A Comparative Study of Reverse Time Migration and Synthetic Aperture Focusing Technique for Damage Detection in Non-Destructive Ultrasonic Testing

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Abstract. The Synthetic Aperture Focusing Technique (SAFT) is a widely applied technique for the detection of flaws in concrete medium. Recently a new technique known as Reverse Time Migration (RTM), typically prevalent in the field of exploration geophysics, has found application in non-destructive evaluation of concrete media. This paper deals with a preliminary comparative study between SAFT and RTM based on experimental investigations. For a clearer understanding of the performance of these techniques, the test medium is made of homogeneous acrylic material with drilled air-void scatterers embedded inside the medium. Ultrasonic transducers with center frequency of 250 kHz are used for excitation of the medium and reception of the scattered field on the surface of the medium. Both monostatic (Pulse Echo) and bistatic configuration of transducers are used. Various imaging conditions are applied to assess the performance of the RTM algorithm. The current work also involves the assessment of the performance of the two imaging techniques when the medium contains a random distribution of scatterers along with the air-voids which is similar to the presence of aggregates inside a concrete medium. In order to take into account the effect of inhomogeneities, the experimental scattered field data is mixed with clutter noise generated from a Finite Difference in the Time Domain (FDTD) simulation of ultrasonic wave propagation in a medium with elastic and density properties similar to acrylic but also containing a random distribution of scatterers of different properties. The work presents a first step towards future assessment of the two imaging techniques in non-destructive testing of real life concrete structures.

1 Introduction

The Synthetic Aperture Focusing Technique (SAFT) has been successfully used for ultrasonic testing of concrete and composites [1-3]. In this technique, a source generates ultrasonic field on the surface of medium and the scattered field from the defect is received on the surface in form of time domain waveforms, by receiver transducers. By applying SAFT on the received field, with prior knowledge of compressional wave velocity of the medium, a subsurface image of the medium can be constructed. The other variant of the SAFT algorithm in frequency domain has been investigated in [4].

Recently a new technique known as Reverse Time Migration (RTM), typically prevalent in the field of exploration geophysics, has found application in non-destructive evaluation of concrete media [5,6]. In RTM, the first step involves acquisition of the scattered field emanating from an anomaly inside the medium. The scattered field is then time-reversed and input back at the receiver positions in a numerical model of the medium containing no scatterers, instead of actual physical medium. The input field propagates in the numerical model and focuses back at the locations corresponding to the actual scatterers of the physical medium. A second simulation is performed to generate the incident field in the same medium without scatterers with the original input being given at the respective transmitter locations. The RTM technique creates subsurface images using a concept called the “Imaging Condition”. This typically involves zero-lag cross-correlation between the incident field and the time reversed field at every pixel location inside the simulation medium. High values of the cross-correlation function at any location in the simulation geometry indicate the
presence of a scatterer [7]. Another type of imaging condition recently explored is the maximum strain energy density based imaging condition [8] which is also applied in the work.

In a strongly inhomogeneous medium like concrete, the signals recorded in pulse echo mode contain high noise level due to scattering by aggregates, which may mask the presence of scatterer of interest, e.g., a rebar. In such situations, by focusing the ultrasonic field by using the time delay method can help detecting the scatterer of interest. The focusing action enables transmission of a substantial portion of the ultrasonic energy towards a desired location, thereby, increasing the possibility of detection of an object. The work in [9,10] present various methods adopted for the purpose of ultrasonic focusing.

In this paper we apply the SAFT and RTM algorithms on experimental data (from homogeneous acrylic medium containing air void scatterers ) mixed with simulated clutter noise of the medium (containing aggregates) to obtain the interior image of an inhomogeneous medium that contains aggregates and the air void scatterers. Both monostatic and bistatic experimental data are utilized. We also perform focusing of ultrasonic field (using bistatic experimental data) for interrogation of individual scatterers in an inhomogeneous medium. The merits and demerits of RTM technique, as compared to SAFT, under the two imaging conditions are tested in the present study. This work presents a first step towards future assessment of the two imaging techniques in non-destructive testing of real life concrete structures.

2 Physical Experiment

In the experimental part, the test medium is made of homogeneous acrylic material with drilled holes inside the medium which act as air void scatterers. The dimensions of the medium are 256 x 204 x 75 mm. The centers of all of the four air voids are located at a depth of $y = 82$ mm from the top edge. The locations of the centers of these scatterers relative to the left hand edge of the block are at $x = 38, 98, 158$ and $218$ mm respectively (Fig. 1). All of the scatterers are of 10 mm diameter except the one at $x = 158$ mm, which is enlarged to make the dimension equal to 24 mm. This is done in order to simulate a damaged region where there is a change in the characteristics of one of the scatterers relative to the others. The top level of the damaged scatterer is 7 mm above the top level of other three scatterers. Ultrasonic transducers with center frequency of 250 kHz are used, the wavelength corresponding to which is $\lambda = 10.8$ mm. The scattered field is recorded on the top surface at 39 receiver positions between $x = \pm 95$ mm. Both monostatic (Pulse Echo) and bistatic configuration of transducers were used for recording the scattered field. The array element spacing of 5 mm is set to half of the wavelength corresponding to compressional wave velocity of 2700 m/s at 250 kHz. This is done in order to avoid formation of sidelobes on the focal plane [12].

