Construction and Building Materials 142 (2017) 1–6

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Recognition of rebars and cracks based on impact-echo phase analysis

P.-L. Liu, L.-C. Lin, Y.-Y. Hsu, C.-Y. Yeh, P.-L. Yeh *

Institute of Applied Mechanics, National Taiwan University, No. 1, Sec. 4, Roosevelt Rd., Da'an Dist. Taipei City 106, Taiwan

HIGHLIGHTS

- The phase spectrum of the impact echo test can be used to differentiate crack echo from rebar echo.
- The phases of crack echoes are nearly 0, while the phases of rebar echoes are nearly $\pi/2$.
- Echo phase = $\pi/4$ can be used as a decision line to judge the type of inclusion.

ARTICLE INFO

Article history:
Received 8 November 2016
Received in revised form 16 February 2017
Accepted 20 February 2017
Available online 19 March 2017

Keywords:
Impact echo test
Nondestructive test
Phase
Crack
Rebar

ABSTRACT

The impact-echo test is often used to detect defects or inclusions in concrete structures. Applying Fourier transform to the surface response of the target structure due to an impact, the depth of the interface can be determined through the impact-echo equation. Although the impact echo spectrum may reveal the existence of an interface in the structure, it cannot tell whether the interface results from a crack or rebar. Such information is crucial in the structural safety assessment and to determine interface depth because the impact-echo equations for cracks and rebar differ.

This research proposes using the phase spectrum to differentiate crack echoes from rebar echoes. Both the amplitude and slope of the phase spectrum at the echo frequency are studied. Fourier analysis of the simplified signals shows that the phases of crack echoes are nearly 0, while those of rebar echoes are nearly $\pi/2$. Numerical and model tests were conducted to verify the results. As expected, the phases can be successfully divided into two groups. The phases of crack echoes are less than $\pi/4$ and cluster around 0, while the phases of rebar echoes exceed $\pi/4$ and cluster around $\pi/2$. Unfortunately, the slope of the phase spectrum at the echo frequency cannot serve as an index for the classification of inclusion type.

Hence, it is suggested that both the magnitude and phase spectra be constructed in the Fourier analysis of the impact echo signals. Use the magnitude spectrum to determine the echo frequency and use the phase spectrum to determine the phase at the echo frequency. Then, use $\pi/4$ as a threshold to judge the type of inclusion. As such, one can obtain the correct type and depth of the inclusion.

1. Introduction

The impact echo test is commonly used in the nondestructive testing of concrete structures. It was originally applied to detect internal flaws in concrete plates [1,2]. Later, it was used to inspect flaws in rod structures, concrete panels, and corrosion damage of rebar in concrete [3–6]. Several imaging methods have been proposed to simplify the interpretation of test results [7–14].

In the impact echo test, a steel ball is used to produce an impact source on the surface of the concrete specimen, and a transducer is placed near the impact source to receive the surface response of the structure. Fourier transform is then used to transform the time signal to the frequency domain.

When a wave propagates in a structure, it reflects as it encounters an interface. The reflected wave then rebounds back to the surface and is reflected again into the interior of the structure. The process repeats and multiple reflections occur between the surface and the interface until the wave fades out, thus forming an echo peak in the Fourier spectrum. The peak frequency f_D is related to the depth of the interface D by the following equations:

$$D = C_p/(kf_D) \qquad k = \begin{cases} 2 \text{ for crack interface} \\ 4 \text{ for rebar interface} \end{cases} \tag{1}$$

* Corresponding author.
E-mail address: d88543003@ntu.edu.tw (P.-L. Yeh).

http://dx.doi.org/10.1016/j.conbuildmat.2017.02.102
0950-0618/

where C_p is the velocity of the longitudinal wave. By locating the peaks in the Fourier spectrum, the depth of an internal crack or a rebar can be determined.

Although the Fourier spectrum of the impact-echo signal may reveal the existence of an interface in the structure, one cannot tell whether the interface comes from a crack or rebar. Such information is crucial in the safety assessment of structures; it is also required in the selection of the k value in Eq. (1). Few studies have addressed this issue. Kuo et al. [15] applied the empirical mode decomposition to find the response difference between cracks and rebars. Ke [16] showed that crack and rebar echoes exhibit different patterns in the bi-spectrum. Although these studies noted some classification features, no clear index was proposed to classify the interface.

This research seeks to develop a method to effectively differentiate crack echoes from rebar echoes using a simple index based on the phase change of the reflected wave without reference to the investigator's subjective judgment.

2. Impact-echo phase analysis

2.1. Fourier phase spectra

Consider a signal $x(t)$. The Fourier transform of the signal is as follows:

$$X(f) = \int_{-\infty}^{+\infty} x(t) e^{-2i\pi f t} dt \tag{2}$$

$X(f)$ is a complex function, and it can be written in the polar form as

$$X(f) = \sqrt{X_{\mathrm{Re}}^2(f) + X_{\mathrm{Im}}^2(f)}\, e^{i\varphi(f)} = |X(f)| e^{i\varphi(f)} \tag{3}$$

$$\varphi(f) = \tan^{-1}\{X_{\mathrm{Im}}(f)/X_{\mathrm{Re}}(f)\} \tag{4}$$

where $X_{\mathrm{Re}}(f)$ and $X_{\mathrm{Im}}(f)$ are respectively the real and imaginary parts of $X(f)$, and $|X(f)|$ and $\varphi(f)$ are respectively the magnitude spectrum and phase spectrum of the signal.

