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Parametric analysis of the impact-echo phase method in the differentiation of reinforcing bar and crack signals

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HIGHLIGHTS

- The phase spectrum can be used to distinguish between crack and steel echoes.
- Effect of impact source, inclusion size/depth, and sample rate/duration is studied.
- Rules for the success of the impact-echo phase method are proposed.

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ABSTRACT

The conventional impact-echo analysis applies the Fourier transform to the surface response of the target structure due to an impact of a steel ball. Then, the amplitude spectrum is used to determine the frequency of the echo signals. Although the amplitude spectrum may disclose the existence of an interface in the structure, it contains no information about the type of interface.

This research group has proposed using the phase spectrum to differentiate reflections from cracks and reinforcing bars. Through numerical and physical tests, it was found that the phase of reflections at an air interface and reflections at steel interface fall within two distinct ranges, $(-\pi, \pi/4)$ and $(\pi/4, \pi)$, respectively.

This study aims at examining the influence of the impact duration, the inclusion size/depth ratio, the sampling rate, and the sampling duration on the effectiveness of the impact-echo phase method. Numerical simulations and physical tests were conducted considering various combinations of impact sizes, inclusion sizes and depths, sampling rates, and sampling durations. The results suggest that the phase offset is an effective indicator of the inclusion type under the following conditions: (1) the product of the impact duration and depth frequency falls in the range $[0.25, 0.8]$; (2) the length-depth ratio of the crack exceeds 0.33; (3) the radius-depth ratio of the reinforcing bar exceeds 0.4; (4) the sampling rate exceeds 6 times of the depth frequency; (5) the product of sampling duration and depth frequency exceeds 33.3.

1. Introduction

The impact-echo test is widely applied in the nondestructive testing of concrete structures. It has been applied to measure plate thickness, detect internal flaws, and evaluate corrosion damage of concrete structures [1–6].

In the impact-echo test, a steel ball is used to produce a point impact on the surface of the concrete specimen. When the resulting P-wave propagates into a structure, it reflects as it encounters an interface. Then the reflected wave returns back to the surface and reflects again into the interior of the structure. The process repeats and multiple reflections occur between the surface and the interface until the wave dissipates. The measured surface motion is transformed into the frequency domain. Then, the amplitude spectrum has a dominant peak corresponding to the frequency of P-wave arrival at the surface. The peak frequency f_d is related to the depth of the interface d by the following equations [1]:

$$d = \frac{C_p}{kf_d} \quad k = \begin{cases} 2 & \text{for crack interface} \\ 4 & \text{for rebar interface} \end{cases} \tag{1}$$

where C_p is the velocity of the longitudinal wave (P wave). Thus, by locating the peaks in the amplitude spectrum, the depth of an internal crack or a reinforcing bar can be determined.

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Although the amplitude spectrum of the impact-echo signal may disclose the existence of an interface in the structure, one cannot tell whether the interface is caused by a crack or a reinforcing bar. Such information is crucial in the safety assessment of the structure. It is also required in the selection of the k value in Eq. (1). Only a few researchers have addressed this issue [7,8]. Although some classification features were noted in these studies, no clear index was proposed to classify the interface.

Recently, our group proposed using the impact-echo phase spectrum as an indicator for the recognition of reinforcing bars and cracks [9]. This study further examines the influence of the impact duration, the inclusion size/depth ratio, the sampling rate, and the sampling duration on the effectiveness of the impact-echo phase method.

2. Impact-echo phase analysis

The Fourier transform of a time domain signal $x(t)$ is as follows:

$$X(f) = \int_{-\infty}^{+\infty} x(t)e^{-2i\pi ft}dt = X_{Re}(f) + iX_{Im}(f) = |X(f)|e^{i\phi(f)} \quad (2)$$

where $X_{Re}(f)$ and $X_{Im}(f)$ are the real and imaginary parts of $X(f)$;

$$\varphi(f) = \tan^{-1}\left\{\frac{X_{Im}(f)}{X_{Re}(f)}\right\} \quad (3)$$

is phase spectrum of the signal.

In the conventional impact-echo method, one examines the amplitude spectrum $|X(f)|$ to determine the thickness of a specimen or the location of an inclusion. In the impact-echo phase method, the phase spectrum is used to determine the type of reflecting interface.

The theoretical basis of the impact-echo phase method is as follows: Consider a uniform medium bounded by two parallel planes. The thickness of the medium is d. The top and bottom surfaces of the medium are traction free. The bottom resembles a concrete-crack interface. Let a compressive plane wave enter the medium normal to the surface. The longitudinal wave (P wave) changes sign when it encounters the bottom free surface. Hence, the incident compressive stress is reflected as a tensile stress wave. As the tensile stress wave reaches the top surface, it pulls the surface inward and reflects as a compressive stress wave. The cycle of compressive and tensile stress waves repeats, and the resulting vertical displacement at the top surface is shown schematically in Fig. 1(a). It is a periodic function with frequency $f_d = C_p/2d$.

