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DETECTION OF INCLINED CRACKS INSIDE CONCRETE STRUCTURES BY ULTRASONIC SAFT

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ABSTRACT. Detection of internal defects in concrete structures is a difficult task as these anomalies are not always observable at the surface, yet have the potential to expand and damage the structure. The focus of this work is to locate and characterize inclined cracks inside a concrete mass which is essential in monitoring the integrity of many civil structures. For this purpose, three concrete slabs were constructed each having a different sub-horizontal crack. To obtain high resolution images of the concrete interior, an extension of the ultrasonic technique known as SAFT is used. SAFT has shown great potential to produce detailed 3D images of tendon ducts, holes and flaws inside concrete structures. The results of this study show that cracks with angles varying from 5 to 15 degrees can be accurately located inside a concrete slab having a thickness of up to 200 mm.

Keywords: SAFT, Concrete, 3D Imaging, Crack Location, Depth Measurement.

PACS: 81.70.Cv, 62.20.mt

INTRODUCTION

Concrete deteriorates over time due to environmental changes and/or poor construction processes which can eventually lead to partial or total failure of a structure. Deterioration in concrete manifests itself under different forms such as corrosion of embedded metals, freeze and thawing, chemical attack, alkali-aggregate reactivity, and surface and internal defects. Locating and repairing internal defects is essential in maintaining the integrity of the structure and preventing any further damage.

Nondestructive testing is now a recognized technique to inspect the integrity of materials. One can use such a technique to measure the thickness, assess the quality of concrete, locate ducts inside it, and detect and characterize defects. A number of techniques have been developed and successfully applied [1-5]. Nondestructive testing of concrete, however, is relatively new with a slower rate of development. This is because concrete is a highly heterogeneous composite material (two-phase solid) made of a mortar matrix and enclosed aggregates with a size range of typically 8 to 32 mm. This property causes difficulties in the propagation of acoustic wave in concrete.

The Miniature Seismic Reflection (MSR) method was developed [1-3] to estimate the elastic properties of concrete and its thickness. MSR works by introducing seismic waves inside a structure using a spherically tipped impact source. A pair of vertical and tangential displacement transducers picks up the reflected signals. MSR is used for inspection of large concrete structures as well as shaft/tunnel lining, due to its penetration range of 2 cm to 300 cm. However, MSR is a non imaging technique and there is a need to develop a method capable of providing a detailed 3D image of the interior of concrete structure.

The acoustic waves transmitted into heterogeneous materials such as concrete are scattered due to the presence of aggregates. To avoid the loss of energy at grain boundaries, lower frequencies in the range of 50 to 500 kHz (wavelength range of 8 to 80 mm with a longitudinal wave speed of 4000 m/s) should be used. Grain size is an important factor that controls the choice of frequencies used. The inhomogeneous composition of concrete, therefore, causes attenuation of signals, especially at high frequencies, which in turn prevents the detection of cracks smaller than the aggregates.

A wave focusing technique can improve the nondestructive evaluation and produce detailed 3D images inside concrete structures. Focusing waves can locate and characterize defects more clearly by improving the signal-to-noise ratio (SNR) and resolution of the inspection system. The Synthetic Aperture Focusing Technique (SAFT) has been successfully applied to detect and size flaws inside homogenous materials [5-7]. More recently, SAFT has been used to inspect inhomogeneous structures such as concrete and has shown great potential to detect tendon ducts, holes and flaws in concrete structures [8-10]. However this method has not been effective in profiling inclined cracks. In this work, a modified SAFT is developed to detect and outline oriented cracks inside concrete.

SAFT PROCEDURE

Basic principle

In this process, the transducer is moved over a 2D grid on the surface of the test object. At each point on the grid, an A-scan is captured and recorded. If there is no defect inside the material, the signals from the transducer on top of the inspection point and from adjacent positions on the linear aperture exhibit only noise. Figure 1 shows a test component where there is a reflector in the medium. Optimally, such a reflector should be in the far field of the transducer. In this case, the A-scans adjacent to and on top of the target exhibit echoes of the reflector relative to their distance to it. In other words, the reflector echoes can be seen not only in the A-scan received by the transducer directly on top of it, but also in other A-scans from positions at some distance from the reflector. As the transducer moves away from the reflector, the echo from the reflector appears later in time and smaller in amplitude.

In SAFT, a coherent summation process is used for reconstruction of the image. In this process, each raw A-scan is shifted along the time axis by an amount equal to a delay calculated based on the transducer position and the selected size of the aperture around the transducer. The shifted A-scans are then averaged over the transducer position (see bottom of figure 1). If a defect is present, a constructive interference of A-scans creates a well-defined signal, locating the defect in space and time. Otherwise, a destructive interference occurs and the resulting A-scan signature would contain no useful information.

FIGURE 1. Top: data collection from a part containing a defect under the central A-scan. Bottom: applying SAFT by shifting data in adjacent A-scans (left) and the SAFT result (right).

SAFT in concrete has proven to be a powerful tool to profile holes, tendon ducts, and rebars inside the structure. This technique, however, has not been tested to its full potential and its capability to outline inclined flaws has not been tested successfully. In this work, the traditional 3D SAFT is modified to perform this task.

