EXTENDED SYNTHETIC APERTURE FOCUSING TECHNIQUE FOR ULTRASONIC IMAGING OF CONCRETE

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Abstract

Quantitative nondestructive characterization of defects and inclusions in portland cement concrete structures are realized in this paper via extended reconstructions for linear array ultrasound systems. This is accomplished through generalization of traditional Kirchhoff -based synthetic aperture focusing technique migration to mitigate the effects of limited aperture and handle multiple scans as a single virtual array with increased effective aperture. Pearson's correlation is utilized to account for uncertainty in relative position of individual measurement and mitigate the need for robotic precision when placing adjacent scans. The robustness of the method is demonstrated on artificially generated data as well as in-situ measurements for assessment of internal portland cement concrete characteristics such as inclusions and cracks.

Keywords: concrete, ultrasound, array, SAFT, imaging

1 INTRODUCTION

There is a longstanding interest in nondestructive characterization of portland cement concrete (PCC) structures, which comprise a significant portion of civil infrastructure [1]. Active elastic wave-based methods, such as impact-echo and ultrasound have been used with varied success for these applications. For example, conventional impact echo is capable of detecting planar layer interfaces [2- 4]. Further advancements such as air coupled impact-echo have allowed for more convenient and productive measurements and multiple measurement pairs [5-10]. Dry-point contact (DPC) low-frequency (~50kHz) shear wave ultrasonic transducers have been shown to mitigate issues with signal variability and sensor positional shift instability [11-13]. Various versions of self-contained DPC pulse-echo arrangements of these transducers have been successfully used for characterization of civil engineering materials [14-18].

In addition to hardware improvements, significant progress has been made in the data processing and interpretation. Traditional A- and B-scan analysis has been improved through the introduction of Kirchhoff-based migration techniques, most notably the synthetic aperture focusing technique (SAFT) [19-21]. However, there are limitations in analysis of some important practical problems due to effects of limited aperture within each self-contained scan [22, 23]. A major factor in this effect is the dependence of the reflectivity within each reconstruction on the relative position below the self-contained device, interfering with the ability to characterize changes in reflectivity within the region of interest (ROI) of the evaluated structure. As explained by Shokouhi et al. (2014), the limited aperture can create situations where “measurements may be inconclusive if the array is located directly above an edge of a defect [23].” These effects, where the magnitude of reflection is affected by the position relative to the aperture and not on the characteristics of interest, can cause misinterpretations.

In this paper, the effect of limited aperture is addressed through generalization of the reconstruction process using overlapping measurements. This creates an effective virtual aperture that is adaptable to the desired region of interest (ROI). The method is also shown to account for uncertainty in the measurement process to eliminate the need for robotic precision. The feasibility and effectiveness of the proposed method for detection of various internal

concrete characteristics is evaluated using artificially generated data and measurements of in-situ concrete structures.

2 METHOD

2.1 Equipment and Data

While the method presented in this paper can be used in conjunction with other linear array systems and testing mediums, the data collected herein were from various PCC structures with a specific linear array device with emitting and receiving DPC transducer pairs at set spacing [11, 15, 24]. This data was used to demonstrate the capability of the proposed extended reconstruction method for evaluation of PCC structures. The data from each scan consists of multiple transmitting and receiving impulse time-history measurements. Figure 1 shows a simple schematic of a PCC slab on a reflecting interface to illustrate the arrangement of the testing equipment and a typical impulse time-history response. Figure 1a shows a schematic of emitting and receiving transducer locations as well as supplementary information describing the type of response evaluated in this study. While a simple schematic of all measurement pairs is denoted with gray lines, a 200 mm spaced transducer pair location is highlighted in black. For this pair, the travel path for a direct shear wave arrival as well as the round-trip travel path reflecting at the depth of the PCC slab thickness “backwall” is shown. Figure 1b shows the corresponding impulse time-history of a scan on an approximately 300 mm thick PCC pavement [25]. A peak in magnitude of the response at the receiving transducer can be observed at the time associated with the shear wave direct arrival as well as the backwall reflection caused by a change in acoustic impedance at the depth of the PCC slab.

