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Analytical reverse time migration: An innovation in imaging of infrastructures using ultrasonic shear waves

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ABSTRACT

The emergence of ultrasonic dry point contact (DPC) transducers that emit horizontal shear waves has enabled efficient collection of high-quality data in the context of a nondestructive evaluation of concrete structures. This offers an opportunity to improve the quality of evaluation by adapting advanced imaging techniques. Reverse time migration (RTM) is a simulation-based reconstruction technique that offers advantages over conventional methods, such as the synthetic aperture focusing technique. RTM is capable of imaging boundaries and interfaces with steep slopes and the bottom boundaries of inclusions and defects. However, this imaging technique requires a massive amount of memory and its computation cost is high. In this study, both bottlenecks of the RTM are resolved when shear transducers are used for data acquisition. An analytical approach was developed to obtain the source and receiver wavefields needed for imaging using reverse time migration. It is shown that the proposed analytical approach not only eliminates the high memory demand, but also drastically reduces the computation time from days to minutes.

1. Introduction

The emergence of linear array systems with low-frequency dry point contact transducers emitting horizontal shear waves offers an opportunity to significantly improve nondestructive testing (NDT) of concrete structures [1–6]. The small contact area of dry point contact transducers with a concrete member allows a direct contact without requiring a coupling agent, therefore, allowing data to be acquired more efficiently. For example, the first version of an ultrasound array system, MIRA, (see Section 3 for more information about the device) provided 45 pairs of signals in less than a second in each scan [2]. In comparison to transducers that transmit longitudinal waves, shear transducers enable detection of smaller defects and inclusions in deeper depths of concrete members. Detection of deeper defects is accomplished by lowering energy loss due to mode conversion [7]. Such an efficient data acquisition system needs powerful imaging techniques to utilize the acquired data.

The well-established imaging method in NDT of concrete members is synthetic aperture focusing technique (SAFT) [8–11]. SAFT has been used extensively to measure thickness and to detect rebar, delamination, and damage [12–15]. SAFT can provide an image of the scanned medium in a few seconds, but it has some shortcomings. For instance, it comes short in locating boundaries and interfaces with a steep slope and bottom boundaries of tendon ducts [16]. Therefore, a more advanced imaging technique is needed to overcome these limitations. Recently, a new imaging method, reverse time migration (RTM) [17–19] technique, has gained attention in ultrasonic nondestructive testing [3,16,20–26]. In contrast to the SAFT, which converts multiple reflections to artefacts, the RTM takes advantage of multiple reflections to locate interfaces and boundaries with steep slopes and bottom boundary of inclusions and defects [26]. Lin and Yuan [20–22], and He and Yuan [23,24] used synthetic and real data and showed the ability of RTM to detect damages in aluminum and laminated composite plates. Müller et al. [16] showed that RTM has the potential of imaging a whole circular boundary of tendon ducts and vertical boundaries of stepped foundations. Beniwal and Ganguli [26] successfully utilized RTM for detection of defects around rebar located in a concrete medium. Grohmann et al. [3,25] demonstrated that RTM can locate the vertical boundary of a large stepped foundation.

Despite the aforementioned capabilities, the RTM suffers from two primary bottlenecks: the method is computationally costly and it demands a massive amount of memory. The RTM requires performing multiple numerical simulations saving the entire time history of the source wavefield in memory or on a disk. The RTM is actively being used in the oil and gas industries where several techniques have been developed to alleviate these bottlenecks. To speed up computations, oil

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and gas industries use parallel computing techniques [27–31]. To alleviate the memory bottleneck, algorithms have been developed [32–36]. These algorithms, however, reduce the size of memory by requiring an additional numerical simulation backward in time to reconstruct the source wavefields. These solutions are effective in the oil and gas industries, but are costly for nondestructive testing applications [3]. For example, imaging a concrete member of considerable size with the RTM can take days. Considering the nature of problems in NDT, more affordable solutions must be developed.

In this study, a technique was developed permitting to eliminate computational and memory bottlenecks so that an operator could apply RTM to data acquired by DPC transducers transmitting horizontal shear waves and quickly obtain an image of the scanned medium using a standard personal computer. To do this, it was assumed that the condition of anti-plane shear deformations in the scanned medium holds. It was also assumed that the scanning is performed from one side of the medium. Using these assumptions, we have generated an analytical approach in which a closed-form term is obtained for the time history of the motion of one particle of the medium with the assumption of anti-plane shear. Only one displacement component is nonzero in anti-plane shear. Then the time history of motion of that one particle is used to obtain the time history of the motion of other particles in the medium.

It will be shown that our analytical approach allows reconstruction of high resolution images at a very low computational cost. Those images can be used for geometry measurement or localization and characterization of inclusions and defects with high accuracy. Moreover, the analytical RTM approach enables imaging each point independently because in this approach the time history of motion of any point is dependent on the time history of the motion of only one particle. This capability of the analytical approach further reduces the computation cost by restricting imaging to a region of interest (ROI) where the probability of defects or inclusions is higher. A low-resolution image reconstructed by the analytical RTM can be used to specify the ROI. The proposed analytical RTM approach offers further advantages that will be discussed in Section 2.2.2. The accuracy and efficiency of the analytical RTM will be shown by imaging the vertical boundary of a stepped foundation of considerable size that is only accessible from its top boundary.

