Time-Frequency Techniques for the Impact Echo Data Analysis and Interpretations

Parisa SHOKOUHI, The University of Texas at El Paso, El Paso, TX, USA
Nenad GUCUNSKI and Ali MAHER, Rutgers University, Piscataway, NJ, USA

Abstract. A very common problem in concrete bridge decks is corrosion induced delamination. Impact echo (IE) is one of the nondestructive techniques used in the bridge deck condition assessment and monitoring to detect presence and position of a delamination. To detect a delamination, the IE technique relies on finding the peak frequency in the spectrum of the signal recorded on the surface of the deck, close to an acoustic impact source. Although, the IE technique has been proven successful in detection of delamination, in many cases its application can be limited to specific situations. For example, large amplitude surface wave components in the signal in proximity of the edges, or the presence of other heterogeneities (e.g. steel bars), may introduce additional frequency peaks. As such, they can mask or change the characteristics of the peaks in the response spectrum that may result in erroneous data interpretation. To enhance interpretation in such situations, a time-frequency analysis of the surface response is proposed as a complementary data analysis tool for the interpretation of the IE results. Presenting the signal in a 2-D time-frequency plane provides an opportunity to distinguish various sources of acoustic emission inside the deck. The approach makes it possible to exclude frequency components contaminating the spectrum. A number of different time-frequency techniques are compared in detection of a planar delaminated surface in a concrete specimen of finite dimensions. It is shown that the time-frequency analysis is effective in enhancing the IE data reduction and interpretation.

Introduction

Health monitoring of highway bridges on a regular basis is essential for their effective and economic management. Bridge deck condition evaluation constitutes a significant part of the health monitoring effort. It enables early detection of deterioration, whether the deterioration manifests itself through material degradation or defect generation. Early detection of progressive defects leads to the development of a cost-effective maintenance plan based on preventive rather than corrective treatments. Nondestructive testing (NDT) techniques provide means for objective condition evaluation of concrete bridge decks.

One of the most common problems in concrete bridge decks is a corrosion induced deck delamination. The current practice of deck inspection by chain dragging is nondestructive and relatively fast. However, it is highly subjective and can only be used to identify delaminations at stages where the deterioration has already progressed to such an extent that major rehabilitation measures are needed [1]. High frequency seismic/ultrasonic NDT methods successfully overcome many of the limitations of chain dragging. It has been demonstrated that impact echo (IE), an ultrasonic seismic technique, can detect and assess delaminations at various deterioration stages [1,2,3] using devices that perform automated data collection and analysis [4,5]. However, precise interpretation of the collected data has yet to be fully defined and automated [6].

The data analysis in IE includes transformation of the record into the frequency domain and inspection of the resulting spectrum for peaks corresponding to the frequency of reflections from the reflecting interfaces beneath the surface of the deck. The interpretation of the IE spectrum is not always straightforward. When the deck is in a fair or poor condition, the IE spectrum usually contains multiple frequency peaks and is not always easy to interpret [1,6,7]. Surface waves and ambient noise in the record further complicate the IE data interpretation [4,8]. Therefore, under many practical circumstances, relying only on the spectrum is not sufficient for accurate interpretation of IE results.

In this paper, time-frequency analysis is proposed as a complementary analysis tool to enhance the interpretation of IE test results. The advantages of using a two-dimensional time-frequency analysis over a one-dimensional spectral analysis are pointed out. Application of a number of available time-frequency techniques in the analysis of IE signal is investigated. Fundamental principles behind each technique, their applicability and their limitation in interpretation of IE results are briefly discussed. The techniques are compared through the analysis of an experimental record. It is shown that the time-frequency analysis can be effectively used to complement the spectral analysis in the IE data interpretation.

