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Effective visualization of local vibration data collected over large infrastructure elements

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ABSTRACT

In this paper, a 4-D presentation format for nondestructive test (NDT) spectral data is suggested. Time domain signals from air-coupled impact-echo (IE) tests are transformed into the frequency domain and arranged along x and y coordinates of the tested surface to give a 3-D data set volume with the 4th dimension, spectral amplitude indicated by gray scale. This presentation, which stacks data in both spatial and spectral domains, includes all spectral data up to the 6 kHz to isolate the response generated by near-surface delamination defects. Visual interpretation of the dense data set of spectral information within the volume is enabled by incorporating transparency/opacity control on the data set, where higher spectral amplitudes are associated with more opacity. Application of this data manipulation and visualization technique to IE data demonstrates improved near-surface delamination detection as compared with conventional data presentation formats.

1. INTRODUCTION

In the standard IE method, a broad-frequency mechanical wave source (point impact event) is applied to a structure, and the resulting dynamic response nearby is monitored using a surface motion sensor, such as an accelerometer. Spectral signals are computed from the time signals, usually by the FFT algorithm, where peaks in the spectra are associated with resonance behavior. Shifts or wholesale changes in the frequency values of these resonances may indicate the presence of internal underlying defects. Typical IE time and spectral signals over solid and near-surface delamination regions, respectively, in a concrete slab are shown in Fig. 1. The slab geometry serves as accurate representation of a bridge deck structure. The spectral response is

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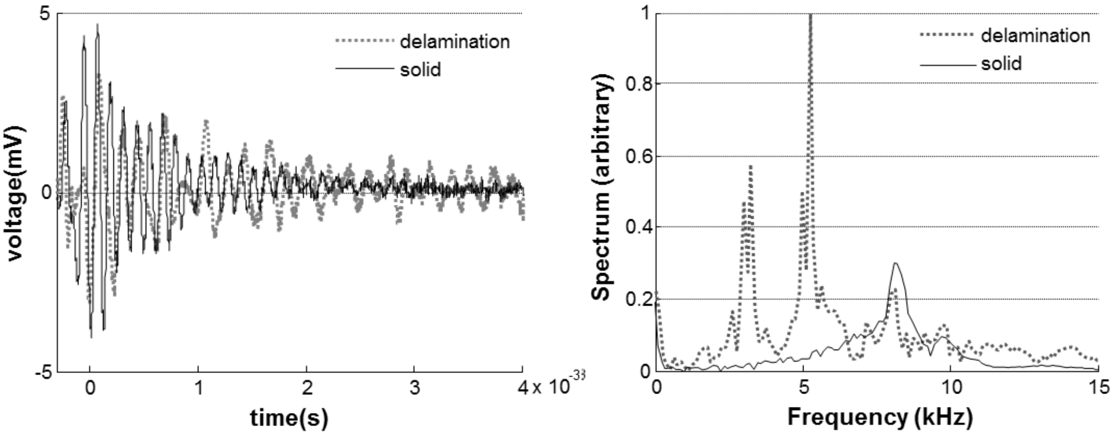
normally interpreted assuming the excitation of some combination of vibration modes, which can vary in fundamental type. Each vibration mode is associated with a distinct mode shape and resonance frequency. In the solid (no defect) region of the slab, the vibration response is dominated by the thickness stretch-type of modes, where usually only the fundamental (lowest frequency) mode can be measured (Gibson and Popovics 2005). This vibration mode is most commonly associated with the impact-echo method in plates, and its frequency can be used to estimate the thickness of slabs and shifts in its frequency can be used to infer the presence of deep underlying defects (Sansalone and Streett 1997). The resonance peak associated with the fundamental thickness stretch mode is seen at approximately 8 kHz in Fig.1b. However the flexural type of vibration modes fully dominate over the regions with near-surface (within 4 -10 cm from the top surface) delamination (Oh et al. 2013a). The modes in these families have fundamentally different modal shape and usually occur at lower frequency than the thickness stretch mode. The analysis approach and equations developed for interpretation of the fundamental stretch mode cannot be applied to the flexural modes, so for example one cannot directly determine depth to a reflector from the frequency of a flexural mode. The two dominant peaks at 3 and 5 kHz are associated with the first two modes (fundamental and first overtone) of the flexural type in Figure 1b. A theoretical analysis that simulates delamination vibration in terms of a plate with semi-clamped boundary conditions and typical mechanical properties of concrete shows that the resonance frequencies of all meaningful near-surface delaminations (greater than 160x160 mm areal size) will fall below approximately 6 kHz, regardless of bridge deck design and material properties (Oh et al. 2013b). On the other hand, the fundamental thickness stretch mode is not expected to fall below 6 kHz for bridge decks with nominal thickness between 20-30cm, which is a typical deck design. Thus the frequency range of 5-6 kHz serves as a natural frequency threshold value to separate thickness stretch mode and flexural mode responses for near-surface delaminations in concrete bridge decks.