![Fig. 1. Homogeneous acrylic test medium used in the experiments, having the four air void scatterers. The medium’s dimensions are shown in mm units.](image-url)
The focusing action is achieved by application of calculated time delays to the signals acquired in the bistatic configuration of the transducers. The time delays are calculated on the basis of the relative path differences between the transducer locations and the focal point.

3 Numerical Simulations

3.1 FDTD Simulation Geometry

Numerical simulations of wave propagation were carried out using a two dimensional FDTD scheme based on the first order differential equations involving stress and velocity field variables [11], in an elastic medium. The density of background acrylic medium is considered as 1176 kg/m$^3$, the Poisson’s ratio as 0.35 and the compressional wave velocity as 2700 m/s. The simulation medium has the same dimensions as the experimental block. The grid size for simulation medium is set to 0.5 mm and the time step of 0.1 μs is decided by the Courant Condition. The medium is excited by backwall echo signal which is isolated from a signal received during a pulse echo mode experiment on undamaged (no air void) acrylic medium to simulate the actual wave propagating incident field inside the medium.

3.1 Simulated Noise

To generate the synthetic data containing clutter noise due to presence of aggregates in concrete, forward wave propagation simulations were carried out and the response (noise) of the medium was recorded at the same receiver positions as in the experiment. For this purpose, the simulation medium comprised of randomly distributed scatterers having a nominal size of 10 mm embedded inside the acrylic medium similar to the presence of aggregates in concrete. The scatterer density is assumed to be 2800 kg/m$^3$. Three volume fractions of scatterer particles, viz. 0.20, 0.30 and 0.40 were considered to generate three different levels of noise response from the inhomogeneous medium. The noise response thus recorded was mixed with respective experimental scattered field data to obtain the scattered field that would have been recorded from inhomogeneous medium.

3.2 Focusing of Ultrasonic Field

In the present study, the focusing action is achieved by applying the time delay law to the received waveforms. The compressional wave velocity of the medium is taken as $V = 2700$ m/s. For a particular receiver position, if two transmit transducers are at distances of $R_i$ and $R_{\text{max}}$ respectively from the desired focal spot, a time delay equal to $\frac{|R_{\text{max}} - R_i|}{V}$ is applied to the signal received from the $i^{th}$ transmit transducer. All of the signals received at a particular receiver location are time delayed according to the above law and summed up. The process is repeated for every receiver location. The modified set of signals at the various receivers now correspond to the field emanating from a scatterer located at the focal spot and on which a focused ultrasonic field is incident.

4 Imaging Results

4.1 Imaging with Pulse Echo Data

This section presents the imaging results obtained by using pulse echo data in the SAFT and RTM algorithms. The image generated by SAFT using the experimental pulse-echo or monostatic scattered field data corresponding to the homogeneous medium is shown in Fig. 2 a). The image shows spots at the four hole locations with the spot on the right of center shifted upwards. The shifted spot corresponds to the damaged air void scatterer, whose upper surface is nearer to top edge in comparison to the other three scatterers by a margin of 7mm. The outer air-voids appear as less due to lesser incident energy on these locations, as compared to the inner air voids. To access the performance of imaging of the inhomogeneous medium, the experimentally recorded data was mixed with clutter noise corresponding to three volume fractions of the aggregates and used to construct the SAFT based images (refer to Fig. 2 b), c) and d)). It is observed that with increasing
level of inhomogeneity due to increase in the volume fraction of the aggregates, there is a degradation in the SAFT generated image. For a maximum volume fraction of 0.4, the brightest spot is observed only at the location of damaged air void scatterer, as shown in Fig. 2d).

Fig. 2. SAFT images of the medium using pulse echo data a) for homogeneous medium; and b), c) and d) for inhomogeneous medium having aggregate volume fraction of 0.2, 0.3 and 0.4 respectively.

The performance of RTM for detection of an anomaly in the homogeneous as well as in the inhomogeneous medium was accessed by using two different imaging conditions – the zero lag cross-correlation Imaging Condition [7] and the maximum strain energy based Imaging Condition [8]. The images obtained by using RTM and the maximum strain energy density based imaging condition, are shown in Figs. 3 a) through d). For the homogeneous medium the image initially contained bright spots for all the four scatterer locations (Fig. 3 a)), and the brightest spot, which is shifted upwards as compared to other three corresponds to the damaged air void scatterer. It is also noted that the image quality degrades with increasing level of inhomogeneity (Fig. 3 b) and c)) and outer two spots disappear at an aggregate volume fraction of 0.3 (Fig. 3 c)). However, the brightest spot still corresponds to the damaged scatterer location.
The images constructed by using the RTM algorithm and the cross-correlation based imaging condition are shown in Fig. 4.