Figure 1: Illustration of the type of data utilized in this paper including a [a] schematic of the measurement setup on a concrete slab including direct and reflection arrival paths and [b] example impulse time history from a transducer pair spaced by 200 mm.

To describe the linear array system, let it have T transducers equally spaced at Δx , and numbered from left to right where transducers from 1 to $T-1$ are emitting and from 2 to T are receiving. Figure 2 shows an example linear array setup with x'_1 being the leftmost transducer channel. The leftmost emitting transducer is located at the leftmost transducer location, $x'_{e1} = x'_1$, leftmost receiving transducer is located adjacent to the leftmost emitting transducer $x'_{r1} = x'_{e1} + \Delta x =$

x'_{e1+1} , rightmost receiving transducer is located at the rightmost transducer location $x'_R = x'_T$, and rightmost emitting transducer is located adjacent to the rightmost receiving transducer location $x'_E = x'_R - \Delta x = x'_{T-1}$.

Figure 2: Linear array representation.

The measured signals for the setup in this study have $T=10$ transducer channel locations at $\Delta x=40$ mm spacing covering a lateral device aperture of 360 mm in each reconstruction. Each channel is comprised of a group of 4 transducer elements where the directivity of the wear tip oscillations are controlled by the phase of parallel piezoelectric elements in each transducer. Each group of 4 transducer elements are designed to produce shear horizontal (SH) waves focused to a plane perpendicular to the surface and centered between the set of 4 transducer elements [11]. Each group of 4 transducer elements can be treated as one channel where the SH wave is polarized parallel to the plane surface of the tested specimen in each self-contained array scan. This allows for 45 sending and receiving pairs operating at a nominal frequency of 50 KHz with a sufficiently short impulse. Figure 1 shows that the direction of particle motion is out of the plane with respect to the evaluated cross-section which is denoted using the convention from Krautkramer et al. with a black dot indicating the polarization [26]. In this case, the particle motion is into and out of the evaluated B-scan plane and is always parallel to the reflecting object, regardless of the pairs used or shape of the inclusion. Along this plane, the SH wave reflection amplitude does not depend on the angle of incidence with no mode change occurring [26]. This mitigates ghost images in the SAFT reconstruction and simplifies analysis. Although not a subject of this paper, it should be noted that mode conversions can be used to extract

additional information and has potential to account for phenomenon other than SH-wave interactions of interest in this study [27].

2.2 Reconstruction Principle

The synthetic aperture focusing technique (SAFT) has shown to be an effective migration heuristic to create focused reconstructions for space domain analysis after assuming or calculating an approximate velocity and system delay [27-30]. This is often applied along a single analysis axis with each measurement from unique emitting/receiving pair locations or along a plane with multiple measurements in set shift factors from a single emitting/receiving location [31-33]. Using the setup in this study, the general SAFT is formalized to allow for interpretation of signals with sending and receiving transducers located at different locations and to allow for a signal sent from one location to be received at various locations along the surface [34-35]. The shear wave direct arrivals from each measurement pair can be used to calculate the approximate shear wave velocity and system delay related shift factor in a similar manner to that described by Blum et al. (1997) [36]. Using these input values and summing over all possible transducer pair locations at discrete points produces a reconstructed image referred to as a SAFT B-scan. Since this is the basis of the proposed method, it is formalized here to provide context. Equations 1 and 2 show the relationships used to create SAFT B-scans for the ultrasonic linear array in this study:

$$\hat{o}_{i,k} = \sum_{e=1}^{T-1} \sum_{r=e+1}^T A(x'_r, x'_e, x_i, z_k) \Psi_{e,r}(x_i, z_k) \quad [1]$$

$$\Psi_{e,r}(x_i, z_k) = s \left(x'_r, x'_e, \frac{1}{c} \left(\sqrt{z_k^2 + (x_i - x'_e)^2} + \sqrt{z_k^2 + (x_i - x'_r)^2} \right) \right) \quad [2]$$

where $\hat{o}_{i,k}$ is the response assigned to each position within the ROI; i and k are the indexes for the horizontal and vertical positions of the ROI, respectively, which is represented by a $W \times D$ set of points located in W columns, and D rows; T is the number of transducer channel locations; e and r are the indexes for the emitting and receiving transducers; and s is the magnitude of the response at the evaluated time of flight for given transducer transducers pair locations, x'_r and x'_e . The apodization coefficient, A , accounts for factors such as the incident angle and other traits of the signal and tested medium [37].