The standard IE method requires sound physical contact between the sensor and tested concrete surface; poor physical contact gives rise to unreliable and inconsistent signals. However, this requirement for physical contact limits practical application to large transportation structures. One solution for the problem is to eliminate the need for the physical contact between the sensor and tested structure by employing a contactless sensing approach (Green, 2004). An obvious advantage is that it greatly speeds up the data collection process, where the data can be processed rapidly and automated scanning is enabled. Contactless IE is an emerging test method that provides a promising approach to visualize the location, size and shape of embedded damage or flaws for evaluation of concrete structures.



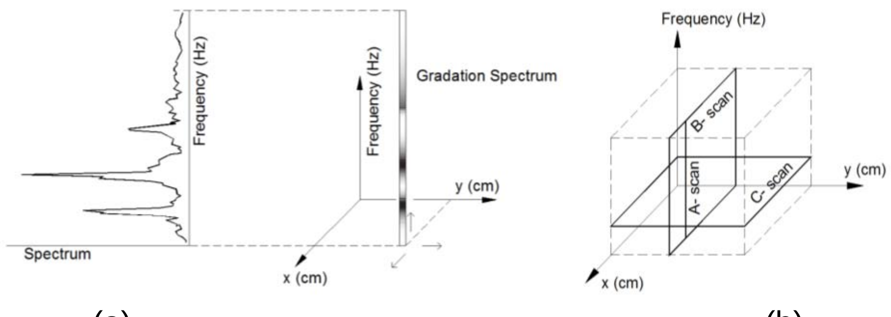
(a) (b)

Fig. 1 Impact-echo signal data collected over solid and delamination regions; (a) time-domain and (b) frequency-domain

2. 4-D SPECTRUM TECHNIQUE

A full volume imaging technique can provide more effective information about the presence and character of internal defects, as compared to methods that provide only a single “slice” of image such as B-scan and C-scan images. Such a “4-D” image (three spatial dimension plus frequency) spectrum uses a data volume comprised of a series of spectral A-scan data collected and across a test area up to some defined limit frequency. In other words, the 4-D data array represents a set frequency signals coordinated by areal position (x and y axis) of the test point and frequency aligned vertically along the z axis. The spectral amplitude is shown by grey/color scale. The concept is illustrated in Fig. 2. The 4-D data volume contains A-, B- and C- scan information, obtained by presenting data along a given plane slice through the data volume.

The construction of the 4-D data volume in this study was carried out using the “MATLAB” platform. The volume is an $m \times n \times p$ volume array containing data at the default location, where *m,n* and *p* are the number of data in *x, y* and *z* directions, respectively. The space between two data points is interpolated by quadratic regression routines provided in the MATLAB.



(a) (b)

Fig. 2 Illustration of basic principles of 4-D spectrum technique: (a) color/grey scale and position mapping within image volume and (b) layout of image planes within image volume.

Even though the 4-D spectrum includes all IR data over defect and solid regions, the internal vibration character is hidden because of the opaque nature of the outer data set. In other words, the display region of the 4-D plots is limited to the outer surface of the data volume and we cannot see inside that outer boundary, even though useful information is contained within. However, spectral features in the interior of the data volume can be selectively revealed by associating image transparency to spectral amplitude. The transparency function controls the relation between spectral amplitude and image transparency. Therefore, dominant frequency components become opaque and thus can be seen through transparent volumes of low spectral amplitude data.

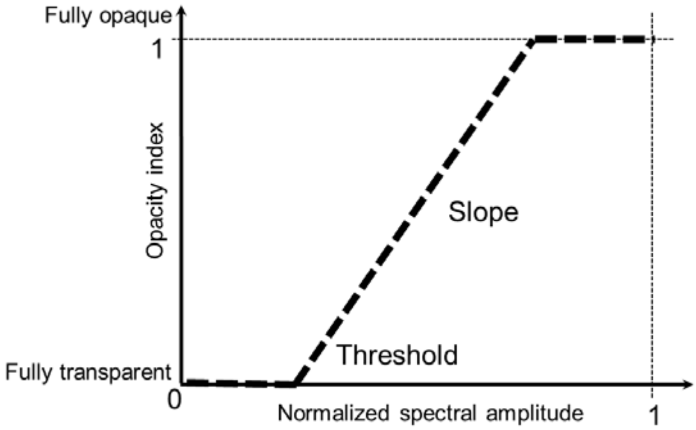


Fig 3. The definitions of the image transparency control parameters.

