Imaging of internal cracks in concrete structures using the volume rendering technique

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Abstract

The impact echo method is effective in detecting concrete defects. It provides a means to determine the depth of defect beneath the test point. However, it is difficult to get an overall picture of the concrete interior by examining the results of numerous point-wise tests. This study proposes a 3D imaging method to depict the internal crack in concrete structures. To acquire the test data, a mesh is drawn on the surface of the concrete. Then, impact echo tests are performed at each grid of the mesh. The frequency-depth transform is applied to the Fourier spectrum to obtain the depth spectrum of the test signals. Finally, the volume rendering technique is adopted to construct the 3D image of the concrete interior using the Fourier depth spectra. Both numerical simulations and model tests are used to verify the proposed imaging method. It is seen that volume rendering technique can be used to detect the internal crack in the concrete specimen successfully.

Keywords: Concrete, Internal crack, 3D imaging, Volume rendering, Impact-echo

1. Introduction

The impact echo method was developed in 1980s[1] and is widely applied in the non-destructive testing of concrete structures nowadays. However, the impact echo test is a point-wise detection method. If the test area is large, a vast amount of test points are needed. It makes the interpretation of test results time-consuming and difficult. For rapid and effective diagnosis of the concrete condition, several 2D imaging methods were proposed to detect the internal crack of concrete structure [2-5]. The concepts of B-scan and C-scan in ultrasonic testing are extended to construct the images of concrete interior using spectral data[6, 7]. The spectral B-scan and C-scan can show the vertical and horizontal test sections of the target structure, respectively. However, if one wants to obtain a whole picture of the crack in the structure, one has to put several B-scan or C-scan images together and try to visualize the location and orientation of the crack. This is inconvenient and may pose difficulties for the inspectors.

The 3D imaging is a tendency in engineering applications. The methods that render 3D images are called volume visualization techniques[8-10]. The development of volume visualization was mainly due to the needs in medical practice, such as computed tomography (CT), magnetic resonance imaging (MRI), and ultrasonic imaging, etc. Recently, the applications of 3D imaging in the non-destructive tests of structures have drawn more and more attention [11, 12].

This study applies the volume rendering method to construct the 3D image of the impact echo data. The 3D image can be used to determine the location of the internal cracks in concrete structures. Both numerical and experimental tests were performed to verify the feasibility and effectiveness of the proposed method.

2 The Impact Echo Test and the Depth Spectrum

In the impact echo test, a steel ball or a hammer is used to impact the surface of a structure. Then, the impact response is measured and transformed to the frequency domain by the Fourier transform (FT). Since interfaces, cracks, or voids induce echo of the stress waves, peaks will form in the Fourier spectrum. As such, the spectrum will reveal the size of the structure or the location of the defect. The echo frequency f and the depth of the interface, d, is related by the following formula:

$$d = \frac{C_p}{2f} \tag{1}$$

where C_p is the velocity of the longitudinal wave. Therefore, by locating the peaks in the Fourier spectrum, one can determine the depth of the structure or the internal cracks.

Yeh and Liu[13] proposed that the frequency axis of the Fourier spectrum be transformed into depth axis using Eq. 1. An obvious advantage of such transformation is that one can tell the depth of the interface directly from the depth spectrum. Better yet, the depth spectrum can be used to construct the 3D image of the concrete interior.

The transformation of frequency to depth is straightforward. Suppose the frequency resolution of the Fourier spectrum is Δf . One simply applies Eq. 1 to $i\Delta f$, $i = 1,2,...$ to find the corresponding depth d_i. Then, plotting $a(i\Delta f)$ versus d_i yields the depth spectrum of the signal.

The above transformation is suitable if it is applied to transform a single spectrum. It should be modified if the depth spectrum will be used for further image processing. This is because the frequency is inversely proportional to depth. A constant interval in f will result in a varying interval in d. That is inconvenient for image processing.