1. Impact Echo

The IE testing procedure is very simple in principle. A mechanical impact is applied on the surface of the deck to generate elastic waves in the concrete. The wave components reflected off the bottom of the deck, as well as those scattered and reflected from the heterogeneities within concrete, the echoes, are recorded by a receiver located on the surface close to the impact source. The data analysis includes transformation of the record into the frequency domain and inspection of the resulting spectrum. The peaks in this spectrum correspond to the frequency of reflections from the reflecting interfaces beneath the surface of the deck. Because of the significant contrast in the impedance of concrete and air, any interface like delaminations, cracks and cavities, is a perfect reflector of an incoming elastic wave. In a case of a sound deck, such an interface exists only at the bottom of the deck (Figure 1). Therefore, a large portion of the input energy is reflected back from the bottom. The spectrum will be, therefore, dominated by a pronounced peak at a return frequency f_r,

$$f_r = \frac{V_P}{2T} \quad (1).$$

V_P is the compression wave velocity and T is the total thickness of the deck (Figure 1). In the case of a delaminated deck, a portion of the elastic wave energy will be reflected back from the interface created by the delamination. A part of the energy will still be reflected from the bottom of the deck. Therefore, other than the return frequency f_r, the spectrum will show a number of higher frequency peaks f_d, corresponding to the frequency of reflections from delaminations at a depth $d < T$,

$$f_d = \frac{V_P}{2d} > f_r \quad (2).$$

The relative amplitude of the peaks depends on a number of factors, including the extent, depth, continuity and location of delaminations, as well as the frequency content of the impact source [1,6,7,9].

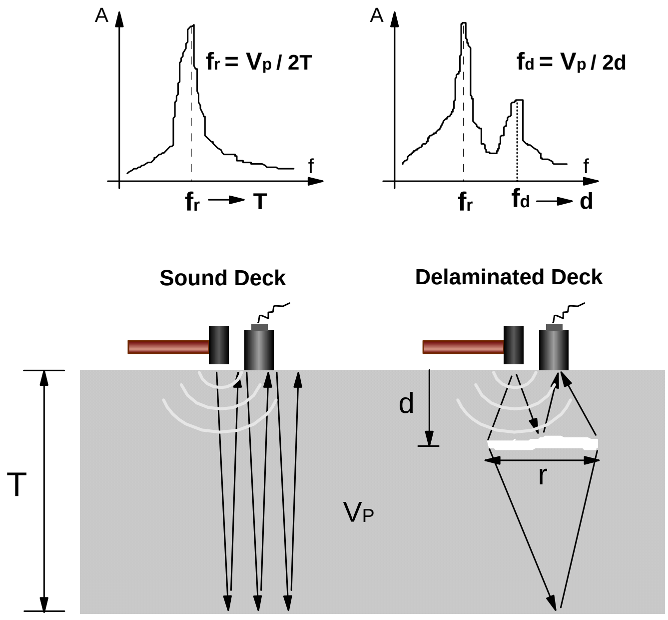


Figure 1. IE testing and data analysis on sound and delaminated concrete decks.

In the case of a shallow and large defect, the part of the deck above the delamination may act as a plate-like structure undergoing flexural vibrations. One or more flexural modes of vibration of this thin concrete section may be excited. In general, the value of the flexural frequency f_f is significantly lower than the delamination frequency. The amplitude of the surface displacement due to flexural vibrations is higher than the same due to wave reflections [4,10]. Therefore, low frequency peaks in the spectrum are an indication of shallow and severe defect. In this case, the depth of the defects can not be estimated.

Interpretation of IE test results is based merely on the analysis of the IE signal in the frequency domain. Fourier transform is used for transforming the IE signal from the time domain into the frequency domain. The IE spectrum is examined to obtain the frequencies and relative amplitudes of the dominant peaks. As described above, the condition of the deck will be assessed based on the values of the observed dominant frequencies relative to the return frequency f_r. In practice, however, it is not always easy to identify the frequency corresponding to the target echoes in the spectrum of the IE signal. The IE spectrum of a delaminated deck usually contains multiple frequency peaks. Their corresponding frequencies and relative amplitudes depend on the location, size, depth and continuity of the delamination, as well as the impact duration. It was also shown that [6,7] delaminations located away from the IE source and receiver, may introduce additional frequency peaks in the IE spectrum. Furthermore, large amplitude incident surface waves and echoes from boundaries of the structure may obscure the frequency of the desired target echoes [1,4,8]. Finally, the heterogeneous nature of reinforced concrete introduces a high level of noise which can greatly complicate the interpretation of the IE spectrum [11]. Therefore, the frequency domain analysis of the IE signal is not always sufficient for interpretation of IE results for condition assessment of concrete decks. A number of theses difficulties arise from the definition of Fourier transform and its inadequacy for analysis of IE signals.

Limitations of the Fourier transform-based spectral analysis of nonstationary signals, such as IE records, are briefly discussed in the following section. Time-frequency analysis is introduced and proposed as a complementary analysis tool for better interpretation of the IE test results.