All of the air void scatterers in the homogeneous medium are correctly located in Fig. 4a). The upward shifted bright spot (third from left) is due to damaged air void scatterer. The background in the images is less noisy. It is observed that the image quality degrades considerably even with the first level of inhomogeneity, i.e. for the aggregate volume fraction of 0.2. Not much information, except for the upwards shift of spot at the location of the damaged scatterer is observed in Fig. 4b).

4.2 Imaging with Focused Field

To improve the images, and also to increase the possibility of detection of damage at a pre-defined location inside the inhomogeneous medium, focusing of ultrasonic field by the transducer array is proposed. The field is focused one by one towards the centers of all of the air void scatterers using the data recorded in the bistatic configuration as explained in a previous subsection. Both SAFT and RTM algorithms are tested with the scattered field information using the focused field.
The images obtained by using the SAFT algorithm on the inhomogeneous medium with aggregate volume fraction of 0.4 are shown in Figs. 5 a) through d). Each figure corresponds to the case where the focused field incident on a particular air-void scatterer. In all of these images bright spots at the air void scatterer locations, along with background ghost images at other locations are observed. The ghost spots impose a limitation on the SAFT approach in the detection of scatterers inside the medium. The images corresponding to the internal scatterers are similar to each other and no qualitative difference is observable corresponding to the damaged condition in Fig. 5 c). So detection of the damaged scatterer by SAFT using the focused incident field does not seem to be a feasible option.

The RTM generated images of inhomogeneous medium using the focused incident field and the maximum energy density imaging condition are shown in Figs. 6 a) through d). Comparatively brighter spots are observed at the inner scatterer locations as shown in Figs. 6 b) and c) with the image corresponding to the damaged scatterer being the brightest (Fig. 6c)). The RTM algorithm using the maximum energy density imaging condition is therefore able to assess the scatterer
condition through a relative qualitative comparison of the images. However, the images are resolved poorly in the axial direction. The upwards shift of the image corresponding to the damaged scatterer is also not observed here.

The zero-lag cross-correlation based imaging condition is applied to obtain RTM generated images, shown in Fig. 7.

![RTM generated images](image)

**Fig. 7.** a), b), c) and d) show RTM generated images of inhomogeneous medium having aggregate volume fraction of 0.4, and using the cross-correlation based condition, under ultrasonic field focused at the four air void scatterer locations.

The focal spots at all of the four scatterer locations are observable in Fig. 7 unlike in Fig. 6 and the axial resolution is better as compared to maximum energy density based imaging condition. The spots at the inner scatterer locations (refer to Fig. 7 b), c)) are comparable in brightness and therefore, no clear assessment of the scatterer conditions can be made from comparison of intensity of the spots. However, the bright spot corresponding to the damaged scatterer (Fig. 7 c)) is shifted slightly upwards as compared to the other three images.

5 Conclusion and Outlook

In this paper, we compare the relative effectiveness of the SAFT and the RTM algorithms to construct subsurface characteristics of an inhomogeneous medium. The RTM algorithm itself has been explored with two types of imaging conditions.

The study demonstrates that under Pulse-Echo mode, in a moderately inhomogeneous medium, the RTM generated images using both imaging conditions correctly locates the damaged scatterer position, with the zero-lag cross-correlation imaging condition showing an upwards shift in the image of the damaged scatterer. The zero-lag cross-correlation imaging condition generates a brighter patch at the damage location that distinguishes it from the images of the other scatterers. The SAFT also detects the scatterers correctly, but shows no particular feature that can distinguish a damaged and an undamaged condition.

Focusing of ultrasound is performed to insonify the medium in order to direct more energy towards a known scatterer location and thereby generate an image using SAFT or RTM to detect relative changes in the images in the presence of damage. The focusing action to a certain extent
circumvents the effect of scattering by the aggregates and enables a better illumination of the region of interest, though we have higher operational load compared to the Pulse Echo modality. The SAFT generated images better resolve the inner scatterers than those on the sides, but it does not show any change in nature of image due to a difference of size of the one of the scatterers (which simulates a damaged situation). RTM with maximum energy density, as in the previous case of the Pulse-Echo mode, generates a brighter spot at the location of the damaged scatterer. However, we can only compare between the centrally located scatterers and the images of the outer scatterers are faint due to limited aperture size. The axial resolution is however worse in comparison to the images generated with the zero-lag cross-correlation imaging condition. The latter approach is also capable of detecting all of the four scatterers and the image corresponding to damaged scatterer is shifted upwards in the image. The study therefore demonstrates that RTM with focused ultrasonic insonification can be an effective tool to detect an anomaly inside an inhomogeneous medium along with assessment of relative change in health condition at various locations.

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