As illustrated in Fig. 3, the relation between spectral amplitude and transparency are controlled using several image control parameters. Within some frequency range, usually between zero Hz (DC) and some upper cut-off frequency value, unwanted portions of the data volume are hidden (made transparent) by setting the image threshold point, such that data with amplitudes below this threshold point are completely transparent. This control is an effective and efficient way to control the appearance of the data volume. The cut-off frequency value also needs to be controlled to screen out uninterested frequencies, such that the dynamic behavior of the delamination only is monitored. This is achieved by setting the cut-off frequency value at a frequency above which flexural resonances from delamination are not expected. High amplitude signals are represented by opaque colors, and low amplitude signals are transparent. Thus, the control in transparency makes it possible to clarify the dominant frequencies and thus to distinguish the delamination region from solid region without removing any data from the volume.
In the 4-D image, data with high spectral amplitude appear as clouds floating in a sky of data volume. Full control of image transparency is critical for creation of an effective image.

3. EXPERIMENTAL DETAIL

3.1 Test method and hardware

Air-coupled impact-echo tests were carried out. A steel ball with 18mm diameter attached to a thin wire handle is used as an impact source. The operator applies the impact by hand, lightly striking the surface of the concrete. The forcing function associated with an impact event of this ball exhibits consistent and broad spectral content, ranging from DC to 15 kHz. The generated vibrations that are set up by the ball impact event are detected by an air pressure sensor (dynamic microphone) that is located nearby the impact event location, 2 to 3 cm above the surface of the concrete. The microphone has 1.85 mV/Pa of sensitivity at 1 kHz, and 50 Hz to 15 kHz of working frequency range. The microphone is connected to a data acquisition system where the analog signals are converted to digital data using a 16-bit resolution at a sampling frequency of 1 MHz. (Fig. 4)

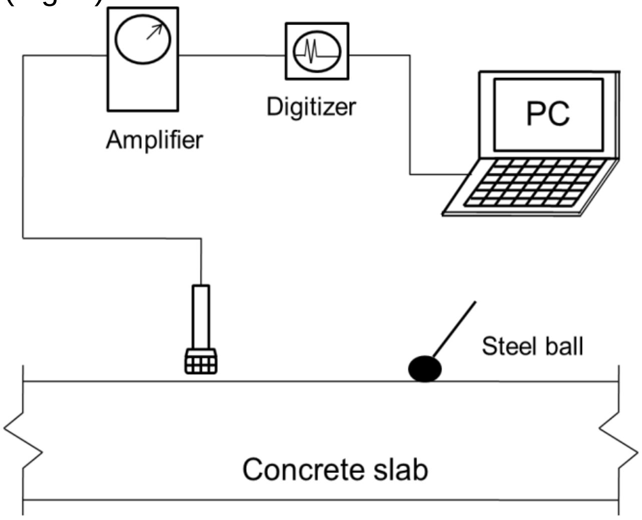


Fig. 4 Experimental test setup for air-coupled impact-resonance test. The air-coupled sensor is positioned as closely on the slab surface.

For each test, a time signal is obtained with a duration of 8 ms. Because the input forcing function at each test point across the concrete surface is inherently inconsistent, the amplitude of each time signal was normalized with respect to the negative peak of the Rayleigh wave pulse arrival within that signal. This normalization provides more consistent air-coupled impact-echo data when both impact source and air-coupled sensor are moved together as a closely spaced set across a testing grid (Oh et al. 2013a). The normalized time domain data are stored on a connected data acquisition computer for subsequent processing. The time data are later converted to the frequency-domain (amplitude spectrum) by Fast Fourier Transformation (FFT) in preparation for spectral image processing.

2.2 Test samples

A reinforced concrete slab sample were used in the experiments. The sample contained well controlled embedded artificial defects with varying shape, areal size and depth that simulate actual delaminations. The slab sample was cast and housed at the University of Illinois. The size of the slab is 1.5 m by 2.0 m with 0.25 m thickness and it contains two layers of steel bars at 60mm and 180mm depths, respectively. The concrete has a 28-day compressive strength of 42.3 MPa. Ultrasonic pulse velocity measurements show that the P-wave velocity of the mature concrete is 4,100~4,200 (m/s). Thus we expect an impact echo (fundamental thickness stretch mode) frequency of around 8.0 kHz for the full thickness of a defect-free slab. This slab contains a variety of embedded artificial delaminations and voids: double-layered plastic sheets and soft foam blocks simulate artificial delaminations. Fig. 5 shows the location and characteristics of the simulated defects in the slab.

