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# Vertical spectral tomography of concrete structures based on impact echo depth spectra

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ABSTRACT

This paper proposes a vertical spectral tomography for use in nondestructive testing of concrete structures. Impact echo tests are conducted along a test line on the concrete surface. Then, the response curves are transformed into depth spectra. Arranging the depth spectra in parallel and representing the amplitude by color scale, one obtains an image of the vertical cross-section under the test line. Three types of spectral tomograms are proposed. Numerical and experimental tests are performed to verify and compare the tomograms. Although different types of tomograms possess different attributes, all three tomograms can depict the internal crack successfully. The internal crack is represented by bright stripes in the tomograms, which can be used to estimate the size and location of the crack. The vertical spectral tomogram provides a direct image of the concrete cross-section. It may serve as a useful tool in the nondestructive inspection of concrete structures.



## 1. Introduction

The elastic wave methods are extensively utilized in nondestructive testing of concrete structures. In the elastic wave test, a wave source is activated on the surface of the structure. As a result, elastic waves are generated and propagate in the concrete structure. If the waves encounter an interface or inhomogeneity, they are reflected, refracted, or diffracted. Then, transducers are used to receive the surface response of the concrete. Since the signal contains information about the interface or inhomogeneity, it can be processed to detect the defects or size of the structure.

Several time domain and frequency domain test methods have been proposed in the literature to process the signals of elastic wave tests [1–4]. Among these methods, the impact echo method is most widely used because of its simplicity and robustness.

However, the impact echo test is a point-wise detection method. It only provides the depth of reflector right beneath the test point. If the test area is large, a thorough examination would require an enormous amount of tests. In that case, the interpretation of the test results to get an overall picture about the condition of the concrete structure is a challenging task. In order to simplify the interpretation, many image methods were proposed. Liu et al. [5] proposed a migration imaging method by processing the time signal to depict the location of a surface-opening crack on a vertical test section. Ohtsu and Watanabe [6] extended the migration image method to frequency domain and developed the stack image method for flaw detection based on impact echo data. Liu and Yiu [7] proposed the scan image method and the spectral *B*- and *C*-scan image methods to detect surface-opening cracks and internal cracks, respectively. Schubert et al. [8] used the spectral *B*-scan image to measure the thickness of finite concrete specimens. Kohl and Streicher [9] utilized the data fusion technique to construct the *B*- and *C*-scan images from the data of ground penetrating radar and ultrasonic test. Tong et al. [10] used the synthetic aperture focusing technique to show the defect image of structures.

In the aforementioned spectral *B*-scan methods, a series of impact echo tests need to be carried out along a test line. Then, the Fourier spectra of the test signals are lined up in parallel to construct an "image" of the vertical cross-section under the test line. In the detection of internal defects, such image certainly provides useful information about the size and location of the defect. However, the independent variable of the Fourier spectrum is frequency, not depth. Therefore, when the spectra are put together to form a 2D image, the horizontal axis of the image is the test location, while the vertical axis is frequency. Hence, one does not get a 'picture' of the interior of the structure. This is certainly a drawback for in situ diagnosis.

This paper proposes a method to construct the vertical spectral tomogram of the concrete structures. The idea is to transform the frequency axis of the Fourier spectrum into depth axis to obtain the depth spectrum. Since the Fourier spectra usually contain ripples and multiple peaks, so do the depth spectra. The spectral tomograms constructed using the depth spectra often contain a

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lot of noise. Hence, measures are also developed in this study to improve the quality of the spectral tomograms.

## 2. Spectral analysis of impact echo data

The impact echo method is a well established nondestructive method for concrete structures. In the impact echo test, a steel ball or a hammer is used to produce an impact source on the surface of a concrete structure, and a transducer is used to measure the response of the concrete near the impact source. If there is an interface beneath the test point, elastic waves will bounce between the top surface and the interface. Hence, a peak is formed in the Fourier spectrum of the received signal. The peak frequency $f$ and the depth of the interface $d$ is related by the following formula [11]:

$$d = \frac{C_p}{2f} \quad (1)$$

where $C_p$ is the velocity of the longitudinal wave. Eq. (1) is valid only when the material on the other side of the interface is softer than the concrete. If the material is stiffer, i.e., steel, the factor 2 in Eq. (1) should be replaced by 4.

By locating the peak in the Fourier spectrum, one can determine the thickness of the structure or the location of a defect by applying Eq. (1).

With proper training, the inspector often can identify the echo peak in the Fourier spectrum successfully. However, the Fourier transform spectra usually contain ripples and multiple peaks. Some of the ripples and peaks do not come from reflections or diffractions. Instead, they are generated by the transform process [12]. Such artificial interferences may jeopardize the interpretation of test results.

Several time–frequency analyses have been proposed in the literature to deal with the interference [13–17], for example, the wavelet transform (WT). In the application of impact echo test, the wavelet marginal spectrum can avoid the inherent interferences [12]. However, the frequency resolution of the wavelet transform is inferior to the Fourier transform due to the uncertainty principle [18]. In the wavelet marginal spectrum, one often finds a hump, not a sharp peak, around the echo frequency. That makes it difficult to pinpoint the peak frequency.