An alternative way of transforming frequency to depth is to select a constant Δd . Apply Eq. 1 to $i\Delta d$, $i = 1,2,...$ to find the corresponding frequency f_i. Determine the maximum amplitude $\hat{a}_i$ in the interval (f_{i+1}, f_i), as shown in Fig. 1. Then, plot $\hat{a}_i$ versus $i\Delta d$ to obtain the depth spectrum of the signal. Notice that the maximum amplitude $\hat{a}_i$ is used to plot the depth spectrum to insure that no peak in the original spectrum is left out in the depth spectrum.

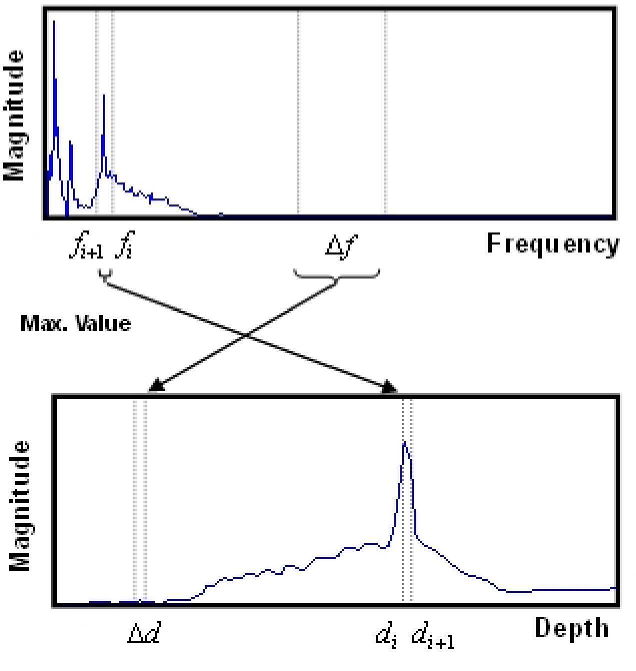


Fig. 1 Frequency-depth transform

3. Volume Rendering Method

When applying the volume rendering method to construct the 3D image of the concrete interior, one has to draw a square mesh on the concrete surface and perform the impact echo test at each grid of the mesh, as shown in Fig. 2. Then, the depth spectrum is constructed for each test signal. If one uses the coordinates of the test points and the depth as the axes, one can construct a 3D matrix (or volume data) for the amplitude of the spectra. Each element in the matrix maps to a voxel (volume element) in the space. Such volume data can be used directly for further image processing.

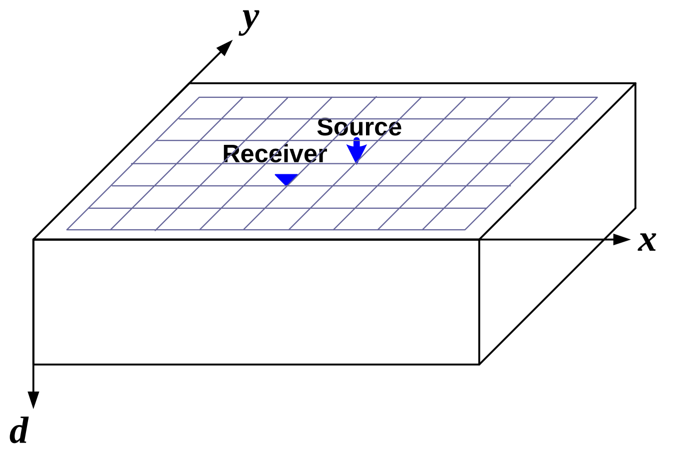


Fig. 2 Test scheme

In the volume rendering method, each voxel is assigned an opacity α based on the volume data. Suppose $V(i,j,k)$ denote the volume data, where *V* is the amplitude of the spectrum, and *i*, *j*, and *k* represent the position of the voxel along the *x*, *y*, and *d* axes, respectively. Then, the opacity of voxel (i,j,k) is computed as follows:

$$\alpha(i,j,k)=\frac{V(i,j,k)-V_{\min}}{V_{\max}-V_{\min}} \qquad (2)$$

where $V_{\max}$ and $V_{\min}$ are the maximum and minimum value of the volume data. Hence, $0\le\alpha\le1$. The opacity represents the level of difficulty that light goes through the voxel. If a voxel is complete opaque, $\alpha=1$. If a voxel is complete transparent, $\alpha=0$,