2. Time-Frequency Analysis

Fourier transform has traditionally been used to obtain the frequency content (or Fourier spectrum) of a signal. The spectrum gives the distribution of energy of the signal among its constituent frequency components. However, Fourier coefficients are the averaged spectral amplitudes over the entire duration of the signal. Therefore, Fourier transform is an ideal tool for spectral analysis of periodic and stationary signals for which the distribution of energy is uniform throughout the signal.

An IE record is clearly a non-stationary signal with non-uniform frequency characteristics. Because of a short duration of the impact and damping of seismic waves propagating in concrete, the IE signal has a transient nature. When surface waves are not very strong, the structure is simple (ambient noise is minimal) and the reflections are clearly recognizable, the spectrum is sufficient to distinguish the frequency peaks of target echoes. However, incident surface waves usually add artificial energy to the IE spectrum over a wide range of frequencies. Furthermore, the target echoes and ambient noise may not be always separable in the frequency domain. Finally, it is sometimes hard to interpret frequency peaks in the IE spectrum when there are multiple reflector interfaces. Therefore, a complementary analysis method, more appropriate for processing of non-stationary signals is needed.

The insufficiency of spectral analysis of noisy IE signals is illustrated by some experimental results. The data is obtained on a surface of an artificially delaminated concrete specimen. The dimensions of the test specimen along with the experimental setup are shown in Figure 2(a). The data was collected by a new IE scanner system developed at the University of Texas at El Paso. As shown in Figure 2, the impact source is fixed at a distance 0.06 m from one edge of the concrete specimen. The scanner is moving automatically across the test specimen in the direction shown in Figure 2(a) and records the surface response at specified locations. The signal shown in Figure 2(b) is recorded at a distance of 0.09 m from the impact source. The signal has 4096 points and is recorded with a sampling frequency of 625 KHz. The spectrum of the signal is shown in Figure 2(c). The surface wave velocity is measured as 2117 m/s. Assuming a Poisson's ratio $\nu = 0.2$ for concrete, the compression wave velocity V_P is obtained as 3780 m/s.

Because of the limited dimensions of the test specimen, the surface records are expected to be very noisy. The incident surface wave components, as well as the "returned" attenuated surface waves traveling all around the specimen, are included in surface records. Body wave reflections from the side walls of the specimen also contaminate the records. In this record, the surface wave components are not strong, compared to the large amplitude structural oscillations. Since the impact excites the natural modes of oscillations of the finite test specimen, large amplitude waves of low frequency will be present in the signal. As a result, higher frequency reflections from the bottom of the specimen or the delaminated plane can not be recognized in the time history of the signal shown in Figure 2(b). The spectrum of the signal is dominated by two very low frequency peaks at 1.2 and 2.2 KHz. Reflections from the bottom of the slab and the delamination have frequencies of.7.4 and 14.9 KHz, respectively. However, because of the ambient noise, neither f_r nor f_d can be singled out in any of the spectra shown in Figure 2(c). It should be noted that the longer this record is, the more ambient noise it contains. Therefore, the spectrum obtained from longer records is expected to be noisier. The spectrum of the full signal was compared to those for the truncated signals (not shown here). While it was observed that lower frequency peaks are less pronounced in shorter records, those still dominated the spectrum even when only the first 1/8th of the record (512 data points) was considered in the spectral analysis [6].