Modified SAFT

Testing in concrete is usually conducted in pitch-catch mode using two transducers, one as a transmitter and the other as a receiver, effectively replacing the pulse-echo method because of the limitation (long ringing time of low frequency transducers) in the design and manufacturing of single transducers acting both as transmitter and receiver. In a pre-processing step, a cross-correlation is performed between each A-scan obtained at every point on the grid and the impulse response of the transducer pair. The results of the cross-correlation make the maximum amplitude in the A-scans consistent with the calculation of path length in SAFT processing [11], which in the case of pitch-catch data collection also involves the separation distance between the transducer pair.

Thereafter, embedded in the modified SAFT, each aperture undergoes a local cross-correlation between its central A-scan in the aperture and the surrounding A-scans. The surrounding A-scans are then shifted using the calculated delay in order to align the ringing signals from the inclined crack within the aperture. The SAFT processing is then applied on the shifted A-scans within the aperture to provide the reconstructed signal for the central A-scan.

The modified SAFT is able to image the slope, characterizing it in terms of its orientation, dip angle and depth. The results of this study show that as the slope angle of crack increases, the performance of the modified SAFT in profiling the crack is maintained, whereas the traditional SAFT loses its resolving power.

EXPERIMENTAL SET-UP

To evaluate the capability of the modified SAFT to provide a 3D image of inclined cracks in concrete structures, three concrete slabs, each with a surface of $1 \times 1 \text{ m}^2$ and a sub horizontal inclined bottom surface, were constructed and analyzed in depths of 100 mm to 300 mm, as shown in Figure 2a. The tests were conducted in pitch-catch mode using two transducers, one as a transmitter and the other as a receiver. The transducers had a nominal frequency of 140 kHz.

A 2-channel data acquisition board was used to generate the signal and capture the reflected waveforms. The data were collected at a high sampling frequency of 25 MHz using 12-bit resolution. The transmitted signals are triggered by a function generator. The signal captured from the test medium is picked up and passed through a signal conditioner with the appropriate low-pass filter before feeding it to the data acquisition system. Figure 2b shows a screen-capture of the software used in this work displaying a typical waveform received from the test slab and recorded by the data acquisition system.

Data were collected from rectangular grids mapped in the middle of slabs with 10 mm spacing between the points. The size of the grid was different for each slab and varied from 21 to 27 cm in both x and y directions. Figure 3a shows a main grid mapped on one of the slabs in this work. The collected waveforms were then analyzed by both the normal and the modified 3D Time-Domain SAFT code developed in MATLAB. Tests on a number of cylindrical concrete samples were performed to measure the velocity of elastic waves in concrete. An average velocity of 4100 m/sec was used to calculate the appropriate time delays in SAFT processing and depth estimation. The aperture size in this work was 7, which means for each point on the grid, 3 points on each side (left, right, top and bottom of the point) were used in the SAFT reconstruction process. Figure 3b shows a schematic of an aperture of 7.

FIGURE 2. a) A concrete slab with a 15 deg bottom surface and b) a typical signal from a concrete slab.

FIGURE 3. a) The grid used for data collection on one slab and b) a schematic of an aperture of 7.

RESULTS

Figures 4-6 show the results for 5, 10 and 15 degree slopes respectively. The modified SAFT is able to outline the inclined crack adequately while the normal SAFT cannot perform this task. In particular, the new SAFT remarkably offers a much improved B-scan image for the 10° slope compared to the raw data as well as with the traditional SAFT. When comparing the results between 5° and 10° slopes, it can be easily observed that as the slope of the crack increases, the traditional SAFT loses its resolving power, while the modified SAFT can properly profile and characterize the slope. This is even more noticeable for the 15° slope, the largest inclination considered in this work, where the new SAFT profiles more clearly than the raw data and especially the traditional SAFT.

From these pictures one can see that as the degree of inclination of the crack increases, the performance of the traditional SAFT diminishes significantly in characterizing the slope, while the efficiency of the modified SAFT method is maintained.

Also, Figure 7 compares 1) the true depth of each inclined crack, 2) the estimated depth from raw data (in terms of the maximum amplitude in the A-scans) and 3) the estimated depth after applying the modified SAFT technique. As shown in the images for different slabs, the modified SAFT is capable of estimating the crack depth very closely to the true depth of the inclined surfaces.

CONCLUSION

In this work, improvements have been made to the traditional SAFT in order to obtain images of sub-horizontal flaws that could not be produced previously. The sensitivity and accuracy of the modified SAFT was analyzed for obtaining a profile of inclined defects inside concrete structures. The new method offers a significant enhancement over the traditional SAFT whereby for the first time the orientation, dip angle and the depth of sub-horizontal flaws can be accurately estimated. Cracks with slopes of 5° , 10° and 15° were adequately profiled using the new SAFT code.

FIGURE 4: Comparison of results for 5° slope for a) rows 5 and b) row 10 of the grid.

FIGURE 5. Comparison of results for 10° slope for a) rows 5 and b) row 10 of the grid.

FIGURE 6. Comparison of results for 15° slope for a) rows 5 and b) row 10 of the grid.

FIGURE 7. Comparison of depths on each slab.

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