To construct the 3D image, let parallel rays emitted from a light source behind the volume transmit through the volume and reach a projection plane, as shown in Fig. 3(a). When a ray passes through the volume, it accumulates the opacity of the voxels it encounters, as shown in Fig. 3(b). The compositing operation is a recursion of opacity, as shown in the following:[9, 10]

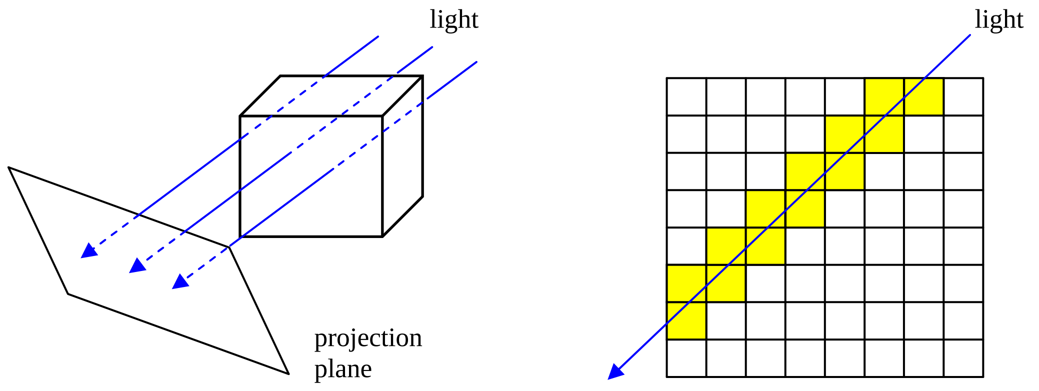
$$\alpha_{out}=(1-\alpha)\alpha_{in}+\alpha \qquad (3)$$

where α is the opacity of the current voxel, α_{in} is the accumulated opacity into the voxel, and α_{out} is the accumulated opacity leaving the voxel. If $\alpha=1$, then $\alpha_{out}=1$ and the light is totally obstructed. On the other hand, if $\alpha=0$, then $\alpha_{out}=\alpha_{in}$ and the light remains unchanged. Therefore, α is an indicator of the degree that light penetrates the voxel.

Equation 3 is applied recursively to determine the accumulated opacity of a ray until it leaves the volume and reaches projection plane. After the accumulated opacity is obtained for each ray penetrating the volume, one can draw a density plot of the accumulated opacity on the projection plane.

Recall that in impact echo test, an interface will induce a peak in the Fourier spectrum. Hence, if a crack appears in the volume, the spectral amplitude along the crack will be large, so will be the opacity. Apparently, the rays passing through the crack will be dimmer than the rays which have not. Hence, one will find a shadow on the density plot if there is a crack or other interface in the volume.

By changing the direction of the incident light, one may get different views of the volume. In this study, an interactive user interface program is developed. One can rotate the 3D image of the test specimen arbitrarily so that the interface in the concrete specimen can be easily located.



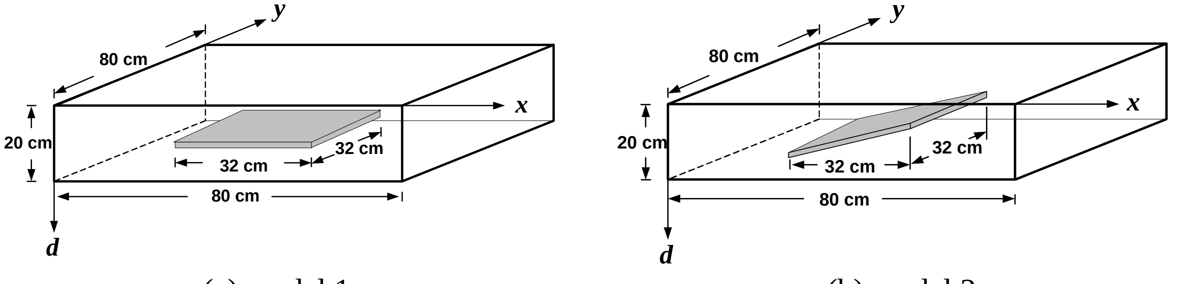
(a) (b)