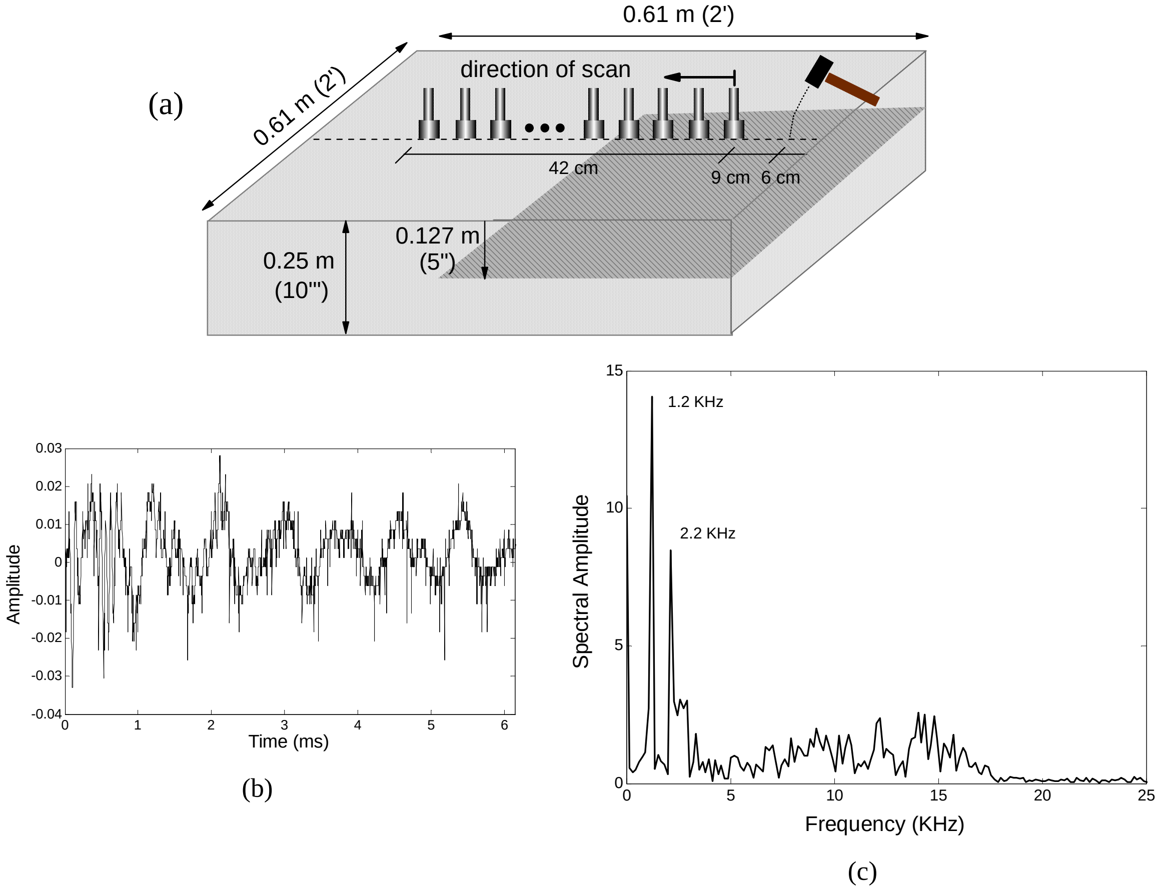


Figure 2. (a) Experimental setup, (b) Noisy IE signal and (c) IE spectrum.

Time-frequency analysis will be used here as a complementary tool for studying complex IE signals. Using this technique, the changing spectrum of the IE signal can be pictured in a two-dimensional time-frequency plane. The surface wave component, the echoes from the geometrical borders or heterogeneities inside the reinforced concrete slabs are separable from the target echoes (reflections from the bottom of the slab or delaminations) in time and/or frequency domains. Therefore, a 2D time-frequency representation of the signal provides an opportunity to distinguish the target echoes in a noisy IE signal, which could go undetected in a FFT-based averaged spectrum.

The advantages of using time-frequency data analysis in applications involving non-destructive evaluation (NDE) of structures have been recognized by many researchers [11,12,13,14,15]. Time-frequency analysis has been recently applied to the analysis of IE signals as well [8,14,16]. Short-time Fourier transform (STFT) was adopted in some of these studies to obtain the time-frequency representation of the IE signals. Abraham *et al.* [16] used STFT to study the changing spectral properties of complex numerical and experimental IE signals. They showed that time-frequency analysis can improve the interpretation of IE results. Kim *et al.* [8] used a simple normalization scheme to modify the STFT representation of the signal. By summing the normalized time-frequency coefficient at every frequency, they obtained a modified spectrum, where the target echoes were more emphasized.

Beside STFT, a number of other time-frequency analysis techniques are available. Fundamentals of STFT and one more recent time-frequency method, continuous wavelet transforms (CWT) are presented in this paper. Potential applications and limitations of each technique in the analysis of IE signals are investigated. The application of a number of alternative techniques such as discrete wavelet transform (DWT) [17] and recently developed Hilbert-Huang transform (HHT) [18] to the analysis of IE data has been explored [6] and will appear in subsequent publications.

