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The pre-stack migration imaging technique for damages identification in concrete structures

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Abstract Pre-stack migration imaging (PMI) method, which is used in geophysical exploration by the performance of single side detection and visually display, can be used to identify the location, orientation, and severity of damages in concrete structure. In particular, this letter focuses on the experimental study by using a finite number of sensors for further practical applications. A concrete structure with a surface-mounted linear PZT transducers array is illustrated. Three types of damages, horizontal, dipping and V-shaped crack damage, have been studied. A pre-stack reverse time migration technique is used to back-propagate the scattering waves and to image damages in concrete structure. The migration results from the scattering waves of an artificial damage are presented. It is shown that the existence of the damage in concrete structure is correctly revealed through migration process. [doi:10.1063/2.1105104]

Keywords ultrasonic waves, PMI, damage identification

In civil engineering, the main parts in structures need real-time diagnosis in a structure. Guided waves in structures can be used to detect the damages on the surface/inside of the structures, but it is difficult to interpret the received signals given their dispersive properties and complicated mode conversion phenomena.[1] Some characteristic parameters, such as time of arrival, phase velocity, group velocity, energy, and attenuation, are used to diagnose the damage based on the comparison of results between intact and damaged structures.[2,3] These methods can only recognize the existence of the damage and cannot provide quantitative information about the damage.

In the last decades, as an advanced signals process method, the migration method is indispensable for reflection wave field in geophysical exploration.[4–7] It potentially offers a promising method to fulfill active, online damage identification in structure health monitoring (SHM). Migration attempts to produce the image of inside damages by migrating the recorded wave field, the inverse process deals with back-propagating the recorded waves to obtain structures information.[8] Liu et al.[9] introduced the migration method into the nondestructive examination nonlinear differential equation (NDE) of concrete structures with surface-breaking cracks. Chien et al.[10] proposed the method of applying migration and numerically studied migration image of the simulated hole-shaped damage in a plate. By using numerical simulation, Yuan et al. correctly imaged a square-shaped damage in an aluminum plate based on the migration technique.[11] These studies were based on post-stack migration, and the post-stack migration cannot accurately image dipped damages where the surface of the damage is not parallel to the sensor array.[12] Xiao and Yuan proposed a pre-stack reverse-time migration to image two arbitrary small damages in an aluminum plate by numerical simulation,[13] and then imaged an arc-shaped crack through experiments using PZT as actuators and sensors alternately.[14] Almost all of the previous studies were validated in theory and experiments for metallic isotropic materials.[15] The pre-stack reverse-time migration was applied to visualize two arbitrary small damages in a composite laminate and validated it by numerical simulation.[16] However, the experimental application using pre-stack reverse-time migration to composite structures has not yet been examined.

In this letter, we present a fully experimental implementation of pre-stack migration imaging (PMI), the scattered wave-field is obtained by the corresponding traces of the horizontal, dipping and V-shaped damages through experiments using a finite number PZT transducer as actuators and sensors alternately in concrete structure and to validate the feasibility of adopting PMI for SHM purposes.

In order to simplify governing equation for guide wave using PMI, we define two new vectors

$$\boldsymbol{u} = \left[\dot{w}, \dot{\psi}_x, \dot{\psi}_y, Q_x, Q_y\right]^{\mathrm{T}}, \ \boldsymbol{q} = [q, 0, 0, 0, 0, 0,]^{\mathrm{T}} \quad (1)$$

where $\dot{w}, \dot{\psi}_x, \dot{\psi}_y$ represent the transverse displacement, rotation with respect to y and x axes respectively. Q_x, Q_y are transverse shear force per unit length acting on the cross section along the x and y direction respectively, q is the transverse force per unit area. Then the

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governing equation can be expressed in a matrix form[14]

$$\frac{\partial \boldsymbol{U}}{\partial t} = \boldsymbol{A}\frac{\partial \boldsymbol{U}}{\partial x} + \boldsymbol{B}\frac{\partial \boldsymbol{U}}{\partial y} + \boldsymbol{C}\boldsymbol{U} + \boldsymbol{q} \tag{2}$$

where $\boldsymbol{U} = \boldsymbol{E}_0\boldsymbol{u}$, $\boldsymbol{A} = \boldsymbol{A}_0\boldsymbol{E}_0^{-1}$, $\boldsymbol{B} = \boldsymbol{B}_0\boldsymbol{E}_0^{-1}$, $\boldsymbol{C} = \boldsymbol{C}_0\boldsymbol{E}_0^{-1}$, $\boldsymbol{A}_0$, $\boldsymbol{B}_0$, $\boldsymbol{C}_0$ and $\boldsymbol{D}_0$ are matrices listed in Ref. 14. From the elastic wave equation, if the wavefield at time t satisfies the wave equation, the wavefield also satisfies in the reverse time $(T - t)$. Due to this reversibility of the wave equation, the scattered wavefield is used to extrapolate the wavefield backward in time. The time interval for migration is equal to the sampling interval of the A/D device; the finite difference mesh is determined by the time interval. At each time step, the sensor array data are extracted as the new boundary value of Eq. (2) and are extrapolated backward wavefield, the imaging condition is applied to produce a partial image of the damage. The complete image is obtained after all times of sensor array data are inputted.