Fig. 3 Volume rendering method

4. Numerical Simulation

Two concrete specimens with internal cracks are considered in the numerical examples. The dimensions of the specimens are both 80 cm (L) × 80 cm (W) × 20 cm (H), as shown in Fig. 4. A 76cm × 76cm test mesh is drawn on the top surface of each specimen, leaving 2cm of margins on the four sides. The grid lines are drawn at a constant interval of 4 cm in both directions. Hence, there are totally 19 × 19 grids. In each test, the impact source and the receiver are located at the upper right and lower left corners of a grid.

The finite element code LS-Dyna970[14] was adopted to simulate the response of concrete specimens due to the impact of a steel ball. 3D solid elements with side length 1 cm were used in the numerical simulation. The mass density, Young's modulus, Poisson's ratio, and the longitudinal wave speed of the concrete are 2300 kg/m^3, 33.1 GPa, 0.2, and 4000 m/s, respectively. A time-varying pressure was applied to the surface to simulate the impact of a steel ball with diameter d = 6 mm. According to Goldsmith[15], the pressure can be approximated by a half sine function with a contact time t_c= 25 μ sec. The sampling rate was 344 KHz and the total time of simulation was 3 msec.



(a) model 1 (b) model 2

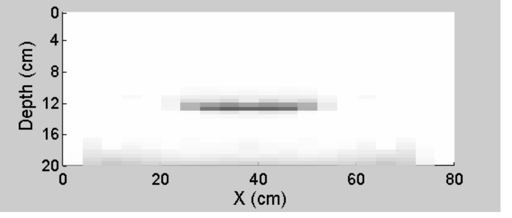
Fig. 4 Numerical and experimental models

Numerical model 1 contains a 32 cm (L) ×32 cm (W) × 1 cm (H) horizontal crack, which is 12 cm beneath the surface. The coordinate of the center of the crack is (x, y, d) = (40, 40, 12) (in cm), as shown in Fig. 4(a).

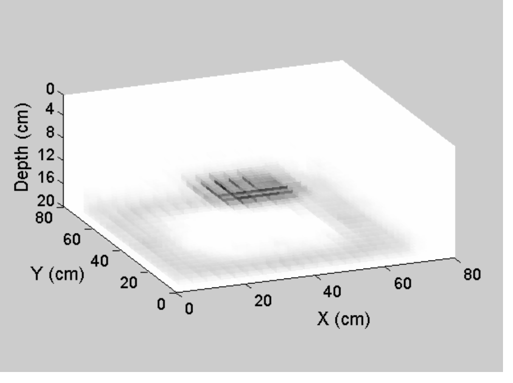
Figure 5 show the side, oblique, and top views of the volume rendering image. All these images are constructed using the Fourier depth spectra. One can find a dark area near the center of each image. These dark areas depict the correct size, location and orientation of the crack.

One can also find the bottom of the specimen in the images. However, a hole is formed on the bottom beneath the crack. This is because the bottom echo is blocked by the crack.

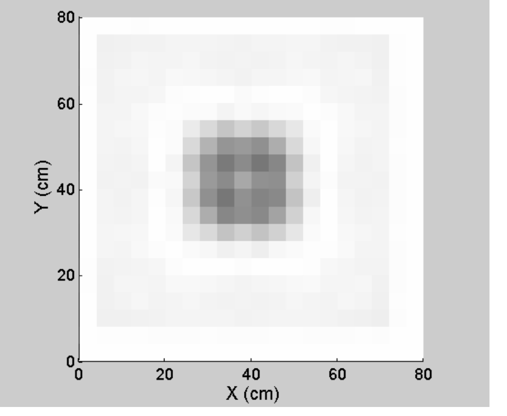
Therefore, the hole in the bottom provides a supplementary evidence for the existence of a defect above this region.