2.1 Short Time Fourier Transform (STFT)

STFT or spectrogram is the most basic available technique for the time-frequency analysis. If the signal is windowed in the time domain using a short duration window function, a short section of the signal is obtained. Fourier transform of this section gives an approximation of the instantaneous frequency content of the signal at the time instant of the center of the window. A time-frequency distribution can be obtained by successively sliding the window function along the time axis and calculating Fourier transform of the windowed signal at each time location. For a time signal $x(t)$ and a window function $g(t)$, STFT can be defined as

$$STFT(t, f) = \int_{-\infty}^{+\infty} x(\tau) g^{*}(\tau - t) e^{-i(2\pi f)\tau} d\tau \qquad (3).$$

where * denotes the complex conjugate.

The spectrograms of the same noisy experimental IE signal (shown in Figure 2(b)) using Gaussian windows of different durations are presented in Figure 3. To emphasize the latter part of the signal, the STFT coefficients at each time step are normalized [8,16]. The time-frequency distribution of the energy of the signal can be studied in these spectrograms. However, the characteristics of the spectrogram are shown to be highly dependent on the size of the sliding window. As the duration of the window increases from 0.032 ms to 0.8 ms (Figure 3 (a) to (d)), the STFT analysis provides time-frequency pictures of the signal with a poorer time resolution and better frequency resolution. In another words, the time location and duration of the target echoes can be best seen when the window is relatively short (Figure 3 (b)). To obtain the frequency of reflections, on the other hand, the spectrograms corresponding to longer windows are more favorable (Figure 33 (c),(d)).

Based on any of the spectrograms shown in Figure 3, one can conclude that a large portion of the energy of the signal is coming from a global low frequency trend. However, the two low frequency peaks at 1.2 and 2.2 KHz (Figure 2 (c)) are not distinguishable in any of these spectrograms. The reason is that the frequency resolution in these spectrograms is not sufficient to separate these two frequency components. The presence of a high energy high frequency wave component at the beginning of the signal can be detected in Figure 3(c) and (d). Having a center frequency of about 15 KHz, it is easy to conclude that the observed high energy section is a result of reflections from the delaminated plane within the concrete specimen. Although the reflections are of considerable energy, because of their limited duration, they do not appear as strong peaks in the spectrum. However, they are easily distinguished in the STFT spectrograms of sufficient frequency resolutions.

STFT is very simple and efficient to implement and therefore, is still the most popular time-frequency analysis method. However, since STFT relies on the traditional Fourier spectral analysis, it inherits many of the limitations associate with Fourier transform. Furthermore, as it was shown here, using windows of different durations results in very different spectrograms. Without a priori knowledge about the structure, the appropriate window size is very difficult to determine. Therefore, to capture both local characteristics of the signal and different frequency features, a number of STFT analysis using windows of different sizes should be carried out.

