NDT&E International 74 (2015) 33–42

Contents lists available at ScienceDirect

NDT&E International

journal homepage: www.elsevier.com/locate/ndteint

Extended synthetic aperture focusing technique for ultrasonic imaging of concrete

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ARTICLE INFO

Article history:
Received 21 November 2014
Received in revised form
13 March 2015
Accepted 1 May 2015
Available online 12 May 2015

Keywords:
Concrete
Ultrasound
Array
SAFT
Imaging

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.

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 (~50 kHz) 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. [23], 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

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http://dx.doi.org/10.1016/j.ndteint.2015.05.001
0963-8695/

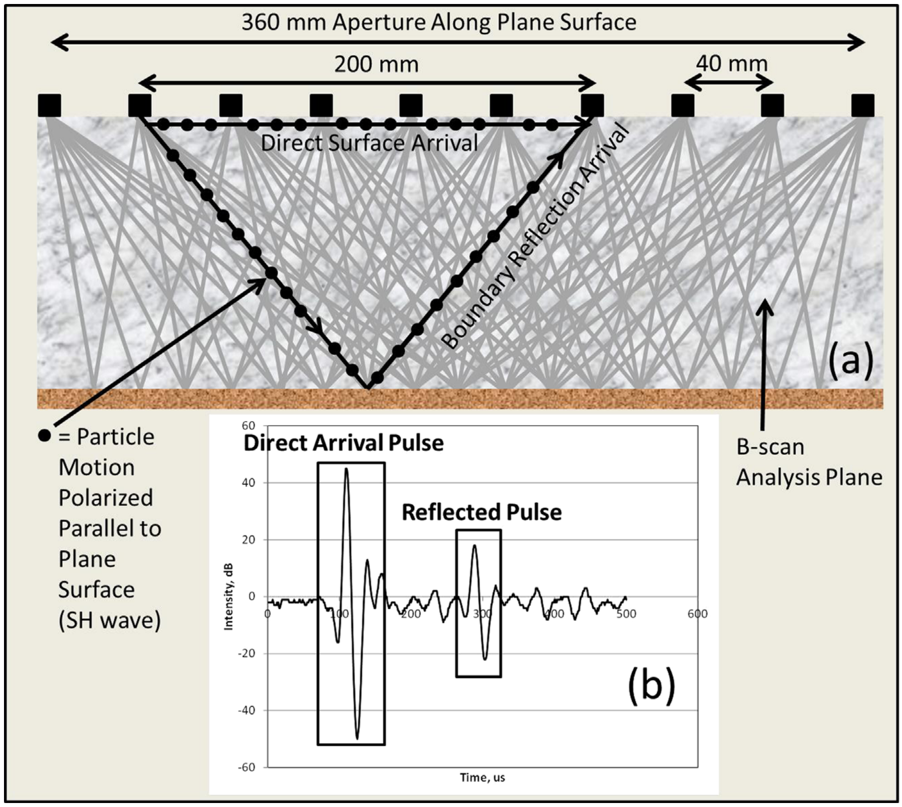

Fig. 1. Illustration of the type of data utilized in this paper including a (a) schematic of the measurement setup on a concrete slab including direct and reflection arrival paths and (b) example impulse time history from a transducer pair spaced by 200 mm.

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. Fig. 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. Fig. 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. Fig. 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.

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. Fig. 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 $x'_E=x'_R-\Delta x=x'_{T-1}$.

The measured signals for the setup in this study have $T=10$ transducer channel locations at $\Delta \mathbf{x}=40$ 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. Fig. 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 Krautktamer 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