By analyzing changes in instantaneous amplitude within the ROI, locations of changes in acoustic impedance, and associated changes in reflectivity, can be identified [25]. The Hilbert transform can be applied to calculate instantaneous attributes of a time series, especially the amplitude and frequency [38, 39]. The Hilbert transform, $Y(z)$, of a given function, $\chi(z)$, is defined by the following equation:

$$Y(z) = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{\chi(s)}{z-s} ds \quad [3]$$

where P is the principal value of the singular integral in equation 3 and the complex analytic signal, $Z(z)$, is given by:

$$Z(z) = \chi(z) + j Y(z) \quad [4]$$

In this case, the absolute value of the complex signal, Z , is calculated at each horizontal coordinate of the SAFT reconstruction to give the instantaneous amplitude as follows:

$$\hat{o}^{IA}(x, z) = \sqrt{(\hat{o}(x, z))^2 + \left(\frac{P}{\pi} \int_{-\infty}^{\infty} \frac{\hat{o}(x, s)}{z-s} ds\right)^2} \quad [5]$$

where the relative reflectivity, $\hat{o}^{IA}(x, z)$, defines the instantaneous amplitude-based SAFT reconstruction and P is the principal value of the singular integral. Since the ROI is represented by a $W \times D$ set of points located in W columns, and D rows, the following matrix formalization can be used to represent SAFT-IA reconstructed image, $[\hat{o}]^{IA}$:

$$[\hat{o}]^{IA} = \begin{bmatrix} \hat{o}_{1,1}^{IA} & \hat{o}_{2,1}^{IA} & \dots & \dots & \hat{o}_{W,1}^{IA} \\ \hat{o}_{1,2}^{IA} & \dots & \dots & \dots & \dots \\ \dots & \dots & \hat{o}_{i,k}^{IA} & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots \\ \hat{o}_{1,D}^{IA} & \dots & \dots & \dots & \hat{o}_{W,D}^{IA} \end{bmatrix}$$

For the ultrasonic linear array used in this study the following apodization factor was found to improve the reconstruction resolution:

$$A(x'_r, x'_e, x_i, z_k) = \alpha_e(x'_e, x_i, z_k) * \alpha_r(x'_r, x_i, z_k) \quad [7]$$

where:

$$\alpha_e(x'_e, x_i, z_k) = \frac{z_k}{\sqrt{(x_i - x'_e)^2 + z_k^2}}$$

$$\alpha_r(x'_e, x_i, z_k) = \frac{z_k}{\sqrt{(x_i - x'_r)^2 + z_k^2}}$$

The above formulation allows for reconstruction from a self-contained array system where each element may act as both a sender and receiver. For an equally spaced transducer array, such as that used in this study, this results in higher energy radiation content towards the center of the reconstruction leading to the effect of limited aperture. It is proposed to address this issue by taking multiple overlapping measurements and combining them into a single panoramic reconstruction using the formulations presented in the subsection 2.3.

2.3 SAFT Panoramic

Consider a set of array measurements taken at prescribed shifts in the direction along the aperture of the linear array. Each prescribed shift is within the aperture of the previous scan. For each of these measurements, a SAFT-IA B-scan, is obtained using the procedure described in subsection 2.2. In the proposed implementation, each individual SAFT-IA B-scan, $\hat{O}_{k,i}^m$ is sequentially converted to the dimensions of the larger region of interest, ROI_{PAN} , where m is an index of the current SAFT-IA B-scan. The vertical dimensions of the new ROI_{PAN} and ROI of each SAFT-IA B-scan $\hat{O}_{k,i}^m$ are the same while the horizontal dimensions are increased. Let the leftmost (lowest) horizontal coordinates of the m -th SAFT-IA B-scan, x_1 , correspond to the x_{i^*} coordinate within the panoramic reconstruction (SAFT-Pan). In this case all intensity values of the original SAFT-IA B-scan within the new ROI_{PAN} are placed according to their physical location with zeros padding any location where no intensity value applies. Each padded SAFT B-scan, $\hat{O}_{k,i}^{PAN,m}$, is created according to the following relationship for all $\hat{O}_{k,i}^m$ horizontal positions within the ROI_{PAN} :

$$\hat{O}_{k,i}^{PAN,m} = \hat{O}_{k,i-i^*+1}^m \text{ for } i^* \leq i \leq i^* + W - 1$$

$$\hat{O}_{k,i}^{PAN,m} = 0 \text{ for } i < i^* \text{ or } i \geq i^* + W \quad [8]$$

