Ultrasonic wavefield inversion and migration in complex heterogeneous structures: 2D numerical imaging and nondestructive testing experiments

Luan T. Nguyen\textsuperscript{a,\textdagger}, Ryan T. Modrak\textsuperscript{b,2}

\textsuperscript{a}International Geothermal Centre, Bochum University of Applied Sciences, Bochum, Germany
\textsuperscript{b}Geophysical Institute, University of Alaska Fairbanks, AK, United States

\textbf{ARTICLE INFO}

\textbf{Article history:}
Received 18 February 2017
Received in revised form 24 August 2017
Accepted 13 September 2017
Available online 21 September 2017

\textbf{Keywords:}
Ultrasonics
Nondestructive testing
Reverse-time migration
Full-waveform inversion

\textbf{ABSTRACT}

Delaminations, cracks and other defects in engineered structures often lie close to the theoretical resolution limit for ultrasonic waves. While ultrasonic waveform tomography has succeeded in detecting such features, recovery is difficult because it requires computationally expensive high-frequency numerical wave simulations and an accurate understanding of large-scale background variations of the engineered structure. Without such knowledge, small defects may be incorrectly imaged or go undetected altogether. To reduce computational cost and improve detection of small defects, a useful approach is to divide the waveform tomography procedure into two steps: first, a low-frequency model-building step aimed at recovering background structure, and second, a high-frequency imaging step targeting defects. The first is naturally formulated as waveform inversion for wavespeed parameters and the second as time reversal migration for reflectivity. Through synthetic test cases, we show that the two-step workflow appears more promising in most cases than a single-step inversion. In particular, we find that new workflow succeeds in the challenging scenario where the defect lies along preexisting layer interface in a composite bridge deck and in related experiments involving noisy data or inaccurate source parameters.

\textcopyright 2017 Elsevier B.V. All rights reserved.

\section{1. Introduction}

Monitoring aging civil infrastructure is critical for risk mitigation and repair cost reduction. To provide early warning of structural defects, such as deterioration in concrete bridge decks,\cite{1} nondestructive testing (NDT) using ultrasonic waves is an increasingly important tool. Classical ultrasonic NDT\cite{2} methods include ray-based synthetic aperture focusing techniques (SAFT) and time-of-flight diffraction (TOFD) carried out on the recorded signals from pulse-echo or pitch-catch measurements. A summary of recent developments in SAFT and TOFD can be found for example in\cite{3–5}. We note that spectrum analysis of frequency shift and second order harmonic of the nonlinear ultrasonic waves can be very effective for indicating qualitatively the damage degree in materials that are undergone fatigue or micro-cracks\cite{6,7}.

In many cases, a structure is simple enough for arrival times of direct and reflected phases to be accurately computed using ray methods. Other times though, the usefulness of ray techniques is limited because of (1) difficulty dealing with structures involving large dips, complex geometry, or high impedance contrasts; (2) insufficient sensitivity to low impedance contrast defects; and (3) lack of accompanying output about the mechanical properties of the anomalous feature.

As a way around such difficulties, modern NDT techniques often involve full acoustic or elastic wave-equation modeling. Time reversal technique based on self-focusing of the reverse wavefield in particular has shown success in imaging acoustic emission sources\cite{8,9}. Based on the spatial and temporal cross-correlation of the forward and the time reversed wavefields, so-called reverse-time migration methods have shown their effectiveness in locating hidden reflectors and scatterers\cite{10,11}. Advantages of such techniques are that no event picking is required and the imaging condition is simple to implement. Besides widespread use in geophysical imaging\cite{12,13}, reverse-time migration has been successfully applied to scatterer location\cite{14} and detection of hidden interfaces and boundaries\cite{15}.

\textsuperscript{\dagger}Corresponding author.

E-mail addresses: luan.nguyen@hs-bochum.de (L.T. Nguyen), rmodrak@alaska.edu (R.T. Modrak).

\textsuperscript{1}Formerly at Faculty of Civil and Environmental Engineering, Ruhr-University Bochum, Bochum, Germany.
\textsuperscript{2}Formerly at Department of Geosciences, Princeton University, NJ, United States.
As a type of wave-equation tomography called full-waveform inversion (FWI) is used widely in geophysical imaging at various scales [16,17] and has shown promise for ultrasonic experiments as well. FWI builds a velocity model by minimizing some measure of the difference between the measured data and the model output. With the potential to resolve sub-wavelength features in the model [18], FWI is very promising for nondestructive evaluations. Interestingly, a prominent early FWI study [19] used ultrasonic data to validate implementation of a frequency domain inversion algorithm. Recently, FWI has been studied in medical imaging, for example, to reconstruct acoustic soundspeed and attenuation in soft tissues [20] and quantitatively image the acoustic impedance in bones [21].

Application of FWI to engineering NDT is not yet in common, but some recent work in this direction has shown promising results. Nguyen et al. [22] demonstrated that FWI is efficient for application in detection of bridge-deck delamination. Köhn et al. [23] showed that FWI using elastic Rayleigh waves can provide the $S$-wave velocity map of a weathered sandstone sample. For imaging the thickness of plate-like structures, FWI can be applied to guided waves by Rao et al. [24]. Seidl and Rank [25] formulated an advanced ultrasound NDT approach for material flaw identification based on the adjoint-based acoustic FWI solution.