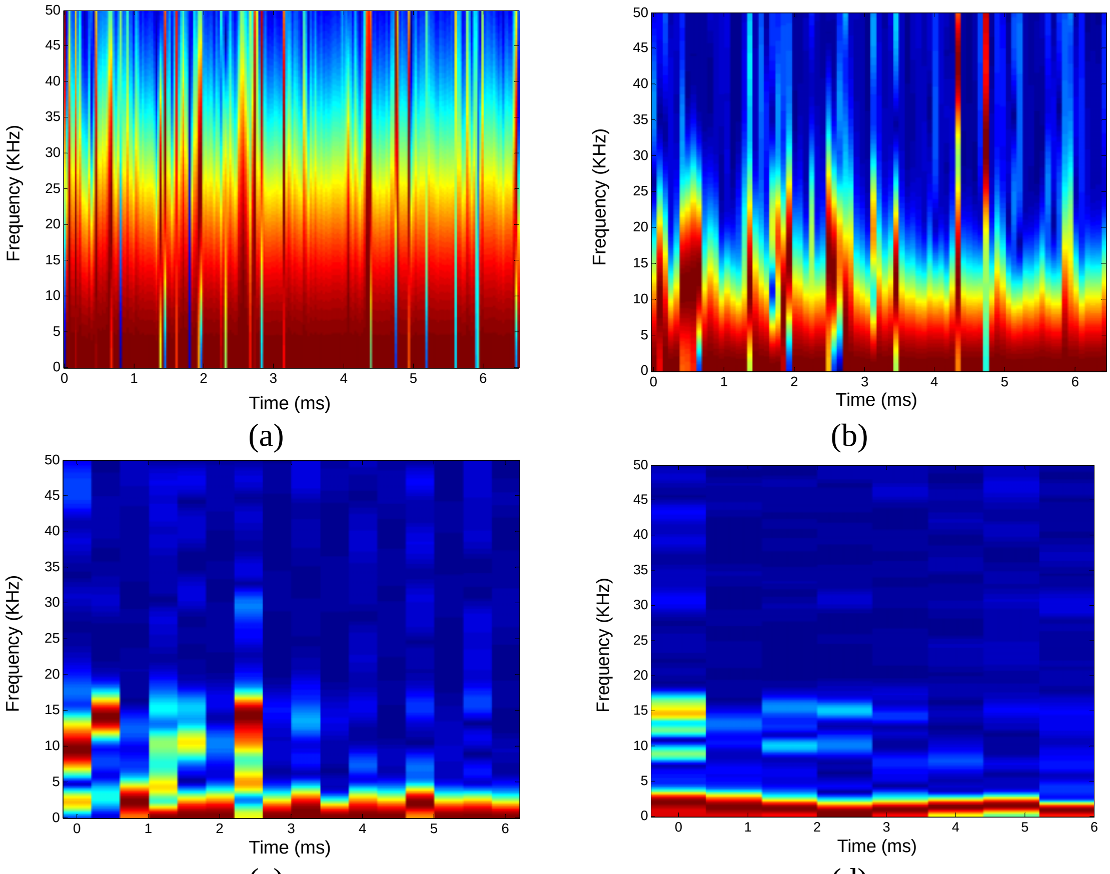


Figure 3. STFT of the experimental IE signal using Gaussian window of a duration (a) 0.032 ms, (b) 0.08 ms, (c) 0.4 ms and (d) 0.8 ms.

2.2 Continuous Wavelet Transform (CWT)

The wavelet transform provides a time-frequency distribution similar to that obtained by STFT analysis, with a few important differences. The wavelet transform is

$$W_{\psi,x}(a,b)=\int_{-\infty}^{+\infty}x(t)\psi^{*}{}_{a,b}(t)dt=\langle x,\psi_{a,b}\rangle \qquad \text{where } \psi_{a,b}(t)=\frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \qquad (4)$$

where * denotes complex conjugate and $\psi_{a,b}(t)$ is a wavelet at scale a and location b. $\psi_{a,b}(t)$ is a scaled and translated version of a single function called “mother” wavelet $\psi(t)$. As a changes, $\psi_{a,b}(t)$ covers different frequency ranges (large values of the scaling parameter a correspond to low frequencies, small values of a correspond to high frequencies). Changing the parameter b allows movement of the time localization center; each $\psi_{a,b}(t)$ is localized around $t=b$. Therefore, similar to Equation (3), Equation (4) provides a time-frequency description of x, sometimes called a scalogram [17]. Both STFT and CWT use the inner products of $x(t)$ with a family of functions. In the case of STFT analysis, the analyzing functions are windows $g_{f,t}(\tau)=g(\tau-t)e^{-i(2\pi f)\tau}$, and for CWT are wavelets $\psi_{a,b}(t)$. The main difference between the two is in the shape of the analyzing functions $g_{f,t}$ and $\psi_{a,b}(t)$. All functions $g_{f,t}$ consist of the same envelope function g of the same time duration, translated to the proper time location (t), and “filled in” with higher frequency oscillations of frequency f. In contrast, $\psi_{a,b}$ have time-widths adapted to their frequency: higher frequency $\psi_{a,b}$ are very narrow while low frequency $\psi_{a,b}$ are much broader [17]. Therefore, wavelet transform can be regarded as an adjustable window Fourier spectral analysis [18]. As a result, the wavelet transform is better able to “zoom in” on very short-lived high frequency characteristics, such as transient signals [17]. This characteristic of CWT makes it a more appropriate tool for the analysis of transient non-stationary data, such as IE signals.