Equation 9 shows the matrix representation of an example panoramic form, $[\hat{O}]^{PAN,m}$, of the m-th applied SAFT-IA B-scan.

$$[\hat{O}]^{PAN,m} = \begin{bmatrix} 0 & 0 & \hat{o}_{i^*,1}^{PAN,M} & & \hat{o}_{i^*+W-1,1}^{PAN,M} & 0 & 0 \\ 0 & 0 & & \hat{o}_{i,k}^{PAN,M} & & 0 & 0 \\ 0 & 0 & & & & 0 & 0 \\ 0 & 0 & \hat{o}_{i^*,D}^{PAN,M} & & \hat{o}_{W,D}^{PAN,M} & 0 & 0 \end{bmatrix}$$

[9]

After this procedure the individual scans can be combined into a single panoramic representation, SAFT-Pan, using the following rule:

$\hat{O}_{k,i}^{PAN} = \max_m (\hat{O}_{k,i}^{PAN,m})$ for all k and i in the ROI_{PAN} , where $[\hat{O}]^{PAN}$ is the matrix form of the SAFT-Pan.

To illustrate the use of SAFT-Panoramic extended reconstructions, consider a reinforced concrete pavement on grade. Figure 3 shows the cross section of the tested location comprised of two 38 mm diameter steel reinforcements embedded in a 300 mm thick portland cement concrete (PCC) slab. This is the cross sectional location and dimensions for the analysis and reconstructions presented in Figure 4, Figure 5, Figure 6, and Figure 10.

Figure 3. Schematic of the reinforced concrete structure used for analysis.

A set of 9 scans were completed by placing the DPC transducer array on the concrete surface starting on the left side of the cross-section shown in Figure 3 and moving to the right in 50 mm target shift factors with each increasing scan. Figure 4 shows three representative SAFT-IA B-scans, labeled (a), (b), and (c), corresponding to the lateral locations with the same labels also shown in Figure 4. The presence of a laterally oblong high intensity reflection (white) can be observed the bottom of each reconstruction. This backwall reflection corresponds to the PCC slab thickness. Presence of round high intensity (white) reflections indicates the existence of the metal inclusions at the mid-depth of the PCC slab.

Further analysis of Figure 4 indicates that the reconstructions only partially describe the physical reality. For example, the PCC slab depth interface high intensity reflection does not extend throughout the width of each scan to match the physical interface. Similarly, the same 38 mm inclusion may appear with a different size and shape within the reconstruction depending on its relative position with respect to the center of the scan. To illustrate this point, the scan corresponding to Figure 4 (b) is discussed. It can be observed from the reconstructions that the reflections from the inclusions are smaller and less circular than the same inclusion reflections in Figure 4(a) and Figure 4(c). It can be observed from the schematic that these inclusions are located close to the edge of the scanned area causing this observed limited aperture effect. This can limit the ability to assess the reconstructions, as it can be difficult to differentiate structural noise from scatterers of interest when the location within the aperture must be taken into account.

(a)

(b)

(c)

Figure 4: Three example scans from a set of nine overlapping SAFT-IA B-scans over 2 round metal inclusions.

Figure 5 shows the corresponding SAFT-Pan reconstruction resulting from the 9 overlapping SAFT-IA B-scans taken in 60 mm target shift factors shown after they have been fused together. By using the SAFT-Pan reconstruction method, the effects caused by limited aperture are mitigated. It can be observed that the resulting panoramic reconstruction is more realistic than the individual SAFT-IA B-scan reconstructions.

Figure 5: SAFT-Pan reconstruction showing the consistent metal inclusions and continuous reflection at the depth of the PCC slab.

