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IMPROVING SIGNAL PROCESSING OF THE IMPACT-ECHO METHOD USING CONTINUOUS WAVELET TRANSFORM

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Abstract: Signal processing techniques can improve the feature identification of impact-echo signals obtained from buried objects in concrete. Steel reinforcement, steel tubes, and PVC tubes embedded in concrete slabs are tested. The received signals, both experimental and simulated, are analyzed using both fast Fourier transform (fft) and continuous wavelet transform. The amplitude spectra, based on fft, can only provide global information and lose - important local effects of frequency components. This is resolved by preserving the transient effects in the frequency domain using continuous wavelet transform. Features related to embedded steel bar and PVC and steel tubes can thus be recognized according to the difference in scales and lasting periods in the magnitude plot of wavelet coefficients. Furthermore, the same peak frequency found in the amplitude spectrum is now distinguishable between PVC and steel tubes at a resolution of 0.2kHz or better. Such findings provide a more effective way to pick up true rebar signals using the impact-echo method.

Introduction: Conventional Fourier analysis provides only mean coefficients representing spectral composition of a signal. These coefficients are independent of time and may not be suitable for analyzing all signals. Two signals with the same spectral density could exhibit completely different transient characteristics, as illustrated by Newland [1]. Furthermore, the information revealed by Fourier analysis is sometimes confounded with a number of frequency components due to noise of various sources. This is particularly important when dealing with elastic wave propagation in concrete. For example, buried objects such as steel reinforcement and pipelines may be indistinguishable and could result in false interpretation of the impulse response. Wavelet transform, on the other hand, can better differentiate transient effect of frequency components within signals. It is one type of the time-frequency analyses in which both frequency content and time information are preserved. Wavelet coefficients C can be obtained by convolving some proper wavelet function ψ with the signal $f(t)$ as

$$C(scale,\ \ position) = \int_{-\infty}^{\infty} f(t)\ \ \psi(scale, position,\ t)\ dt \quad (1)$$

The magnitude of C indicates how closely correlated the wavelet function is with one section of the signal. The variable *scale* is related to frequency content while *position* is related to the time information of the signal. Further details of wavelet transform can be found in many papers and textbooks such as the one authored by Mallat [2].

Experimental Procedures: An 80X80X15 concrete slab is constructed using a cement/water ratio of 0.65. The material composition is listed in Table 1. One steel bar (rebar), one PVC tube, and one steel tube are embedded in parallel in the concrete slab, as shown in Figure 1. The diameter of the steel rebar is 33mm and that of both tubes is 38mm. The cover thickness is 54mm and 52mm, from the concrete surface to the top of the rebar and tubes, respectively. To obtain the impulse response directly above the embedded object, the measurements are taken at the grid points, also shown in Figure 1. The elastic wave is excited and detected using an impact-echo system [3] and the resulted signals are digitized in a sampling period of 2.67 μs. Spectral analysis is then applied to the recorded signals as part of a standard impact-echo inspection.

Table 1 Material composition

Water/cement	Water	Cement	Fine aggregate	Coarse aggregate
0.65	222.9 Kg/m^3	342.0 Kg/m^3	785.8 Kg/m^3	923.5 Kg/m^3

Signal Processing Using Continuous Wavelet Transform: The mathematical consideration of various wavelet functions has been studied extensively [1, 2, 4]. There are a great number of wavelet functions to choose from in the literature. A universal criterion does not seem to exist for selecting an optimal wavelet function for a given application. In the following, we will restrict our analysis to the complex Morlet wavelet due to several aspects of its characteristics. The advantage of using a complex wavelet function over its real counterpart is that the phase information can also be obtained in addition to the absolute value of the wavelet coefficients, as specified by equation (1). This is an important feature for analyzing discontinuities of the signal and will be illustrated later on.
The complex Morlet wavelet is specified in the frequency domain by its center frequency f_c and variance (bandwidth) f_b and is given by [4]

$$\psi_m(t) = \frac{1}{\sqrt{\pi f_b}} \exp(j2\pi f_c t - \frac{t^2}{f_b}) \quad (2)$$

