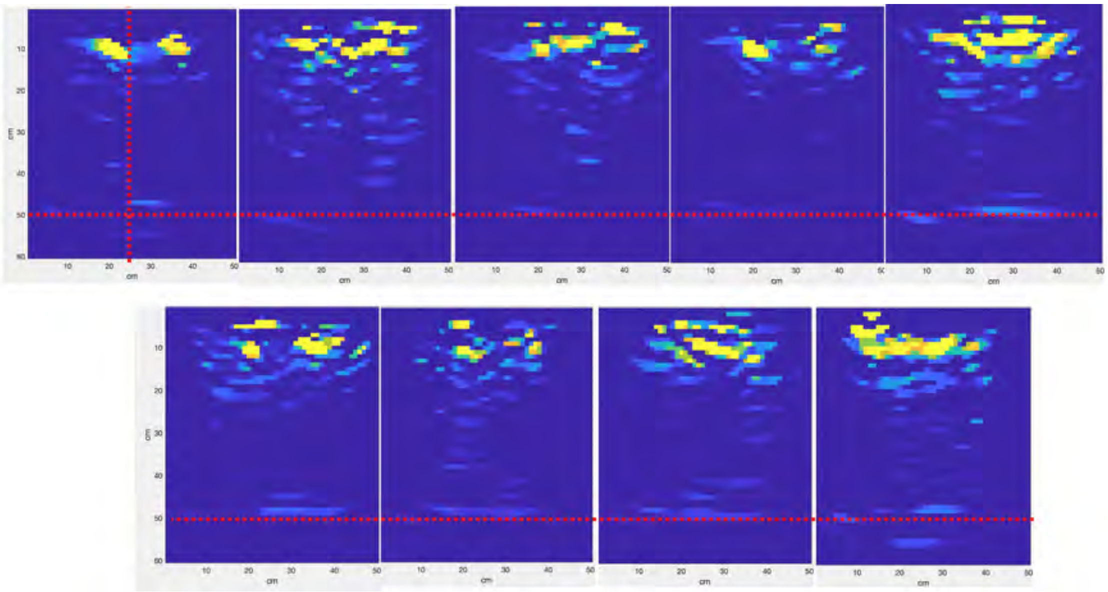


Figure 3. MBIR reconstruction of Alpha 1-1 to 1-9 cross sections produced by the MBIR algorithm.

4 CONCLUSIONS AND FUTURE WORKS

Further refinement and development of the proposed U-MBIR is necessary to establish reliable, accurate, and robust reconstruction images. Researchers will continue to explore the capabilities of the proposed algorithm using the data collected from the four concrete samples discussed herein. More specifically, key parameters embedded within the image reconstruction code will be adjusted to more accurately capture and characterize the collected specimen data. To this end, several staff that are new to the project will be trained to use the U-MBIR code. This multi-disciplinary team will assist in improving the algorithm's ability to handle dynamic input including values of important parameters that should be automatically optimized within the code. In the near term, the goal is to fine-tune the U-MBIR code to ensure accurate depictions of the embedded defects within the concrete samples with relatively low uncertainty. In particular, the identification of rebar is of great concern and a key metric in understanding the performance of the reconstruction code.

After developing this robust code, the aim of this project will be to perform a sensitivity analysis to validate and calibrate the proposed U-MBIR approach on new datasets. Important factors that should be explored include sensor type/configuration, steel reinforcement location/size/condition, and material composition/strength/stress-state. Monitoring of material degradation and performance in extreme environments should also be considered. For example, concrete specimens subjected to ASR could provide more insight regarding the capabilities, limitations, and robustness of the U-MBIR. Overall, in the long-term, the objective of this project will be to continue to collaborate with EPRI and other university partners to further develop, improve, verify, and calibrate image reconstruction techniques considering a variety of material properties, hazards, and experimental configurations.

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