(a)



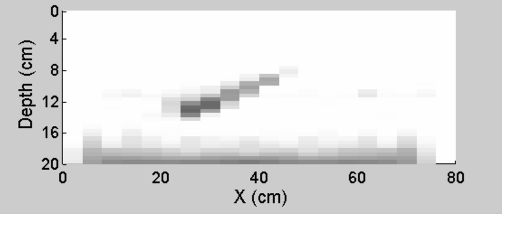
(b)



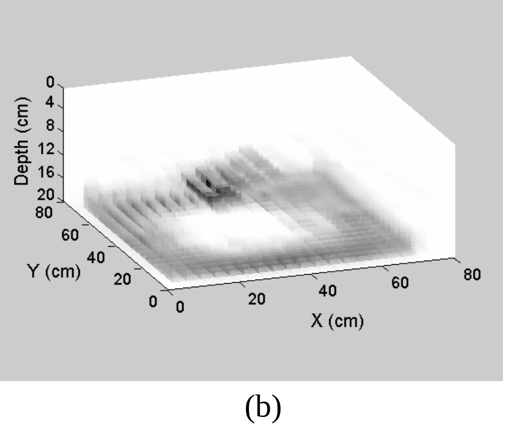
(c)

Fig. 5 3D images of numerical model 1, (a) oblique view, (b) side view, and (c) top view

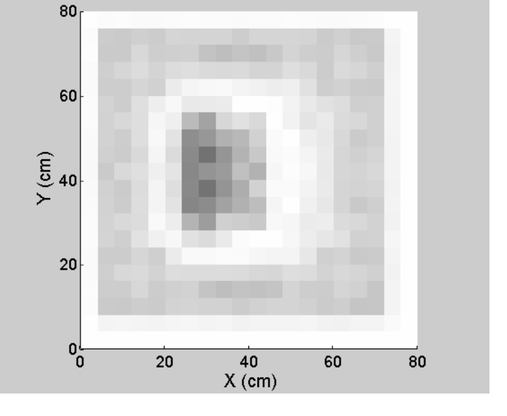
From the side view, one can tell that the crack is 12cm deep beneath the surface. It is also seen that the dark area is about 1cm thick. However, the thickness of the dark area does not represent the thickness of the crack. In fact, the impact echo test cannot provide information about the thickness of the crack. The thickness of the dark area results from the width of the echo peak in the spectra. Hence, the true depth of the crack should be determined based on the location of the darkest pixels in the image.



(a)



(b)



(c)

Fig. 6 3D images of numerical model 2, (a) oblique view, (b) side view, and (c) top view

Numerical model 2 contains an inclined crack with depth ranging from 7cm to 12cm beneath the surface. The coordinates of the four corners of the crack are (*x*, *y*, *d*) = (24, 24, 12), (24, 56, 12), (56, 24, 7), and (56, 56, 7) (in cm), as shown in Fig. 4(b).

Figure 6 shows the side, oblique, and top views of the volume rendering image of model 2. The dark area denoting the crack is observed in all three images. Similar to model 1, a hole is formed on the bottom beneath the crack, as seen in Fig. 6(b). The side view clearly shows the inclination of the crack.