The experimental IE signal shown in Figure 1(b) is analyzed using $Gaus_{10}$ from the Guassian family of wavelets [6,17] and the corresponding normalized scalogram is shown in Figure 4. The wavelet transform clearly provides an efficient time-frequency representation of the signal. Different frequency components of the signal and their duration can be identified in the scalogram. One approach to interpret and quantify the time-frequency information of scalograms involves selecting a number of peaks in the time-frequency distribution of the signal. Peaks with relative normalized amplitudes above a certain threshold are selected. In the next step, based on their corresponding frequency coordinates, the selected peaks are categorized into a number of “peak sets”. The final step is to plot the designated “peak sets” in a time-frequency plane. The plots give approximate duration and average frequency for each set. This procedure has been applied to the scalogram in Figure 44 and the results are presented in Figure 55. The average frequency for each peak set is calculated and the values are shown in Figure 5(b). The low frequency components show average frequencies of 1.1 KHz and 2.3 KHz, which are very close to those expected at 1.2 KHz and 2.2 KHz. However, the average frequency of the reflected waves was obtained as 13.7 KHz, which is 8% lower than the expected value of 14.9 KHz.

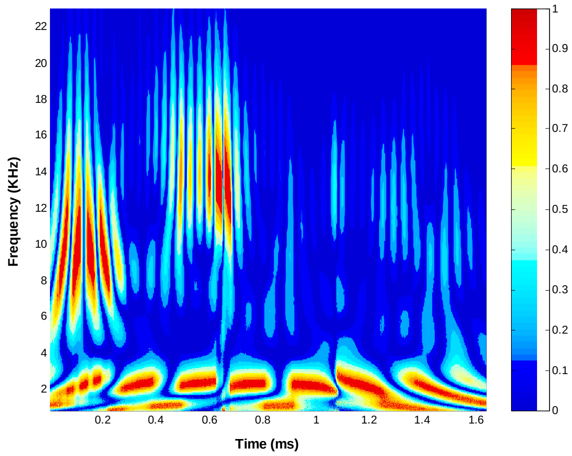
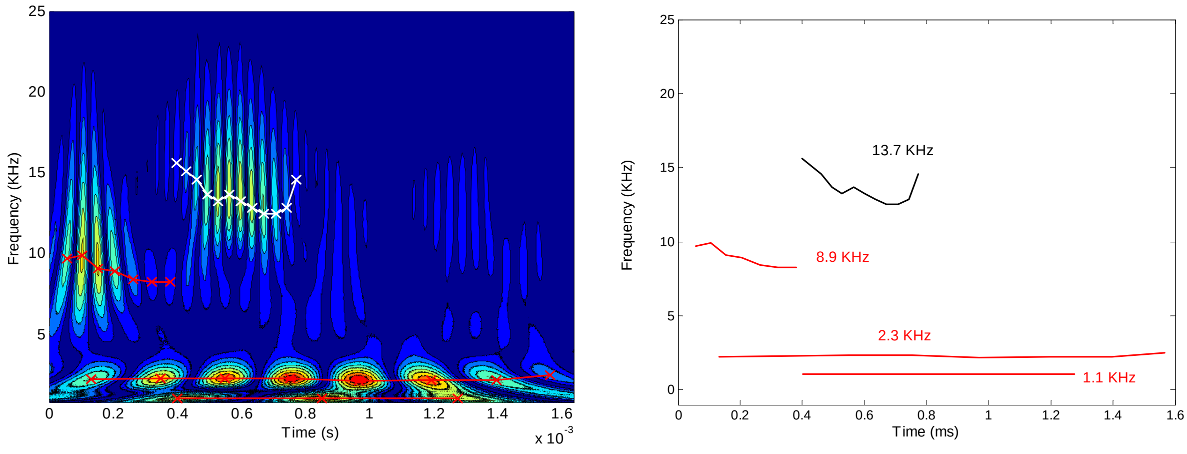


Figure 4. Time-frequency scalogram using $Gaus_{10}$ wavelet (obtained from normalized magnitudes of wavelet coefficients).



(a) (b)

Figure 5. (a) Time-frequency scalogram using $Gaus_{10}$ wavelet and selected “peak sets”, (b) “Peak sets” in a time-frequency plane.

3. Conclusions

Time-frequency analysis was used as a complementary analysis tool to enhance interpretation of IE test results. While both the short time Fourier transform (STFT) and continuous wavelet transform (CWT) techniques can be used for this purpose, the wavelet transform has shown to provide a more efficient tool for extracting time and frequency information of the signal.