However, there are situations where the physical location of each SAFT-IA B-scan is not known precisely. In this case, the SAFT-Pan procedure can introduce significant error. Figure 6 shows an example of a SAFT-Pan reconstruction which combines 9 individual SAFT-IA reconstructions. Unlike in the example in Figure 4, there was some uncertainty in the accuracy of the relative position of the individual scans. When using the target 60 mm shift factor in SAFT-Pan analysis the reconstruction in the middle exhibits a blurred reflection. This type of reflection may indicate presence of damage or poor consolidation of the concrete around the steel reinforcement, but may also indicate an error in the measurement placement.

Figure 6: Example SAFT-Pan indicating potential scan placement inaccuracy.

A possible approach to resolving this ambiguity is to mitigate scan placement error through the use of a robotic system with dense measurement grids. These types of systems have been developed to allow for precise measurement grids that provide reconstructions of larger areas by stacking individually processed ultrasonic scans [40]. There have been multiple systems developed to accomplish these types of measurements [41-43]. However, the drawbacks of these systems include high cost as well as low flexibility and productivity.

2.4 SAFT Enhanced Panoramic

To address the problem of imprecise measurement locations, an iterative procedure for enhanced panoramic reconstruction is proposed. Rather than assuming precise knowledge of the relative shift between scans, the shift factor for placement of each individual scan is assumed to be within a certain range. This procedure incorporates a similarity of overlapping regions to determine the placement of each scan. It is based on the concept that inclusions and defects within the region of interest should result in similar relative reflectivity, regardless of the location of the scan, assuming the effect of limited aperture is taken into account.

First, each SAFT-IA B-scan is numbered according to increasing coordinate in the horizontal direction. Then, the individual SAFT-IA B-scans are added sequentially a panoramic reconstruction. Denote the panoramic reconstruction after the m -th SAFT-IA B-scan is added as $[\hat{O}]^{\text{EPAN},m}$ and the number of columns in this reconstruction as $W^{\text{EPAN},m}$. The increment of adjacent positions, ΔS , is assumed to be within a certain range defined by equation 10:

$$\iota_1 \Delta x \leq \Delta S \leq \iota_2 \Delta x$$

[10]

where ι_1 and ι_2 are integers and Δx is the difference in horizontal position between two adjacent columns in the reconstruction.

The difference in the adjacent positions of scans m and $m+1$ can be expressed in terms of number of additional step increments, ι . For each ι within the range $[\iota_1, \iota_2]$ a similarity between portions of the overlapping regions within $[\hat{O}]^{EPAN,m}$ and $[\hat{O}]^{IA,m+1}$ is determined. To account for the effect of limited aperture, the first W_1 columns of $[\hat{O}]^{IA,m+1}$ and last W_1 columns of $[\hat{O}]^{EPAN,m}$ are not considered in determining similarity. In many cases, the stability of the process is improved if only a portion of the reconstruction in the vertical direction $[D_1, D_2]$ is included in the comparison. Figure 7 illustrates the process of determining overlapping regions used in the similarity analysis.

Figure 7: Determination of overlapping regions between the reconstructions and determination of the next panoramic reconstruction.

The degree of similarity of the overlapping regions, $H(\iota)$, is determined based on Pearson's correlation as follows [44]:

$$H(\iota) = \frac{\sum_{i=a}^b \sum_{k=D_1}^{D_2} (\hat{o}_{c,k}^{\text{EPAN},m} - \hat{o}_{\text{mean}}^{\text{EPAN},m})(\hat{o}_{i,k}^{m+1} - \hat{o}_{\text{mean}}^{m+1})}{\sum_{i=a}^b \sum_{k=D_1}^{D_2} (\hat{o}_{c,k}^{\text{EPAN},m} - \hat{o}_{\text{mean}}^{\text{EPAN},m})^2 \sum_{i=a}^b \sum_{k=D_1}^{D_2} (\hat{o}_{i,k}^{m+1} - \hat{o}_{\text{mean}}^{m+1})^2} \quad [11]$$

where

$$\hat{o}_{\text{mean}}^{\text{EPAN},m} = \frac{\sum_{i=g}^f \sum_{k=D_1}^{D_2} \hat{o}_{i,k}^{\text{EPAN},m}}{(W - 2W_1 - \iota)(D_2 - D_1 + 1)}; \quad \hat{o}_{\text{mean}}^{m+1} = \frac{\sum_{i=a}^b \sum_{k=D_1}^{D_2} \hat{o}_{i,k}^{m+1}}{(W - 2W_1 - \iota)(D_2 - D_1 + 1)}$$