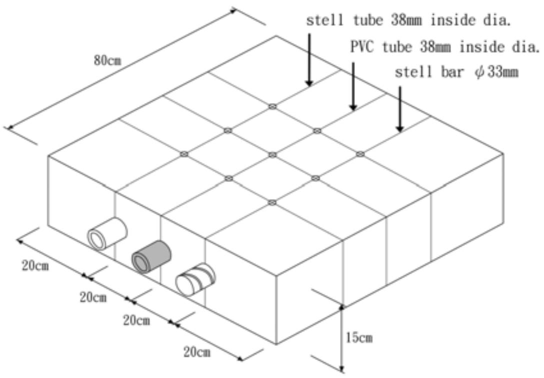

Figure 1 Measurement points on the concrete slab

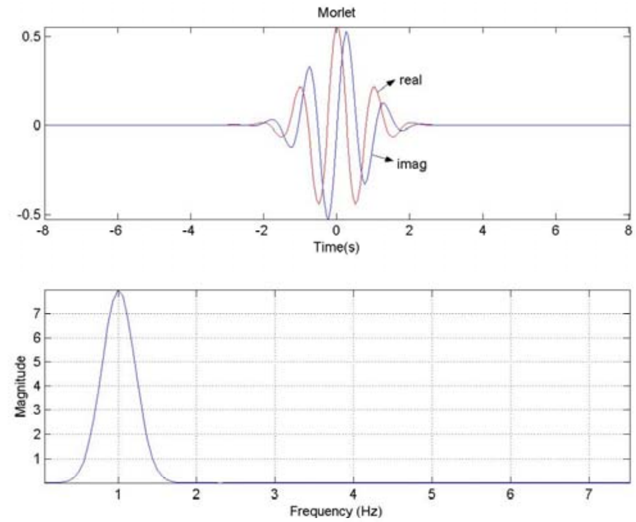

Figure 2
Complex Morlet wavelet function in the time domain (top) and the frequency domain (bottom).

The complex Morlet wavelet function and its Fourier transform with $f_c = f_b = 1$ are displayed in Figure 2. Both the real and imaginary part of $\psi_m(t)$ are symmetric, as shown in Figure 2. The same number of oscillation is preserved regardless of dilation (scale) or translation (position) after the wavelet transform, equation (1), is applied. A commercially available software MATLAB® is used to performed most of the computations associated with the signal processing. The absolute value and phase angle of the resulted wavelet coefficients for a typical signal are plotted in Figure 3. The vertical axis is the scale while the horizontal axis corresponds to the time-related position. Note that the pseudo-frequency is related to the level of scale and is given as

$$f_s = \frac{f_c}{s \bullet \Delta t} \quad (3)$$

where f_s is the pseudo-frequency with respect to scale s and Δt is the sampling period of a digitized signal.

Results:
CWT with a center frequency of 1.5 is first applied to the output signal taken above the rebar (at position a2 in Figure 1). The resulted coefficients are shown in Figure 4. The main feature is located between scales 10 and 26 (21.6 kHz and 56.2 kHz), as indicated by the red area near the bottom left of the magnitude plot. The first arrival of the analyzed signal can be identified at the bottom of the magnified phase plot. The frequency resolution of the magnitude plot can be improved by increasing the center frequency of CWT. The result of CWT, $f_c = 4$, is

obtained for the same output signal, as shown in Figure 5. The main feature is again identified near the bottom left, between scales 50 and 68, or 22.0kHz and 30.0kHz. Comparison can be made with the peak frequency at 25 kHz and its vicinity in the amplitude spectrum of the signal, also shown in Figure 5. The result of CWT provides more information and is easier to interpret than that of the spectral analysis.

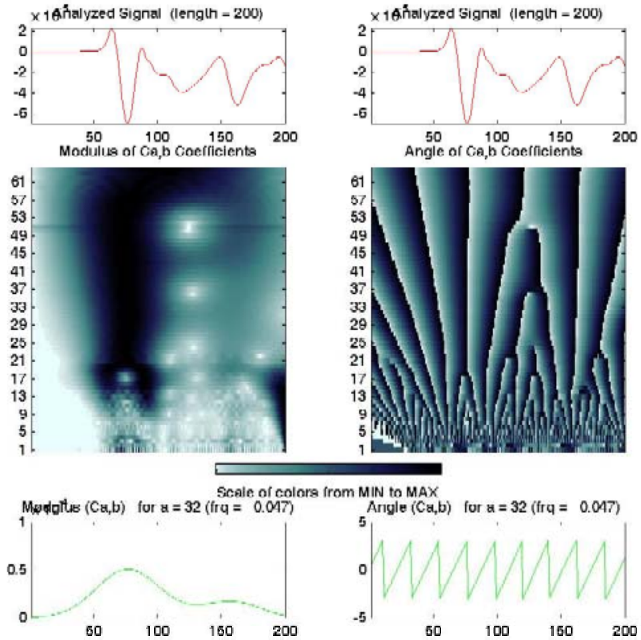

Figure 3 CWT results for a typical signal. Magnitude plot is shown on the left and phase plot is shown on the right. The time axis is arbitrary.