On the other hand, consider a second medium of thickness $d/2$. Its bottom is bonded to a material with higher acoustic impedance, resembling a concrete-steel interface. The incident compressive stress wave remains a compressive stress wave as it reflects from the bottom interface. When the compressive stress wave reaches the top free surface, it pushes the surface outward and reflects as a tensile stress wave. When the wave arrives at the top surface the second time, it is a tensile wave and pulls the surface inward. Thus, the top surface moves alternately outward and inward. The vertical displacement at the top surface is shown schematically in Fig. 1(b). Although the thickness of the second medium is only one-half the thickness of the first medium, the frequency of the periodic displacement curve is still $f_d = C_p/2d$.

Notice that the depth frequencies in these two cases are the same. However, the phase change of the stress waves differs.

If the vertical displacements at the top surfaces of the two media are simplified as

$$x_c(t) = -e^{-2\pi\varsigma f_d t}|sin(\pi f_d t)| = -r^{f_d t}|sin(\pi f_d t)| \quad (4)$$

$$x_s(t) = -e^{-2\pi\varsigma f_d t}sin(2\pi f_d t) = -r^{f_d t}sin(2\pi f_d t) \quad (5)$$

where ζ is the damping ratio, and $r = e^{-2\pi\zeta}$ is the ratio of two consecutive wave amplitudes, one can show that [9]

$$\varphi_c(f_d) = tan^{-1}\left\{\frac{8\varsigma}{3 - 4\varsigma^2}\right\} \quad (6)$$

$$\varphi_s(f_d) = tan^{-1}\left\{\frac{2}{-\varsigma}\right\} \quad (7)$$

For $r = 1.0 \sim 0.5$, $\varphi_c(f_d) = 0 \sim 0.09\,\pi \cong 0$, and $\varphi_s(f_d) = 0.5\pi \sim 0.52\pi \cong \pi/2$. Numerical and physical tests have been conducted in [9]. It is found that the phase associated with reflections from an air interface and reflections from a steel interface fall within two distinct ranges: $(-\pi, \pi/4)$ and $(\pi/4, \pi)$, respectively. $\phi(f_d) = \pi/4$ seems to be a good boundary to distinguish between an air interface and a steel interface.

The procedure of the impact-echo phase method is illustrated in Fig. 2. Fig. 2(a) shows the simulated vertical displacement of a specimen with a 12 cm deep crack. Its amplitude and phase spectra were obtained using the Fourier analysis, as shown in Fig. 2(b) and (c). In Fig. 2(b), one can see the echo frequency f_d is located at 16.03 kHz. After pinpointing f_d, one can determine the corresponding phase offset at f_d in Fig. 2(c). In this case, the phase offset $\phi(16.03\ \text{kHz}) = 0.14\pi$ falls in the range $(-\pi, \pi/4)$. Hence, it is judged that the echoes come from a crack.

3. Parametric study on the impact-echo phase method

To examine the limitation of the impact-echo phase method, the influences of the impact duration, depth of interface, the size of inclusion, the sampling rate, and the sampling duration are studied in this research.

The finite element code LS-Dyna971 [10] was used to simulate the response of concrete specimens due to the impact of a steel ball. The dimensions of the concrete specimens are 80 cm (L) × 80 cm (W) × 20 cm (H). Three-dimensional solid elements were used in the simulation. The meshes of the specimens were generated by the ANSYS preprocessor. The side length of the elements ranged from 0.2 cm to 1 cm. The Young's modulus of elasticity, mass density, Poisson's ratio, and longitudinal wave speed were 33.1 GPa, 2300 kg/m3, 0.2, and 4000 m/s, respectively, for the concrete, and 207 GPa, 7850 kg/m3, 0.28, and 5800 m/s, respectively, for the steel. Absorbing boundary conditions were applied on the four sides of the models to simplify the wave behavior.

A time-varying pressure was applied to the surface on an element facet to simulate the impact of a steel ball. The pressure was approximated by a half-sine function with different contact times to simulate the impact of balls of different sizes [11]. The vertical displacement of a node 3.5 cm away from the impact source was recorded. Unless specified otherwise, the total simulation time was 3 ms, and the sampling time interval was 3 ms/1024 = 2.93 μs.

3.1. Influence of impact duration

The impact of a steel ball can be approximated by a half sine function with a contact time t_c [1]:

$$t_c = 0.0043D \quad (8)$$

where D (in units of m) is the diameter of the steel ball. This study uses the dimensionless parameter $t_c f_d$ to examine the influence of impact duration on the echo phase.

In the numerical simulations, 14 impact balls with different diameter D were used, namely, D = 2, 3, 4, 6, 8, 9, 10, 11, 12, 13, 15, 18, 23, and 29 mm. These impact sources were used to simulate impact-echo tests for 12 conditions, namely, 6, 8, 10, 12, 16, 20 cm