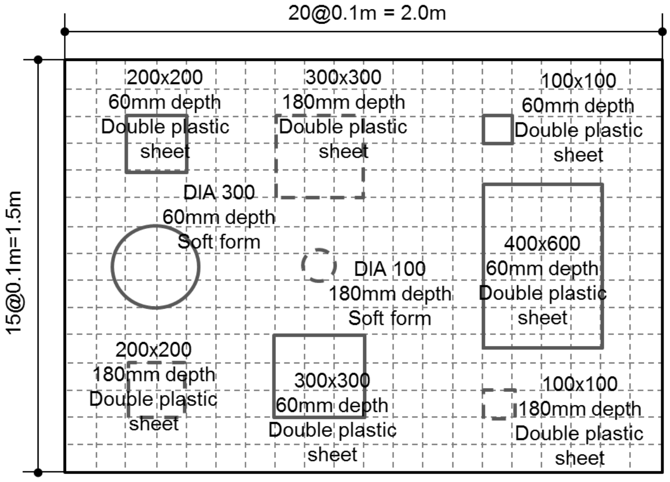


Fig. 5 The 2.0m × 1.5m reinforced concrete slab; The position of near-surface delamination defects are indicated with bold solid lines, those of deep delamination by bold dashed lines. The testing grid is indicated with light dashed lines

4. COMPARATIVE EVALUATION OF IMAGES

The 4-D plotting scheme is now applied to several IE data sets, using the image parameter optimization procedure described above. IE data were collected from the laboratory sample shown in Fig. 5, where the test point grid position is indicated with light dashed lines. The optimized 4-D image plot of the data set from the global 10cm × 10cm scans across the entire face of the test sample are shown in Fig. 6; darker colors indicate higher spectral amplitude. The position of near-surface defects are indicated with heavy solid lines and deep defects with heavy dashed lines. The full spectral data volume is viewed from the top (x-y) perspective, meaning that all spectral response data across the frequency range (between zero Hz and the cutoff frequency value) are compressed into a single stacked frequency plane. The indications in these 4-D plots detect the presence and well represent actual extent of near-surface delaminated regions, resulting in an image that is easy to interpret. The 4-D plot results shown in Fig. 6 are similar to previous work on the same sample using peak frequency images (Zhu and Popovics 2007), in that the extent of near-surface delamination is fairly well predicted in the images. The 4-D plot for the slab sample shows little extraneous noise and false indication outside of the expected delamination area, but the plot for the full-scale bridge samples does show several indications that lie outside of the expected delamination locations; we were not able to confirm the deamination condition at those locations.

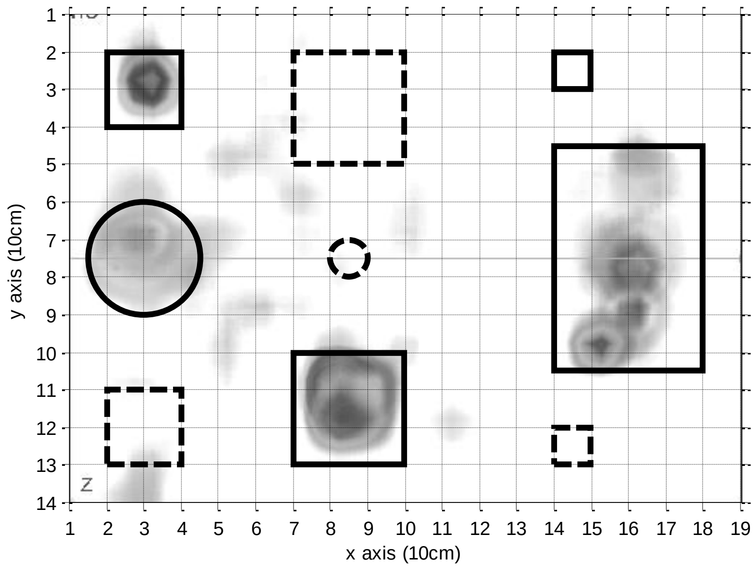


Fig. 6 Top (x-y) perspective of 4-D IE data plot. Data up to 6 kHz collected over entire face of 2.0m×1.5m slab specimen along 10cm square grid

5. CONCLUSIONS

We introduced the 4-D plot concept, which constructs transparency-controlled stacked frequency (amplitude) spectra across the surface of a concrete structure, for presentation of spectral NDT (impact-echo) point test data. The application and interpretation of the 4-D plot is made effective by associating image transparency with spectral amplitude, including all spectral amplitudes over a natural frequency range (up to 6 kHz) expected for near-surface delamination defects.

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