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Reverse time migration of acoustic waves for imaging based defects detection for concrete and CFST structures

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ABSTRACT

Ultrasonic non-destructive testing (NDT) technology has been widely used for defect inspection of concrete structures in civil engineering. However, most of the current data processing methods can only provide qualitative information regarding the existence of concrete inner defects. In this study, an ultrasonic inner defects inspection approach with a high-resolution imaging method which combines travel time tomography (TTT) and reverse time migration (RTM) is proposed for concrete and concrete-filled steel tube (CFST) columns. TTT estimates a reasonable distribution of ultrasonic velocity over the cross-section of the concrete and CFST columns from the first arrival time of the ultrasonic transmission signal. The velocity distribution is used as an input of the initial model for RTM to image the defects inside the concrete and CFST column cross-sections with a high resolution. Numerical experiments demonstrate that the air cavity inside the concrete and CFST columns, and the debonding between the concrete core and the steel tube of the CFST column can be identified clearly, and that the location, size and shape of both defects can be determined accurately. It is concluded that the proposed defect detection approach with a high-resolution imaging method is efficient for the non-destructive inspection of concrete and CFST structures using ultrasonic waves.

1. Introduction

In recent years, concrete-filled steel tube (CFST) columns have been widely employed in high-rise buildings and long-span bridges due to their advanced mechanical behaviors such as higher load-carrying capacity and more ductility under dynamic excitation, compared with normal reinforced concrete (RC) structures. However, various types of defects, such as cracks, air-void, honeycomb and debonding between concrete reinforcement in concrete structures and CFST members impose a huge threat to the structural safety [1]. For example, the interface debonding between concrete core and steel tube of CFST member affects the mechanical behavior of CFST members due to its negative effect on the confinement of steel tube

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on concrete core and finally decrease the load-carrying capacity and ductility. Therefore, the detection for concrete core defect and interface debonding between concrete core and steel tube of CFST is an emergent concern in civil engineering and represents a more challenging task due to the inaccessibility of concrete core covered by steel tube and the electromagnetic shielding effect of steel tube.

Ultrasonic technology has been widely used in nondestructive testing (NDT) and evaluation of concrete structures in civil engineering owing to its high resolution [1,2]. In addition to achievement in ultrasonic testing hardware development, significant progresses have been made in ultrasonic data processing and interpretation for defect detection [4]. Traditional A-scan analysis methods, such as time-frequency analysis [5,6], wavelet analysis [7,8], time-of-flight (TOF) analysis [9] and etc., can be used to analyze signal characteristics and qualitatively detect defects in concrete structures. Xu et al. proposed a piezoceramic lead zirconate titanate (PZT) based active interface debonding detection approach for CFST members and verified the performance of the approach experimentally, but it is still a challenging task to detect the location and dimension of the interface debonding [7,10]. Most of these A-scan data analysis methods can detect the existence of defects in concrete structures but the quantitative evaluation is still a challenging task. From B-scan or C-scan data, ultrasonic imaging techniques can characterize the inaccessible defects embedded in concrete structures.

Tomography utilizing transmission measurements, in which transmitting and receiving transducers are placed on opposite sides of a structure, has been commonly used in seismology and seismic exploration [11–14], and is recently adopted for ultrasonic imaging. Both travel time tomography (TTT) [15] and attenuation tomography [16] have been applied for concrete structure inspection. Experimental application of attenuation tomography to a large concrete structure has been rarely reported. TTT can detect soft defects such as a void, but can hardly detect a hard inclusion such as reinforcement in reinforced concrete structures [17]. Besides, TTT fails to resolve discontinuities in the velocity profile [18] and can only represent the embedded defects as a low-velocity anomaly [15]. Therefore, it is difficult to accurately determine the location and size of concrete defects embedded in concrete structures.

Synthetic aperture focusing technique (SAFT), which is also called migration in seismic data processing, focuses reflected ultrasonic waves recorded at multiple aperture points on one side of a concrete structure and can create a high-resolution image for its defect inspection [3,19,20]. However, SAFT usually utilizes a ray-tracing based back-projection algorithm and cannot handle multiple reflection. Reverse time migration (RTM) is a prestack imaging method based on full wave extrapolation [21] and has been commonly used in seismic exploration in the past twenty years [22]. Although RTM is recognized as the most accurate imaging method among the current migration methods [23], it is sensitive to the initial model, which requires accurate velocity distribution as an input. In practice, the ultrasonic velocity of concrete can be highly variable depending on the aggregate, porosity, temperature and stress. Therefore, it is desired to measure the velocity distribution as an input for RTM to improve the imaging quality.

This paper presents an integrated imaging algorithm, which combines TTT with RTM Specifically, an inhomogeneous velocity distribution over the cross-section of a concrete structure estimated by TTT with a high accuracy is used as the initial velocity model for RTM, of which the imaging quality can be greatly improved. From the reconstructed image by RTM, the defects embedded in both concrete structures and CFST columns are detected and their location and size are accurately determined. The following of this paper is organized as follows. After the introduction to the theory of the proposed imaging algorithm, three numerical experiments on concrete structure with air void and CFST member with air void and interface debonding defects are carried out to validate the advantage of the proposed imaging-based inspection approach. The results and conclusions are given in the fourth and fifth sections, respectively.

2. Proposed integrated imaging algorithm with TTT and RTM

2.1. Acoustic wave equation

Usually, a concrete member such as beam or column or a CFST member can be modeled as a bar or truss member since it extends much longer in one direction than the other two directions. The NDT for a concrete or CFST member is generally carried out with an emphasis on a specific cross-section. It is reasonable to consider a two-dimensional wave equation to describe the acoustic wave propagation in a concrete or a CFST member, where the concrete structure is assumed to be infinitely long in the z direction. Therefore, the first-order velocity-pressure partial differential equation is employed to calculate the acoustic wave fields, as shown in the following equations [24]

$$\begin{cases} \rho \frac{\partial v_x}{\partial t} = \frac{\partial P}{\partial x} + f_x \\ \rho \frac{\partial v_y}{\partial t} = \frac{\partial P}{\partial y} + f_y \\ \frac{\partial P}{\partial t} = \lambda \left(\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} \right) + g_p \end{cases} \tag{1}$$

where ρ is the density of the medium, $\boldsymbol{v}_x$, $\boldsymbol{v}_y$ denote the velocity components, P is the pressure, f_x, f_y are the density of a point source, g_p is the density of the pressure source, and λ is the Lame constant. The finite difference time domain (FDTD) method with second-order accuracy in both time and space is employed to solve the first-order differential equation of velocity-pressure [25] and to calculate the wave fields for RTM.