Below, we give the algorithm of the reverse time migration technique. Then, the proposed analytical approach is presented and its benefits are discussed. Afterwards, some comments on its implementation are given. In the results section, accuracy and efficiency of the analytical RTM approach are shown by imaging the bottom boundary of a homogeneous foundation.

2. Methods

2.1. Reverse time migration algorithm

Reverse time migration (RTM) is an imaging method that processes data collected by an acquisition system consisting of sources and receivers to reconstruct an image of the scanned medium. In this study, we assume that the medium is accessible only from one side. In most cases for NDT, the RTM algorithm requires the average density, velocity of the wave, and the source wavelet as inputs. RTM involves the following steps for each pair of source and receiving transducers to reconstruct an image of the scanned medium:

Step 1. A numerical simulation is performed assuming a homogeneous elastic medium that has an average density and an average shear wave velocity of the scanned medium excited by a sender located at the position of the source and emitting the source wavelet. This simulation is used to reconstruct the entire time history of the wavefield of the source ($S(\boldsymbol{x},t)$), where $\boldsymbol{x}$ represents the coordinates of a point in the medium and t denotes time.

Step 2. In a second numerical simulation, the same homogeneous elastic medium is excited by sources placed at the location of the receivers corresponding to the source at step 1. The recorded signals by the receivers are reversed in time. Then, the sources transmit the time-reversed signals to the homogeneous medium to reconstruct the receiver wavefields ($R(\boldsymbol{x},T-t)$), where T is the total time of data collection. It should be noted that because the signals are reversed in time, the obtained wavefields are at time $T-t$.

Step 3. Cross-correlation (Eq. (1)) is used as an imaging condition [37] to reconstruct the image of the scanned medium:

$$I(\boldsymbol{x}) = \int_0^T S(\boldsymbol{x},t)R(\boldsymbol{x},t)dt. \tag{1}$$

In practice, the integral in Eq. (1) is estimated numerically (Eq. (2)):

$$I(\boldsymbol{x}) \cong \sum_{m=1}^{n} S(\boldsymbol{x},m\Delta t)R(\boldsymbol{x},m\Delta t) \tag{2}$$

where $T = n\Delta t$. A change in the value of image intensity, I, from one point to another indicates the change of acoustic impedance between those two points leading to the detection of reflectors.

For multiple sources, steps 1 to 3 would be repeated for each source, and then the corresponding reconstructed images would be stacked to obtain the final image (Eq. (3)):

$$I(\boldsymbol{x}) \cong \sum_{k=1}^{n_s} \sum_{m=1}^{n} S_k(\boldsymbol{x},m\Delta t)R_k(\boldsymbol{x},m\Delta t), \tag{3}$$

where n_s is the total number of sources.

The reason for the high memory demand of RTM is that the cross-correlation (Eq. (1)) needs the source and receiver wavefields at the same time. Nonetheless, the source wavefield, $S(\boldsymbol{x},t)$, is propagated from time zero up to maximum time, and the receiver wavefield, $R(\boldsymbol{x},T-t)$, is propagated in the reversed time direction from maximum time down to zero. Therefore, one of the wavefields must be saved in memory. Because a very fine temporal and spatial grid has to be used to avoid instability and grid dispersion, memory demand is high.

The reason for the high computational cost of RTM is that RTM requires two numerical simulations for each sending and receiving. Because a large number of sending and receiving is performed in scanning a medium, numerous simulations are required for imaging using RTM. While these simulations can be parallelized, the computation time and memory requirements remain a significant obstacle in implementation of this technology.

2.2. The proposed analytical RTM approach

In this study, we develop an analytical approach to overcome the bottlenecks of the reverse time migration technique when data are acquired using transducers that emit horizontal shear waves. To obtain the time history of motion of one particle of the medium, we consider the wave equation corresponding to anti-plane shear. Assuming that the waves propagate in the x-z plane and are polarized in the y-direction, the only nonzero displacement component is u_y and the wave equation is [31]:

$$\frac{\partial^2 u_y}{\partial x^2} + \frac{\partial^2 u_y}{\partial z^2} = \frac{1}{c_s^2}\frac{\partial^2 u_y}{\partial t^2}, \tag{4}$$

where c_s is $\sqrt{\mu/\rho}$ and represents the velocity of shear wave in the medium, μ is the shear modulus and ρ is the mass density.

Next, we derive the time history of motion of a point at distance R from a DPC shear transducer. Because the contact area of a DPC transducer with the scanned medium is very small, we can assume that the size of source is very small as well. We also assume that the source is located at the free surface of a half-space elastic homogeneous medium and has a small width, a. The source transmits a stress signal (Eq. (5)) to a half-space medium.

$$\sigma_{zy}(x,0,t) = \sigma_o f(t), \tag{5}$$

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