$a = W_1 + 1$; $b = W - W_1 - \iota$; $c = W^{\text{EPAN},m} - W + \iota + 1$;

$f = W^{\text{EPAN},m} - W_1$; $g = W^{\text{EPAN},m} - W + \iota + W_1 + 1$;

The ι that results in the maximum value of function $H(\iota)$ on the interval $[\iota_1, \iota_2]$ is denoted as the optimal shift factor, ι^* . The next SAFT-EPan reconstruction, $[\hat{O}]^{\text{EPAN},m+1}$, is defined as follows:

$$\hat{O}_{i,k}^{\text{EPAN},m+1} = \hat{O}_{i,k}^{\text{EPAN},m} \text{ for } i < W^{\text{EPAN},m} - W + \iota^* + W_1 \quad [12]$$

$$\hat{O}_{i,k}^{\text{EPAN},m+1} = \max(\hat{O}_{i,k}^{\text{EPAN},m}, \hat{O}_{i-W^{\text{EPAN},m}+W-\iota^*,k}^{m+1})$$

for $W^{\text{EPAN},m} - W + \iota^* + W_1 \leq i \leq W^{\text{EPAN},m}$

and

$$\hat{O}_{i,k}^{\text{EPAN},m+1} = \hat{O}_{i-W^{\text{EPAN},m}+W-\iota^*,k}^{m+1}$$

for $W^{\text{EPAN},m} < i \leq W^{\text{EPAN},m+1}$

where, $W^{\text{EPAN},m+1}$ is the width of the new SAFT-EPan as defined:

$$W^{\text{EPAN},m+1} = W^{\text{EPAN},m} + \iota^*$$

Each subsequent reconstruction, $[\hat{O}]^{\text{EPAN},m+1}$, is obtained from addition of $[\hat{O}]^{\text{EPAN},m}$ and the next SAFT-IA B-scan, $[\hat{O}]^{\text{IA},m+1}$. The additional number of columns in the new reconstruction, ι^* , is determined by comparing the similarity between portions of the overlapping regions within $[\hat{O}]^{\text{EPAN},m}$ and $[\hat{O}]^{\text{IA},m+1}$. The additional columns, ι^* , are chosen from within the range of potential shift factors $[\iota_1, \iota_2]$.

3 RESULTS AND DISCUSSION

3.1 Illustrative Example

This section demonstrates how the procedure described in the SAFT-Enhanced Panoramic section is used to determine the optimal shift factor, ι^* , when fusing multiple overlapping scans into an extended reconstruction. Figure 8 shows artificially generated reconstructions where an identical square inclusion exists in both the current SAFT-EPan reconstruction $[\hat{O}]^{\text{EPAN},m}$ and the next SAFT-IA B-scan, $[\hat{O}]^{\text{IA},m+1}$, which is shifted by 50 mm. Figure 8c shows Pearson's similarity correlation function, $H(\iota)$, where the shift factor is assumed to be somewhere between 30 mm to 70 mm for the corresponding overlapping regions within this interval taken with a step of 0.8 mm. As can be observed from Figure 8c, the maximum similarity value of $H(\iota) = 1$, indicating a perfect correlation, corresponds to the actual shift factor between measurements.

Although a perfect correlation is not realistic to expect from field data, use of this type of analysis often result in significant similarity at the determined shift factor, typically greater than 0.9, for overlapping regions when a strong feature is located within the ROI. Examples of this type of analysis conducted on field data taken on a concrete slab are given below.

Figure 8. Shift factor determination for artificially generated reconstructions (a) m-th SAFT-EPan reconstruction (b) m+1 SAFT I-A reconstruction with an identical inclusion and (c) Pearson's correlation for various shift factors.

3.2 Field Trials

The SAFT schemes proposed above have been utilized on several full-scale in-situ testing locations to provide practical non-destructive evaluation information when interrogating concrete structures. This includes location of inclusions and determination of internal flaws such as cracks or defects.