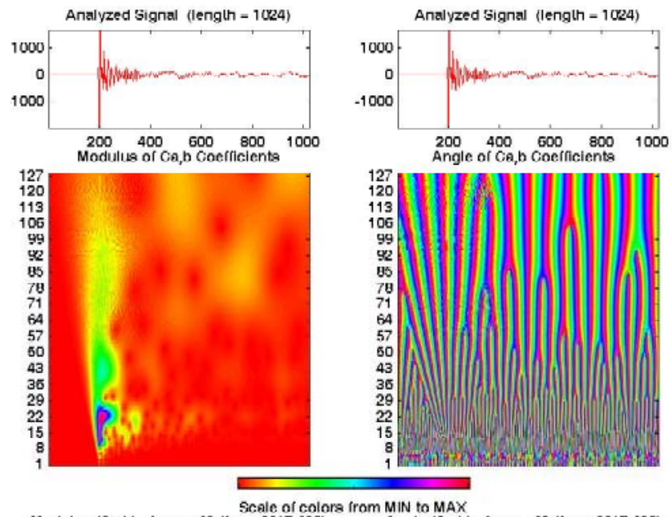

Figure 4 CWT results using a center frequency of 1.5 for signal taken above the rebar: the magnitude plot (left) and the phase plot (right)

Features at frequencies lower than 12 kHz can be identified in the magnitude plots of signals, taken at position a4 (PVC tube) and a6 (steel tube), as shown in Figure 6. Differentiation between buried PVC tube and steel tube is subtle but possible, since the main feature in Figure 6(left) is located at higher scales. There are, however, less obvious features at frequency higher than 32 kHz. These are due to reflections from the concrete-tube interface and can be found at scales less than 37 for PVC tube and 46 for steel tube, respectively.

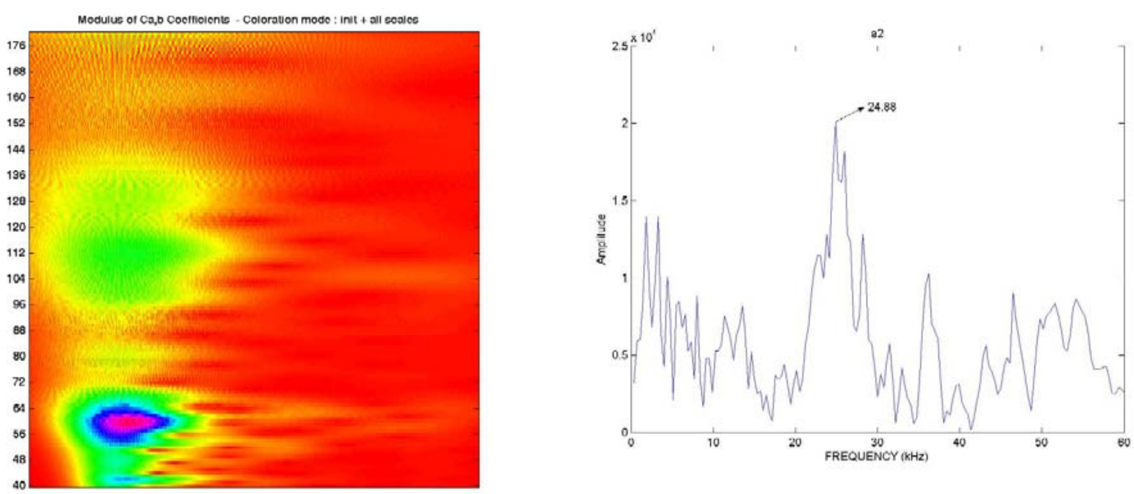

Figure 5 The same signal as in Figure 4: magnitude plot of CWT using a center frequency of 4 (left) and corresponding amplitude spectrum (right). (color code is the same as in Figure 4)