Pre-stack reverse-time migration, a proposed damage identification algorithm, is to interpret the sensor array signals. The first step is computation of the imaging condition in the image space. Using ray tracing and energy velocity, we can construct the imaging condition for each actuator exciting the waves by forming the incident wave-front locus at each time step. Then the locus data are saved as a reference table in a computer. The second step includes backward extrapolation of the scattered wave-field in time. In reverse-time migration, sensor signals on the linear array are used as the boundary conditions and are extrapolated backward in time. Successive iterations backward in time are taken until the initial time is reached. During this reverse-time process, the image of the damage is formed. By exciting the waves from another actuator location and repeating the two procedures mentioned earlier, another image can be formed. The third procedure is to stack these imaging results to visualize the damages.

In this section, pre-stack migration algorithm is applied to experimental results to validate its feasibility of damage identification. The experimental setup is shown in Fig. 1. The setup comprises a wave generator, wideband power amplifier and digital oscillograph. A computer is used to control and collect data from multi-channel actuator/sensor. The concrete specimens (1 000 mm × 240 mm × 240 mm) are prepared, a horizontal crack (Fig. 5(a)), a dipping crack (as shown in Fig. 5(b)) and a V-shaped crack (Fig. 5(c)) through a y-direction with 8 mm width and 60 mm length are cut to simulate damages. The simulated damages can be approximately considered as a perfect reflector for propagating waves.

As shown in Fig. 2(a), the measurement and scanning proceed along the survey lines on the top of the specimen. Each pair of eleven pairs of the PZT transducers is set to detect the damages respectively. When the actuator is excited at the location of point A_1, all

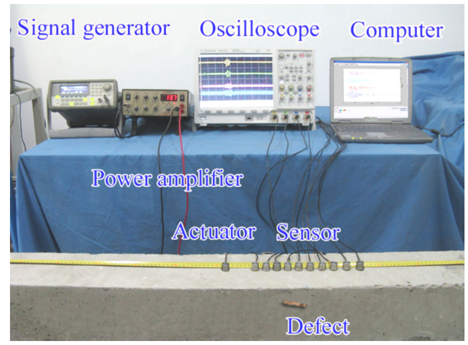

Fig. 1. The configuration of the experimental setup.

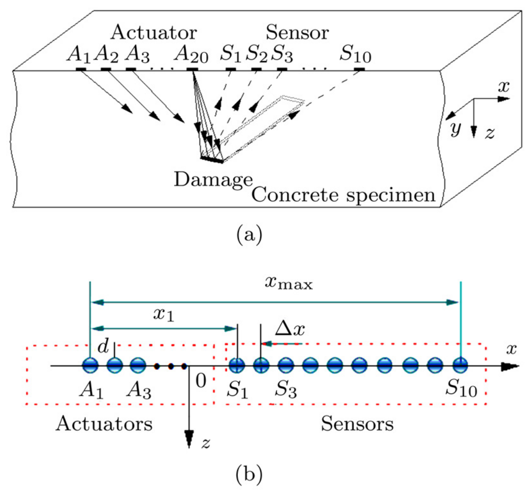

Fig. 2. (a) Geometrical configuration and the damage. (b) Layout of sensor/actuators.

other ten sensors (from point S_1 to S_{10}) on the survey line simultaneously record the reflected echoes from the structure. Next, the actuator and sensors group move forward to a unit distance d for the second measure, the actuator is triggered at the location of A_2 and the ten sensors (from point S_2 to S_{11}) record the reflected echoes, and so forth. As shown in Fig. 2(b), Δx (5 mm) is channel interval and x_1 (50 mm) is minimal actuator-sensor distance. $x_{\max}$ (95 mm) is the distance between actuator and the last sensor, and d (5 mm) is actuator interval.

The excitation wave from an actuator is shown in Fig. 3. Based on the reverse-time extrapolation of scattered wavefield algorithm, the scattered wave-field is

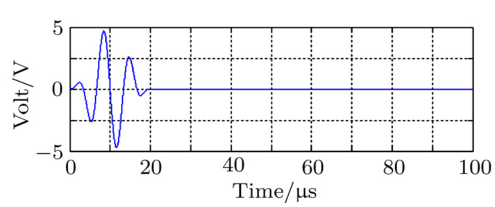

Fig. 3. The excitation waveform in the domain.