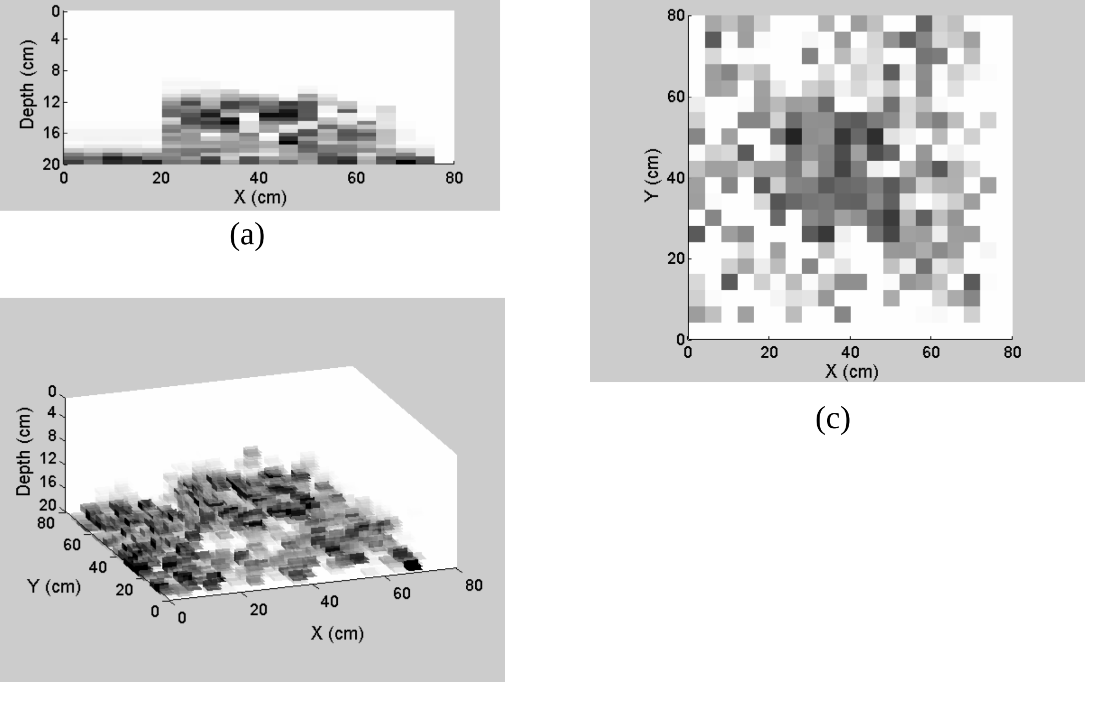
Compared with the true location, the crack image is seen to shift horizontally towards the deep edge. The phenomenon indicates that the amplitude of the echo peaks near the shallow edge is smaller than the amplitude near the deep edge. This is because the same impact source was used throughout the simulation, and the echo energy from different part of the crack varies. Fortunately, the hole on the bottom surface can help the inspector to estimate the size of crack.

5. Model Tests

Two model tests were carried out in this study to verify the feasibility of the volume rendering method in processing the impact echo data. The dimensions of the concrete specimens and the crack locations are identical to those of the numerical models. The longitudinal wave velocities of models 1 and 2 are 3890 m/s and 3900 m/s, respectively. The tests meshes are also the same as described in the numerical examples.

Unlike the numerical tests, the energy of the impact source may vary from test to test. Therefore, the experimental data need to be normalized. In this study, the test signals are normalized based on the amplitude of the surface wave.

There is another discrepancy between simulation and model test. The experimental data contain a lot of noise. When the Fourier depth spectra were used to construct the 3D image, poor images were rendered. In order to improve the image quality, the enhanced Fourier depth spectra were adopted in the image processing[16].



