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Spectral tomography of concrete structures based on impact echo depth spectra

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ABSTRACT

This paper proposes a spectral tomography for nondestructive test of concrete structures based on the spectral data of impact echo test. Firstly, a mesh is drawn on the surface of the concrete. Then, impact echo tests are performed at the grids. The recorded signals are processed to obtain the spectra of the concrete. The spectra are further transformed into the depth spectra and assembled into 3D volume data. Finally, spectral tomography is applied to the volume data to construct the image of the concrete structure for arbitrary cross-sections. Both numerical and experimental tests are performed to verify the effectiveness and reliability of the proposed imaging method. It is seen that the spectral tomography can be used to show the internal cracks in the concrete specimens successfully.

1. Introduction

The impact echo method is a nondestructive test of concrete structures. In the impact echo test, an impact force is applied on the surface of the target structure. Then, a transducer is used to measure to response of the structure. Transforming the time signal to the frequency domain, one can determine the depth of the reflector beneath the test point.

The impact echo test is point-wise detection method. The nondestructive examination of a structure usually requires numerous tests. How to integrate the test results to get an overall picture about the condition of the structure is a challenging task. In order to simplify the interpretation, many imaging methods were proposed. Liu and Yiu [1] proposed the scan method and the spectral B- and C-scan image methods to detect surface-opening cracks and internal cracks. Schubert et al. [2] used spectral B-scan image to measure the thickness of finite concrete specimens. Kohl and Streicher [3] utilized the data fusion technique to construct B- and C-scan images from the data of ground penetrating radar and ultrasonic test. Yeh and Liu [4], and Liu and Yeh [5] applied the surface-rendering and volume-rendering techniques, respectively, to generate the 3D images of internal cracks.

In the aforementioned spectral B-scan method, a series of impact echo tests are carried out along a test line on the surface of the structure. Then, the Fourier spectra of the test signals are assembled to construct an image of the vertical cross-section of the structure. In the detection of internal defects, such image certainly provides useful information about where or how large the defect is. However, the independent variable of the Fourier spectrum is frequency. 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, not depth.

In order to provide a more intuitive image, the vertical spectral tomography was proposed by Liu and Yeh [6]. The idea is to transform the frequency axis of the Fourier spectrum into the depth axis to obtain the depth spectrum. Then, assembling the depth spectra along a test line yields a "picture" of the vertical cross-section under the test line. An obvious advantage of such image is that one can locate an internal defect directly from the tomogram.

This paper extends vertical spectral tomography to tomography of arbitrary cross-sections. As such, the inspector could examine the interior of a structure from various angles to get better understanding of its condition. Both numerical and experimental tests are performed to verify the feasibility and effectiveness of the proposed imaging method.

2. The impact echo test and depth spectrum

In the impact echo test, a steel ball or a hammer is used to produce a wave source on the surface of the structure. Consequently, stress waves will be generated and propagate in the structure. A transducer is placed near the impact point to measure

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the response of the structure. Then, the received signals are recorded for data analysis.

If there is an interface beneath the test point, the longitudinal waves generated by the impact will bounce between the top surface and the interface. Such echo waves will form a peak in the spectrum of the signal. The peak frequency f and the depth of the interface d is related by the following formula [7]:

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

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

It is proposed in the literature [8–12] that the depth obtained by Eq. (1) be multiplied by a correction factor β to eliminate the discrepancy between the actual and predicted depths. The correction factor β is dependent on the geometry of the structure, and its value has been determined for a few types of structural members. When tomography is adopted to examine structures with defects, the geometry of the target structure is complex. It is almost impossible to choose an appropriate value for β. Hence, Eq. (1) is used directly without correction in this study.

The Fourier analysis is the most widely used approach to construct the spectrum of test response. Several time–frequency techniques have also been proposed in the literature to serve this end, for example, the wavelet transform and the Hilbert–Huang transform [13–17]. No matter which approach is adopted, the horizontal axis of the spectrum is the frequency axis. Hence, the spectrum is not suitable for the construction of tomograms.

The horizontal axis of the spectrum can be easily transformed into the depth axis by applying Eq. (1). This idea was firstly proposed by Pratt and Sansalone [18] to construct the normalized amplitude spectrum, in which 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 [4] for the purpose of image processing. Suppose $a(f)$ is the original spectrum of a signal. Their transformation procedure is as follows:

1. Select an appropriate depth interval Δz.
2. Apply Eq. (1) to $i\Delta z$, $i=1,2,\ldots$ to find the corresponding frequency f_i.
3. Determine the maximum amplitude $\hat{a}_i$ in each interval (f_i,f_{i-1}), $i=1,2,\ldots$, as shown in Fig. 1.
4. Plotting $\hat{a}_i$ versus $i\Delta z$ yields the depth spectrum of the signal.