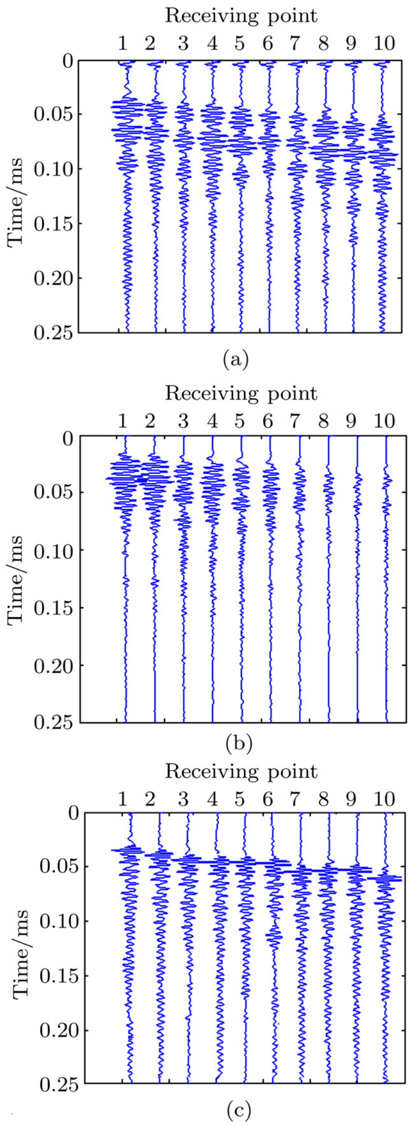

Fig. 4. (a) The signals with horizontal damage. (b) The signals with dipping damage. (c) The signals with V-shaped damage.

then obtained by the corresponding signals of the horizontal, dipping and V-shaped crack damages. Figure 4 gives the typical traces of the scattering waves excited with the horizontal, the dipping, and the V-shaped crack damages.

Figure 5 shows the concrete structure image migrated from the data recorded in the experiment. While the major part of the damage is imaged, there are some scattered blocks around the damages. These errors are mainly due to the coarse approximation of arrival time introduced in the process of reconstructing the scattered wavefield through interpolation. This could be corrected by using more sensors and thus omitting the interpolation process. In addition, an advanced interpolation algorithm needs to be developed such that the sensor spacing could be larger than the spacing of reverse-time migration algorithm mesh, thus the time section could be constructed by using a smaller number of sensors. Although the image migrated from the experimental data do not look perfect, it does demonstrate the feasibility of detecting arbitrary damages by interpreting the signals through the migration method.

The experimental studies demonstrate the guide wave based on pre-stack reverse time migration that can be used in an active SHM system. The PMI can detect not only the existence of damages; it may also provide the information about the location, orientation, and severity of damages in concrete structure. The monitoring information can be visually displayed by migration technique. It is not necessary to assume a damage pattern prior to applying the PMI, thus it makes it feasible to identify multiple damages. The PMI can effectively interpret the sensor data recorded by a distributed linear array sensors and make it possible to establish an active, online, and intelligent monitoring system.

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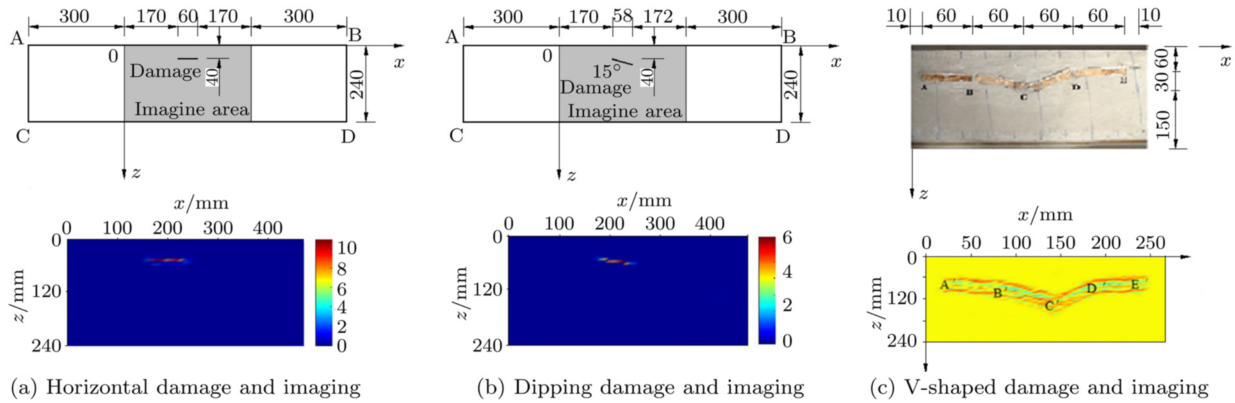

Fig. 5. Image of the damages migrated from the experimental data.