3.2.1 Inclusion Characterization

Implementation of the SAFT-EPan scheme has shown to be especially useful for applications where there is a designed inclusion located within multiple overlapping scans. One such example was introduced in Figure 5 where 9 overlapping measurements were taken on a 300 mm thick portland cement concrete (PCC) slab with two 38-mm diameter steel reinforcements at the mid-depth of the slab. Figure 9 shows example determination of the shift factor for placement of the 6th SAFT-IA reconstruction where one of the steel reinforcements exists in both the current reconstruction (see Figure 9a), $[\hat{O}]^{EPAN,m}$, and the next individual SAFT-IA B-scan (see Figure 9b), $[\hat{O}]^{IA,m+1}$, to be placed. The results of Pearson's similarity correlation function, $H(l)$, for the shift factors within interval [30 mm, 70 mm] are shown in Figure 9c. In this case, the maximum value of Pearson's similarity correlation used to determine the shift factor is not an exact similarity of 1. However, the highest reflectivity location is significant at over 95% at slightly less than 50 mm, which was over 10 mm less than the target shift factor. Correction of the shift factor using SAFT-EPan for cases like this can improve resolution of the resulting panoramic reconstruction and have a significant impact on the interpretation.

Figure 9. Shift factor determination for in-situ reconstructions (a) m-th SAFT-EPan reconstruction (b) m+1 SAFT I-A reconstruction with an identical inclusion and (c) Pearson's correlation for various shift factors.

Figure 10a shows the SAFT-EPan reconstruction obtained from the same individual SAFT-IA scans from Figure 5. The shift factors were determined by using the highest similarity of overlapping regions using the procedure described in equation 11 resulting in shift factors significantly less than the 60 mm target shift factors on average. It can be observed that the new shift factors, determined using the enhanced panoramic reconstruction procedure, resulted in focusing of the reflectivity reconstruction in the area of the dowel. This type of focused reflectivity in the reconstruction should be expected at a round steel reinforcement embedded in sound surrounding concrete.

A core at the doweled location is also shown in Figure 10b indicating a single dowel with relatively sound surrounding concrete. This validates that the blurred reflectivity in the region of the dowel observed in Figure 5 was caused by the error in the pre-defined 60 mm shift factors used in the SAFT-Pan reconstruction. This also validates that the SAFT-EPan reconstruction correctly focused the reflectivity to the actual change in acoustic impedance to the region of the embedded dowel. It should be noted that, while the center of gravity of the inclusion reflectivity approximates the inclusion location [15], the diameter of the inclusion representation depends on the selected threshold. It can be observed that the diameter of the reconstruction inclusion for the chosen threshold is similar, but slightly larger than the actual inclusion represented by the black circle on the reconstruction. Determination of the absolute diameter of an inclusion without any prior information is not feasible using the method described in this study. However, by accounting for the limited aperture effect on reflectivity in the extended reconstructions, comparison of relative sizes of inclusions can be conducted.

Figure 10. (a) SAFT-EPan reconstruction allowing for ± 30 mm error and (b) subsequent forensics at the example overlapping scans location.

3.2.2 Flaw Detection

In addition to locating and characterizing inclusions such as reinforcements, SAFT-EPan reconstructions can be useful for identifying flaws that are thin in the lateral dimension such as vertical cracks in concrete. To validate the ability of the proposed method, measurements were taken on a specimen where controlled vertical cracks were fabricated by placing 254 mm by 76 mm triangular wedges into the backside of a 254 mm concrete wall and removing after the initial set. The wedges included in this study were a 1.5 mm thick steel sheet (CR1) and 3 mm thick polycarbonate sheet (CR2). These defects were fabricated by Hiltunen et al. [43] and tested on the front (uncracked) side by the authors as part of a study by Clayton et al. [17]. Figure 11 shows a schematic of the cross section below the scans analyzed as part of this paper. The portion of the triangular wedge associated with the measurements in this study were 5 mm in height from the opposite side surface with respect to where the scans were taken.

Figure 11: Concrete wall specimen with no visible distress on the front side and two simulated cracks on the back side.