4. References

[1] Gucunski, N., Antoljak, S. and Maher, A. (2000). “Seismic Methods in post Construction Condition Monitoring of Bridge Decks.” Use of Geophysical Methods in construction, Geotechnical Special Publications, No. 108, Eds. Nazarian, S. and Diehl, J., Geo Institute, ASCE, 35-51.

[2] Gucunski, N. and Maher, A. (1998) In Proc. of International Conference *MATEST ‘98 - Life Extension*, Brijuni, Croatia, October 1-2, 39-45.

[3] Sansalone, M. J. (1993) In Proc. of the British Institute of Non-Destructive Testing International Conference *NDT in Civil Engineering*, April 14-16, Liverpool, U.K., 807-820.

[4] Sansalone M. J. and Streett W. B., Impact-Echo Nondestructive Evaluation of Concrete and Masonry, 1997, Bullbrier Press, Ithaca, N.Y.

[5] Nazarian, S. and Yuan, D. (1997) Research Project 7-2936, The Center for Highway Materials Research, The University of Texas at El Paso, El Paso.

[6] Shokouhi, P. (2006), *Comprehensive Evaluation of bridge Decks using Impact Echo*, Ph.D. Dissertation, Rutgers University, New Brunswick, New Jersey.

[7] Shokouhi, P., Gucunski, N., and Maher, A. (2006), “Applicability and Limitations of Impact Echo in Bridge Deck Condition Monitoring”, In Proc. of Symposium on the Application of Geophysics to Environmental and Engineering Problems, SAGEEP 2006, EEGS, Seattle, WA.

[8] Kim, Dong-Soo, Kim, Nam-Ryong and Seo, Won-Seok (2004), “Time-Frequency Analysis for Impact Echo-SASW (IE-SASW) Method”, Key Engineering Materials, Vols. 270-273, 1529-1534, © 2004 Trans Tech Publications, Switzerland.

[9] Colla, C. and Lausch, R. (2003), “Influence of Source Frequency on impact-Echo Data Quality for Testing Concrete Structures”, NDT&E international, v. 36, 203-213.

[10] Mori, K., Spagnoli, A., Murakami, Y., Kondo, G. And Torigoe, I. (2002), “A New Non-contacting Non-destructive Testing Method for Defect Detection in Concrete”, NDT&E international, 35, 399-406.

[11] Legendre, S. , Goyette, J. and Massicotte, D. (2001), “Ultrasonic NDE of Composite Material Structures Using Wavelet Coefficients”, NDT&E international, 34(1), 31-37.

[12] Neild, S. A., McFadden, P.D. and Williams, M.S. (2003), "A Review of Time-Frequency Methods for Structural Vibration Analysis", Engineering Structures, 25, 713-728.

[13] Jeong, H. (2001), "Analysis of Plate Wave Propagation in Anisotropic Laminates Using a Wavelet Transform", NDT&E international, 34, 185-190.

[14] Abbate, Agostino, Koay, Jeff, Frankel, Julius, Schroeder, Stephan C. and Das, Pankaj (1997), "Signal Detection and Noise Suppression Using a Wavelet Transform Signal Processor: Application to Ultrasonic Flaw Detection", *IEEE Transactions on Ultrasonics, Ferroelectrics & Frequency Control*, 44(1), 14-26.

[15] Shyu, H.-F. and Pai, Y.-D. (1997), "A New Tool for Impact-Echo Measurements: Wavelet Transform", Insight: Non-Destructive Testing and Condition Monitoring, 39(5), 337-339.

[16] Abraham, Odile, Leonard, Christelle, Cote, Philippe and Piwakowski, Bogdan (2000), "Time Frequency Analysis of Impact-Echo Signals: Numerical Modeling and Experimental Validation", ACI Materials Journal, 97(6), 645-657.

[17] Daubechies, I., Ten Lectures on Wavelets, 1992, CBMS-NSF Reg. Conf. Series in Applied Mathematics.

[18] Huang, Norden E., Shen, Zheng, Long, Steven R., Wu, Manli C., Shih, Hsing H., Zheng, Quanan, Yen, Nai-Chyuan, Tung, Chi Chao and Liu, Henry H. (1998), "The Empirical Mode Decomposition and the Hilbert Spectrum for Nonlinear and Non-Stationary Time Series Analysis", Proceeding of Royal Society of London, A454, 903-995.