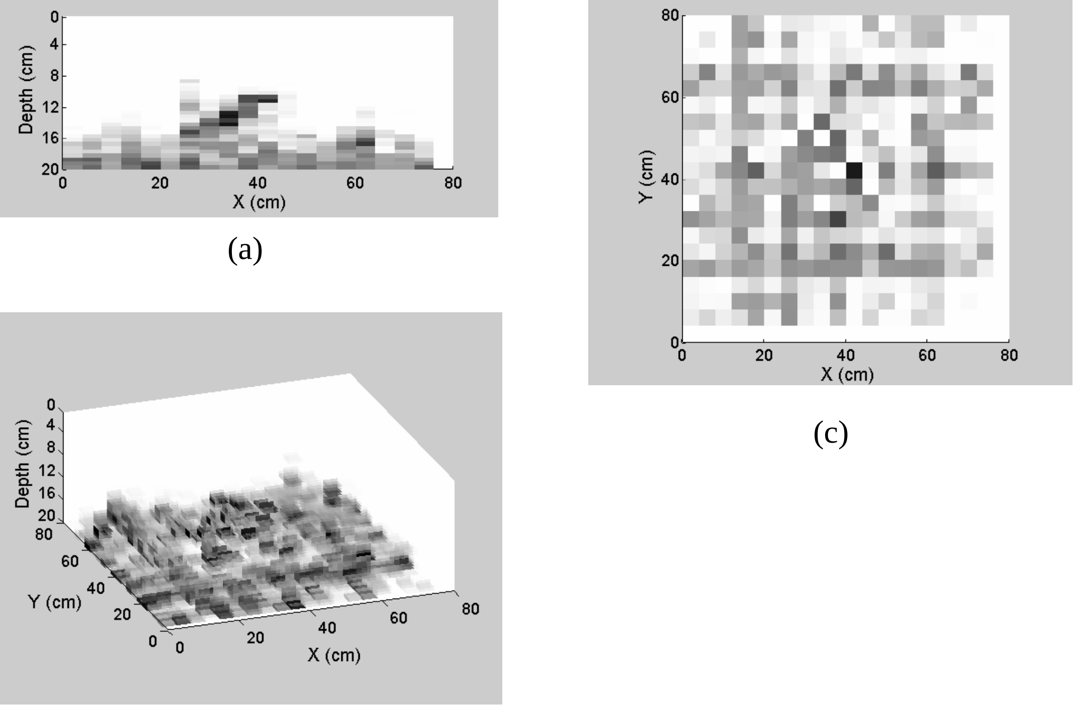
(b)

Fig. 7 3D images of model test 1, (a) oblique view, (b) side view, and (c) top view

The oblique, side, and top views of model 1 are shown in Fig. 7. Because the experimental signals are contaminated by noise and the impact source is unsteady, the 3D images are not as clear as in the numerical examples. Normalization of the signals may only minimize the influence of the intensity of the source function, but not its shape. Hence, the crack appears as a cluster of dark patches in the central area of the image.

Nevertheless, one can still locate the crack by viewing the specimen from different angles. For example, in side view a horizontal crack can be detected around 12 cm deep; one can also be found the bottom near the depth of 20cm. The oblique view in shows a hole at the bottom right beneath the crack. The approximate dimensions of the crack can be obtained from the top view in Fig. 7(c).

Model 2 contains an inclined crack as shown in Fig. 4(b). The oblique, side, and top views of this model are shown in Fig. 8. Similar to the first model test, the images contain a lot of noise. Nevertheless, one can find a cluster of dark patches revealing the location, orientation, and size of the crack.



(a) (b) (c)

Fig. 8 3D images of model test 1, (a) oblique view, (b) side view, and (c) top view

6. Conclusion

This paper applies the volume rendering technique to process the impact echo data so that the 3D image of the internal defects in concrete can be constructed. The frequency axis of the Fourier spectrum is transformed into depth axis so that the depth spectra can be used in the image processing.

From the numerical examples and model tests, it is shown that the volume rendering method can generate images of the concrete interior. A crack appears as a dark zone or a cluster of dark patches in the image, which can be used to estimate the size, location, and orientation of the crack. Because the crack blocks the wave from reaching the bottom directly, in the image a hole is formed at the bottom beneath the crack. That provides supplementary information about the size and location of the crack.

Since the experimental data is noisy and the impact source is unsteady, one does not get a clear image of the crack as in the numerical examples. In that situation, one may use the enhanced Fourier spectra to construct the image to improve its quality.

The interactive imaging program developed in this study provides a useful tool to view the specimen. The inspector may rotate the 3D image arbitrarily to obtain a better view of the crack. This is important especially when the image quality is poor.

Although the 3D imaging method may provide the most direct information about the defects in concrete structures, its practical applications are hindered by two issues. Firstly, the test is very time-consuming because a vast amount of tests are required. Secondly, the unsteadiness of the impact source deteriorates the quality of the image. To deal with these problems, an automatic test system seems to be a good solution. It is hope that the automatic test system can be developed in the near future so that the 3D imaging technique can be widely applied in the inspection of concrete structures.

Acknowledgments

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