Figure 12 a shows the location of the backside crack, CR1, in relation to the two individual SAFT-IA reconstructions adjacent to the vertical crack, as indicated by the arrows. The SAFT-IA reconstructions do not give a clear indication of any discontinuity since it is difficult to resolve shadowing from the crack versus reduction in reflectivity due to limited aperture toward the edges.

Figure 12: SAFT-IA reconstructions at the CR1 location during vertical scanning.

Figure 13 shows analysis of SAFT-EPan reconstruction results from eleven overlapping scans with 102 mm shift factors taken on top of the area with cracks on the backside. As can be observed from Figure 13, there is no direct reflection corresponding to the tip of the crack location. This is typical for laterally thin defects that are perpendicular to the measurement surface. However, the cracks can be detected indirectly by observing the reduction of reflection or “shadowing” [19] at the “backwall” thickness interface of the PCC. It can be observed from Figure 13b and c that there is a reduction in intensity or even a slight discontinuity in the backwall reflection at the crack locations. Figure 13d shows a plot of the relative reflectivity values along the depth associated with the PCC thickness leading up to and away from the CR1 crack location. The vertical crack location can be clearly identified by the drop in relative reflectivity. This highlights the importance of using SAFT-EPan reconstructions, where relative reflectivity values can be quantitatively compared within the reconstruction without potential misinterpretations caused by limited aperture.

404

405 Figure 13: Use of SAFT-EPan and relative reflectivity measures to identify a vertical crack.

406 4 CONCLUSIONS

407 Although SAFT-based migration techniques in conjunction with linear array systems have been
 408 used to provide useful nondestructive information on subsurface condition of concrete, the effect
 409 of limited aperture has been identified as impedance to quantitative interpretation. The SAFT-
 410 EPan reconstruction methodology presented in this paper was demonstrated to address this
 411 limitation through generalization of traditional migration methods to handle virtual arrays. The
 412 proposed implementation uses quantitative similarity measures of overlapping regions to account
 413 for imprecision in adjacent scan measurement placement. This is especially important for
 414 situations where robotic precision of scan placement is not feasible. Analysis of full scale

controlled tests on PCC slabs demonstrated improved resolution and reliability for characterization of defects or inclusions.

5 ACKNOWLEDGEMENTS

Part of the work presented in this paper was conducted for Oak Ridge National Laboratory (UT-Battelle, LLC), acting under contract DE-AC05-00OR22725 with the U.S. Department of Energy. Dr. Chris Ferraro from the University of Florida was led the specimen construction efforts and coordinated testing of the simulated crack used in this paper.

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Figure 1: Illustration of the type of data utilized in this paper including a [a] schematic of the measurement setup on a concrete slab including direct and reflection arrival paths and [b] example impulse time history from a transducer pair spaced by 200 mm.

Figure 2: Linear array representation.

Figure 3. Schematic of the reinforced concrete structure used for analysis.

Figure 4: Three example scans from a set of nine overlapping SAFT-IA B-scans over 2 round metal inclusions.

Figure 5: SAFT-Pan reconstruction showing the consistent metal inclusions and continuous reflection at the depth of the PCC slab.

Figure 6: Example SAFT-Pan indicating potential scan placement inaccuracy.

Figure 7: Determination of overlapping regions between the reconstructions and determination of the next panoramic reconstruction.

Figure 8. Shift factor determination for artificially generated reconstructions (a) m-th SAFT-EPan reconstruction (b) m+1 SAFT I-A reconstruction with an identical inclusion and (c) Pearson's correlation for various shift factors.

Figure 9. Shift factor determination for in-situ reconstructions (a) m-th SAFT-EPan reconstruction (b) m+1 SAFT I-A reconstruction with an identical inclusion and (c) Pearson's correlation for various shift factors.

Figure 10. (a) SAFT-EPan reconstruction allowing for +/- 30 mm error and (b) subsequent forensics at the example overlapping scans location.

Figure 11: Concrete wall specimen with no visible distress on the front side and two simulated cracks on the back side.

Figure 12: SAFT-IA reconstructions at the CR1 location during vertical scanning.

Figure 13: Use of SAFT-EPan and relative reflectivity measures to identify a vertical crack.