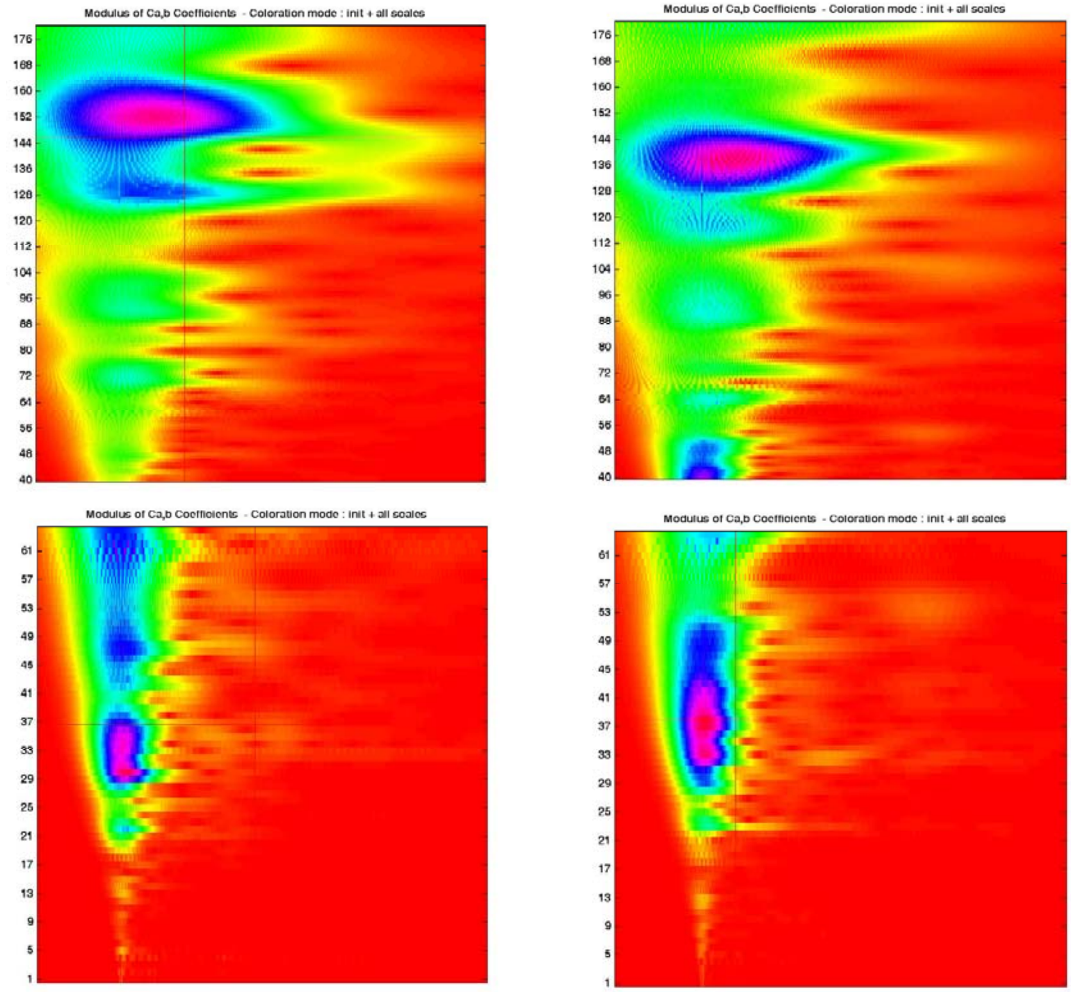

Figure 6 Magnitude plots (same color code in Figure 4) for signals taken above PVC tube (left) and steel tube (right)

Discussion:

The results based on CWT and spectral analyses of the measured output signals are summarized in Table 2. Also shown are the peak frequencies in the amplitude spectra of simulated signals, obtained by finite element analysis. The main feature of CWT magnitude plots is obvious, as indicated by the red areas in Figures 5 and 6. The corresponding pseudo frequency is selected based on the maximum wavelet coefficient of the magnitude plot. The numbers appear in the parentheses are the upper and lower boundaries of scale occupied by the main and secondary features, respectively. The secondary feature of magnitude plots usually occupies a area where the scales range appears to be greater than the main feature but only for a brief moment. In the cases of PVC and steel tubes, peak frequencies at 10kHz are virtually indistinguishable in the amplitude spectrum, as shown in Figure 7. Although secondary peaks do existed at higher frequencies, they are also confounded with multiple reflections, scattering effects, and other complications in the concrete slab.