Notice that $\hat{a}_i$, instead of $a(f_i)$, is used to plot the depth spectrum. This is to insure that no peak is left out in the depth spectrum since peaks are the most important information in the spectrum. One should also know that the transformation cannot start from $z=0$ because it maps to $f=\infty$.

The depth spectrum constructed as above has a constant depth interval, which is convenient for image processing. However, the data points in the Fourier spectrum are not totally retained. Therefore, some of the details in the Fourier spectrum are not reproduced in the depth spectrum. The peaks, which contain the most important information, are preserved, but they may not appear at the precise depth. The maximal depth deviation of a peak is $\Delta z/2$. Therefore, it is advisable to make the depth interval as short as possible.

The depth spectrum is useful for the imaging of impact echo data. It has another advantage if the depth D of the concrete structure is known. In the impact echo test, several vibration modes of the structure will be induced. The impact echo is one of them. Unfortunately, the peaks caused by the lower modes are often higher than the echo peak in the spectrum. This complicates the interpretation of results. The frequencies of the lower modes usually correspond to depths greater than D. Hence, if the depth spectrum is drawn only for the depth range $0 \le z \le D$, the lower-mode peaks do not appear in the tomogram. This makes the image much easier to interpret.

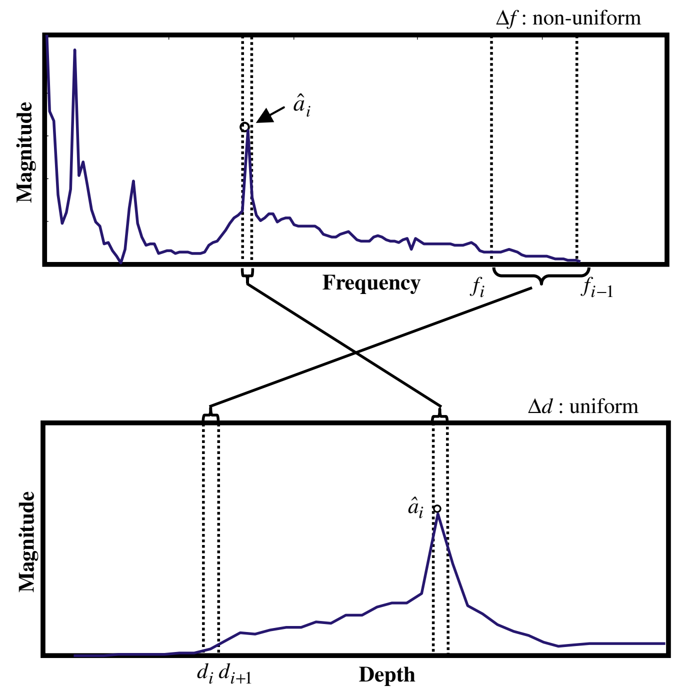

Fig. 1. Frequency–depth transform.

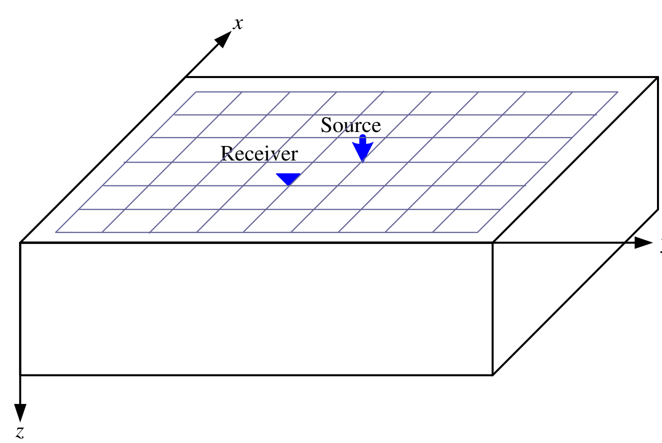

Fig. 2. Test scheme.

3. Spectral tomography

The spectral tomography consists of three basic steps, namely, data acquisition, data construction, and image processing.

To acquire data for use in tomography, one has to conduct a series of impact echo tests on the structure. Firstly, a coordinate system is chosen such that the x–y plane coincides with the surface of the target structure. Draw a mesh of $n_x \times n_y$ grids on the concrete surface, as shown in Fig. 2. It is suggested that square grids be adopted. Then, perform the impact echo test at each grid of the mesh. Apply the Fourier transform or other transforms to the test signals to obtain the response spectra. The spectra are