In order to take advantage of both the wavelet and Fourier transforms, Yeh and Liu [12] proposed the enhanced Fourier transform (EFT) as follows:

$$E(f) = F(f)M(f) \quad (2)$$

where $E(f)$ is the enhanced Fourier spectrum, $F(f)$ and $M(f)$ are the Fourier spectrum and wavelet marginal spectrum respectively.

The wavelet marginal spectrum can be considered as a band-pass filter. Multiplying $F(f)$ with $M(f)$ amounts to applying the band-pass filter $M(f)$ to $F(f)$. As such, the frequency components in $F(f)$ around the peak of $M(f)$ are magnified, and the frequency components away from the peak are held back. Consequently, the ripples and multiple peaks induced by the Fourier transform are suppressed, while the echo peak is enhanced.

Fig. 1 shows the Fourier spectrum, wavelet marginal spectrum, and enhanced Fourier spectrum of an impact echo signal. It is seen that the Fourier spectrum contains ripples and multiple peaks. The wavelet marginal spectrum is smooth, but the echo peak is not as sharp as in the Fourier spectrum. The enhanced Fourier transform apparently damps out the interferences while retaining the high resolution.

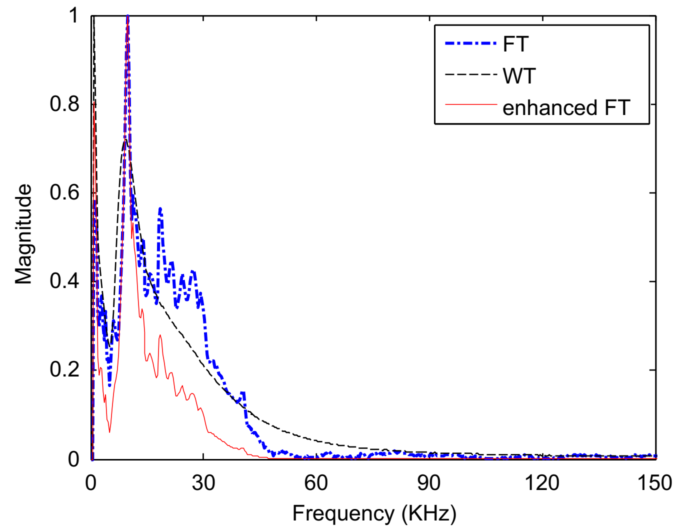


**Fig. 1.** Comparison of Fourier spectrum, wavelet marginal spectrum, and enhanced Fourier spectrum.

## 3. The depth spectrum

The horizontal axis of the Fourier spectrum, wavelet marginal spectrum, or enhanced Fourier spectrum is the frequency axis. It can be easily transformed into the depth axis by applying Eq. (1). This idea was firstly proposed by Pratt and Sansalone [19] to construct the normalized amplitude spectrum such that signal interpretation could be automated. In the normalized amplitude spectrum, depth was presented as a percentage of the full thickness of the structure, and a logarithmic scale was adopted for the depth axis.

The notion of frequency-depth transformation was proposed again by the Yeh and Liu [20] for the purpose of image processing. The procedure is as follows: Suppose the frequency resolution of the spectrum is $\Delta f$. One applies Eq. (1) to $i\Delta f$, $i = 1, 2, \ldots$ to find the corresponding depth $d_i$. Determine the amplitude $a$ of the spectrum at $i\Delta f$. Then, plotting $a(i\Delta f)$ versus $d_i$ yields the depth spectrum of the signal.

The above approach is not appropriate if the depth spectrum will be used for further image processing. This is because $f$ is inversely proportional to $d$. A constant interval in frequency will result in varying intervals in depth, as shown in Fig. 2(a). The non-uniform grid points are inconvenient for image processing.

An alternative way to obtain the depth spectrum is to select a constant $\Delta d$. Apply Eq. (1) to $i\Delta d$, $i = 1, 2, \ldots$ to find the corresponding frequency $f_i$. Then, plotting $a(f_i)$ versus $i\Delta d$ yields the depth spectrum of the signal. Notice that $f_i$ in general is not a multiple of $\Delta f$. Hence, interpolation may be needed to find the amplitude of the spectrum at $f_i$. This approach could provide a spectrum of constant $\Delta d$. However, there is a high possibility that the peaks in the original spectrum are bypassed in the transformation, as shown in Fig. 2(b). The situation is especially severe in the shallow range because the distance between $f_{i+1}$ and $f_i$ increases as $d$ decreases.

In order to insure that no peak is left out in the depth spectrum, the following modification is suggested. Instead of using $a(f_i)$ as the amplitude at $i\Delta d$, the maximum amplitude $\hat{a}_i$ in the interval $(f_{i+1}, f_i)$ is determined, as shown in Fig. 2(c). Then, plotting $\hat{a}_i$ versus $i\Delta d$ yields the depth spectrum of the signal. This spectrum is useful in the image processing of impact echo data.

Notice that the depth spectrum can be obtained by applying the frequency-depth transformation to various spectra, including