If $\varphi(f)$ is replaced by $\varphi(f) + 2k\pi$ in Eq. (4), where k is any integer, $X(f)$ remains unchanged. Hence, the phase function $\varphi(f)$ is often restricted to the range $[-\pi, \pi]$, called the wrapped phase. If the actual phase is outside this range, it is increased or decreased by a multiple of 2π to put the phase value within the $[-\pi, \pi]$ range.

2.2. Phase of simplified echo data

The impact-echo phase analysis is based on the phase change of a stress wave as it encounters different interfaces. The theoretical basis of the method is explained 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 at a right angle. The longitudinal wave (P wave) changes signs 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 reflects as a compressive stress wave, as shown in Fig. 1(a). The cycle of compressive and tensile stress waves repeats and multiple reflections occur between the top and the bottom. The resulting vertical displacement at the top surface is schematically shown in Fig. 1(b). It is a periodic function with a frequency $f_D = C_p/2D$, according to Eq. (1).

Alternatively, consider a second medium of thickness $D/2$. Its bottom is not traction-free but is bonded to a material with higher acoustic impedance, resembling a concrete-rebar 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 reflects as a tensile stress wave, as shown in Fig. 1(c). The vertical displacement at the top surface is schematically shown in Fig. 1(d). 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 $C_p/2D$, according to Eq. (1).

Now, simplify the vertical displacement at the top surface of the first medium as a sequence of decaying half-sines, i.e.,

$$x_c(t) = -|\sin(\pi f_D t)| \tag{5}$$

and the vertical displacement at the top surface of the second medium as a sine wave, i.e.,

$$x_s(t) = -\sin(2\pi f_D t) \tag{6}$$

The Fourier transform of $x_c(t)$ and $x_s(t)$ are as follows:

$$X_c(f) = (-2/\pi)\delta(f) + \sum_{n=1}^{\infty}[4/(4n^2-1)][\delta(f - nf_D) + \delta(f + nf_D)] \tag{7}$$

$$X_s(f) = i\pi[\delta(f - f_D) - \delta(f + f_D)] \tag{8}$$

Since $X_c(f)$ is real and $X_s(f)$ is imaginary, according to Eq. (4), the phases of $X_c(f)$ and $X_s(f)$ at $f = f_D$ respectively are

$$\varphi_c(f_D) = 0 \tag{9}$$

$$\varphi_s(f_D) = \pi/2 \tag{10}$$

Notice that there is no attenuation in $x_c(t)$ and $x_s(t)$. To take attenuation into account, $x_c(t)$ and $x_s(t)$ are modified as follows:

$$x_c(t) = -e^{-2\pi\varsigma f_D t}|\sin(\pi f_D t)| = -r^{f_D t}|\sin(\pi f_D t)| \tag{11}$$

$$x_s(t) = -e^{-2\pi\varsigma f_D t}\sin(2\pi f_D t) = -r^{f_D t}\sin(2\pi f_D t) \tag{12}$$

where ζ is the damping ratio, and $r = e^{-2\pi\varsigma}$ is the decay ratio of the wave amplitude in one period, as shown in Fig. 2. One can show that

$$\varphi_c(f_D) = \tan^{-1}\{8\varsigma/(3 - 4\varsigma^2)\} \tag{13}$$

$$\varphi_s(f_D) = \tan^{-1}\{2/(-\varsigma)\} \tag{14}$$

For $r = 1$–0.5, $\varphi_c(f_D) = 0 \sim 0.09\pi$ and $\varphi_s(f_D) = 0.5\pi \sim 0.52\pi$, still very close to 0 and $\pi/2$, respectively. It seems that $\varphi(f_D)$ is a good indicator of the interface type.

Although the decay ratio has little influence on $\varphi(f_D)$, the slope $\varphi'(f_D)$ is more sensitive to the decay ratio. The expressions of $\varphi_c'(f_D)$ and $\varphi_s'(f_D)$ are as follows:

$$f_D\phi_c'(f_D) = [-8\varsigma(4\varsigma^2 + 5)/(256\varsigma^4 + 16\varsigma^2 + 9)] + [4\pi e^{-2\pi\varsigma}/(e^{-4\pi\varsigma} - 1)] \tag{15}$$

$$f_D\phi_s'(f_D) = (-4 - 2\varsigma^2)/[\varsigma(4 + \varsigma^2)] \tag{16}$$

In the above equations, the slopes are multiplied by f_D to make them dimensionless.

Fig. 3 shows the influence of amplitude decay ratio on $|f_D\phi_c'(f_D)|$ and $|f_D\phi_s'(f_D)|$. The absolute value of the slope is taken here because the slopes are negative. It is seen that the type of inclusion has no visible effect on the result. The two curves almost overlay one another. However, the slope is sensitive to the amplitude decay ratio. If the decay rates of the crack echo and rebar echo are different, the slope may serve as another index to identify the type of inclusion.

Notice that the context of the above discussion is restricted to the propagation of normal incident plane waves in a medium with two parallel surfaces. In the following, numerical simulations are