Nevertheless, high-resolution imaging of engineered structures is challenging because of the high degree of heterogeneity, attenuation, and possibly anisotropy of materials used in construction, and often because of limited access or surface area for ultrasound measurement. This study is aimed at exploring the potential of geophysical imaging methods of full-waveform inversion (FWI) and reverse-time migration (RTM) of elastic waves in ultra-high frequencies for imaging of civil and industrial materials and structures. In particular, we propose performing FWI first at a lower frequency to reconstruct the large-scale features of the unknown background for use later in a high-frequency RTM procedure to reconstruct the reflectivity image of small-scale defects.

In this study, we review FWI and RTM and show how they can be combined to image a high-contrast defect in an unknown heterogeneous structure. In two numerical experiments, we analyze the capabilities of the combined workflow for imaging a delamination in randomly inhomogeneous and layered concrete bridge decks. Finally, we examine complications that can arise in laboratory or field settings involving reflections from the sides and inaccurate source wavelets.

2. Methods

2.1. Reverse-time migration

RTM images the interior of a structure by numerically backprojecting waves recorded at the structure's surface. Based on the principle that reflectors are points where incident and scattered waves coincide [26], a reflectivity image can be obtained by cross-correlating the incident and backprojected wavefields. RTM differs from other migration methods in that the wavefield simulations are carried out without ray approximations.

In practice, two numerical solutions of the elastic wave equation per source are needed to produce a reflectivity image. Adopting the notation of Tromp et al. [27], the first solution represents a wavefield propagating forward in time away from the source

$$s(x, t) = \int G(x, x_s, t - t') f_s(t') \, dt',$$

where $G$ is the acoustic or elastic Green's function, $x_s$ is the source location, and $f_s(t)$ is the source-time function. Letting $d_i(t)$ denote the data recorded at the receiver location $x_i$ ($i = 1, \ldots, N_i$), the second simulated wavefield

$$d_i'(x, t) = \sum_{i=1}^{N_i} \int G(x, x_i, t - t') d_i(t') \, dt',$$

represents an extrapolation of the data backward in time away from the receivers.

From $s$ and $d'$, the reflectivity image for a time window $t \in [0, T]$ is given by

$$l(x) = \int_0^T s(x, t) d_i'(x, T - t) \, dt.$$  

To perform the cross-correlation, both the forward wavefield $s$ and reverse wavefield $d'$ must be simultaneously accessible. To avoid the need to store either wavefield in its entirety, $s$ can be reconstructed on-the-fly from checkpoints or from values stored on the boundary while $d'$ is being simulated [28].

For RTM to work successfully, the velocity model used for the wavefield simulations is ideally a smooth estimate of the actual target structure. An incorrect model may lead to unfocused reflectivity images or even spurious reflectors [29].

2.2. Full-waveform inversion

FWI is a data-fitting technique in which comparisons between observations and synthetics are used to iteratively update a model of the target structure. Unlike RTM, which is formulated implicitly or explicitly in terms of reflectivity, FWI is used to update wave-speed parameters or related elastic moduli. The total number of updates required for a satisfactory inversion result varies depending on accuracy of the starting model and the complexity of the target structure.

Through a measure of fit between data and synthetics such as

$$\chi(m) = \frac{1}{2} \sum_i \int |s_i(t; m) - d_i(t)|^2 \, dt,$$  

where the sum is taken over all available sources and receivers ($i = 1, \ldots, N$), FWI explicitly casts the inversion problem as a nonlinear optimization procedure. The functional $\chi(m)$ above, represents a conventional waveform-difference measure of fit [30]. In this approach, the wavespeed model $m$ is iteratively improved by using a nonlinear optimization algorithm to minimize the waveform differences.

For the NDT experiments below, we adopt the conventional waveform-difference misfit function given by Eq. (4). For computational efficiency, we use a quasi-Newton algorithm with backtracking line search to update the model. In other words, we compute model updates by

$$m_{k+1} = m_k - \alpha_k H^{-1}_{\text{QN}} g_k,$$  

where $H^{-1}_{\text{QN}}$ is the L-BFGS approximation to the inverse Hessian, $\alpha$ is the step length determined by the line search, and $g$ is the gradient of the misfit functional obtained through an adjoint-state method [27,31]. For both the nonlinear optimization procedure itself and related pre- and post-processing tasks we use the SeisFlows framework (github.com/rmodrak/seisflows). Forward and adjoint modelings are carried out using SPECFEM2D [32].

2.3. Combined inversion and migration workflow

One's ability to resolve small features through inversion or migration depends on the spatial and temporal frequency content of the recorded data. Often features of interest in nondestructive
دریافت فوری
متن کامل مقاله

امکان دانلود نسخه تمام متن مقالات انگلیسی
امکان دانلود نسخه ترجمه شده مقالات
پذیرش سفارش ترجمه تخصصی
امکان جستجو در آرشیو جامعی از صدها موضوع و هزاران مقاله
امکان دانلود رایگان ۲ صفحه اول هر مقاله
امکان پرداخت اینترنتی با کلیه کارت های عضو شتاب
دانلود فوری مقاله پس از پرداخت آنلاین
پشتیبانی کامل خرید با بهره مندی از سیستم هوشمند رهگیری سفارشات