One may notice the non-linearity of range, corresponding to the maximum difference in either scale or pseudo frequency, shown in Table 2. There are various aspects regarding this issue. The pseudo frequency is inversely proportional to the scale, as described by Equation (3). This is further complicated by the selection of the maximum scale of CWT. The higher the maximum scale, the better resolution in frequency is achieved. This is, of course, at the cost of increasing effort in computation. At any given sampling period, a digitized signal should and can be analyzed with an optimal set of combination, including the maximum scale, the center frequency of the wavelet of choice, and the primary frequency (or frequency band). In this work, the author has established that the maximum scale is 180 and the center frequency is 4 such that the resolution is 0.2 kHz (scale higher than 130) for tubes and 0.6 kHz (scale higher than 50) for rebars. The main feature in the magnitude plots is readily identified, as shown in Table 2.

Table 2 Summary of CWT results for signal features in magnitude plots

Buried object	Position of measurement	CWT: Main feature kHz (scales)	CWT: Secondary feature	Spectral analysis: peak frequency, kHz
Rebar	a2	25.0* (50:68)	12:16 (96:120)	24.9
	b2	25.8* (56:64)	13:14 (104:118)	25.3
	c2	22.0* (56:63)	13:17 (88:118)	22.7
	Range	8.0 (18)	5 (22)	2.6
PVC tube	a4	10.3* (146:164)	42:48 (31:36)	10.1, 42.8
	b4	10.6* (141:158)	42:47 (32:36)	10.0, 43.9
	c4	9.9* (151:164)	36:50 (30:41)	10.0, 42.8
	Range	1.2 (18)	14 (11)	N/a
Steel tube	a6	11.0* (130:144)	36:47 (32:42)	10.2, 40.6
	b6	10.7* (140:145)	34:38 (39:44)	10.2, 36.6
	c6	10.7* (134:146)	39:44 (34:38)	10.2, 41.7
	Range	1.2 (16)	10 (12)	N/a

* Pseudo-frequency based on the scale of the maximum wavelet coefficient
&Results based on simulation of frequency response of a cylindrical hole, 42mm in diameter

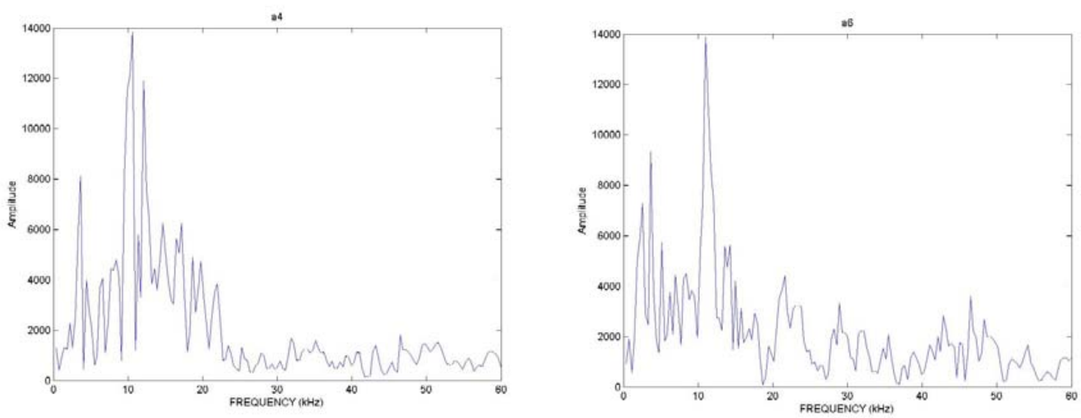

Figure 7 Amplitude spectra of PVC tube (left) and steel tube (right).

Conclusions:

The interpretation of elastic wave propagation in concrete is usually difficult when buried pipelines or steel reinforcement is involved. The amplitude spectra can only provide global information and lose some important local effects of frequency components. This should be resolved by preserving the transient effects in the frequency domain. The effect of CWT is similar to a multi-channel bandpass filter. Not only the frequency components are separated, their transient behaviors are also preserved. Wave propagation in concrete with different buried objects can thus be better perceived, in terms of frequency band and lasting period of the results of CWT. As a result, better signal processing is achieved for the impulse responses due to different objects inside the concrete slab. Features are readily identified, due to the steel rebar, the PVC tube, and the steel tube, in the magnitude plot of wavelet coefficients. The same peak frequency found in the amplitude spectrum is now distinguishable between PVC and steel tubes at a resolution of 0.2kHz or better.

References:

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