The Assessment and Comparison of Three TFRs for Extraction of Dynamic Properties from Truss Deck of Firoozeh Railroad Bridge Using Seismic Response

Hamid Reza Ahmadi, Farhad Daneshjoo
Tarbiat Modares University, Tehran, Iran

SUMMARY:
The numbers of time-frequency representations are considerable. However, their capabilities for signal processing and feature extraction are different. Therefore, in this study, three time-frequency representations consisting of Wigner-Ville distribution, Choi-Williams distribution and Pseudo Wigner-Ville distribution were evaluated and assessed to extract dynamic properties of the decks of railroad bridges. To perform the evaluation, an analytical model of the truss deck of Firoozeh railroad bridge was used. The bridge is located near the city of Isfahan. To create its finite-element model according to the current condition, extensive in-situ measurements and inspection were performed. Furthermore, vibrations of the truss deck were recorded during train passages. Three ground motion records were applied to the finite-element model, and its responses were recorded. Finally, time-frequency plans were calculated and dynamic characteristics of the seismic responses were extracted. According to the calculated plans, the representations were compared and the best one to process the seismic response signals of bridge decks was identified.

Keywords: square time-frequency representation, Firoozeh railroad bridge, time-frequency plan, truss deck,

1. GENERAL INSTRUCTIONS

The signal methods are well-known for processing signals and feature extraction. Based on the signal methods, changes in the structural characteristics are obtained directly from the measured time histories. Signal procedures are divided into three categories: time domain methods, frequency domain methods and time-frequency domain methods [De Stefano et al, 2001, Neild et al., 2003, Roshan-Ghias et al., 2007].

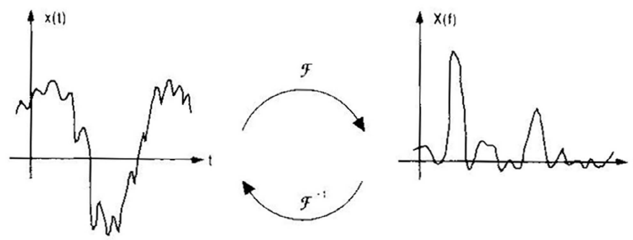
In the time domain methods, using linear and nonlinear functions, features are extracted from the structural time history responses without transformation of the frequency domain. Auto-Regressive (AR) model is the simplest time series models. By adding the exogenous input, the ARX model is obtained. In addition, with the addition of Moving Average, Auto-Regressive Moving Average model (ARMA) is derived. In general, the Autoregressive-Moving Average model with eXogenous input (ARMAX) is defined [Ljung, 1999].

In most of the frequency domain methods, Fourier's analysis is used to transfer the measured time histories from time domain to frequency domain. Fourier transform decompose a signal into sine or cosine waves of different frequencies. Fourier transform of a signal and its inverse is defined as equation 1.1 and 1.2, respectively.

$$F(\omega)=\int_{-\infty}^{\infty} f(t)e^{-i\omega t}dt \tag{1.1}$$

$$f(t)=\frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega)e^{i\omega t}d\omega \tag{1.2}$$

where, t and ω are time and angular frequency, respectively. f(t) and F(ω) are continuous signals in time domain and frequency domain, respectively.
Using Fourier transform to extract the feature of the stationary signal, is useful. However, using Fourier transform for nonstationary signals which their characteristics are varying with time, has limited application as the transform do not provide the full information regarding the time localization of the signal components. Transforming between time domain and frequency domain, using Fourier transform and its inverse is displayed in figure 1.



Time domain (signal)

$$x(t) = \int_f X(f)\, e^{j2\pi t f}\, df$$

Frequency domain (spectrum)

$$X(f) = \int_t x(t)\, e^{-j2\pi f t}\, dt$$

Figure 1. Transforming between time domain and frequency domain [Hlawatsch et al., 1992]

2. TIME-FREQUENCY DOMAIN METHODS

In the time-frequency domain methods, to extract features and identify systems, time-frequency representations (TFRs) can be used. TFRs form a much more suitable approach to processing time-varying signals [Papandreou-Suppappola, 2003]. Often identification of the signal characteristics with a time domain graph is difficult. However, by using time-frequency analysis, another axis is added to the signal graph, and frequency axis with respect to time axis (or vice versa) is plotted accordingly. A time-frequency representation, by expressing frequency content regarding time, allows to analyse evolving signals. Square time-frequency representations are used in various fields including radar, image processing, biomedical engineering, geophysics, quantum mechanics, signal processing, mechanics and electronics [Boashash, 2003].

Principles of TFR have been established many years ago but to our knowledge, there is no recent published on the use of square TFRs for feature extraction and system identification of bridges. In this study, the use of square TFRs is proposed to extract the dynamic characteristics of bridge structures under seismic load. The main advantage of using TFRs is that these functions can process all signals such as stationary, nonstationary and nonlinear [Zhang et al., 2003, Qiao, 2009, Bradford, 2006, Wang et al., 2011, Ahmadi et al., 2012].

A large number of time-frequency representations have been suggested by researchers. However, their capabilities for signal processing and feature extraction are different. There is no single ideal time-frequency representation for every application. The operator needs to select a representation that most clearly reveals the information of interest for a given signal [Bradford, 2006]. Therefore, in this study, three well known time-frequency representations consisting of Wigner-Ville distribution, Choi-Williams distribution and pseudo Wigner-Ville distribution were evaluated and assessed to extract dynamic properties of the decks of railroad bridges.

2.1. Wigner-Ville distribution

The best-known Cohen's class of distribution is the Wigner distribution (WD) [Guo et al., 1994]. The WD was firstly proposed by E. Wigner in 1932, to derive a joint representation of position and momentum in quantum mechanics [Wigner, 1932]. It can be shown that any TFR that is a member of Cohen's class can be derived from the Wigner distribution by applying the appropriate kernel in this manner [Cohen, 1989]. In 1948 J. Ville proposed the Wigner-Ville Distribution (WVD) [Ville, 1948]. The WVD is defined similar to the WD but it is applied to the analysis of complex (analytic) signals [Boashash, 2003]. The WVD is defined as follows [Ville, 1948]:

$$WVD(t,\omega)=\int_{-\infty}^{\infty} x(t+\tau/2)x^{*}(t-\tau/2)e^{-i\omega\tau}d\tau \tag{2.1}$$

where, t and ω are time and angular frequency, respectively. x(t) is analytical signal and * indicates the complex conjugate. Analytical signal is defined as follows:

$$Hann(\upsilon)=0.5+0.5Cos(\frac{2\pi\upsilon}{\tau}) \tag{2.2}$$

Where, s(t) is the real signal and H(t) is the Hilbert Transform. Hilbert Transform is described as below [Mertin, 1999, Boashash, 2003]:

$$H[s(t)]=\frac{1}{\pi}PV\int_{-\infty}^{\infty}\frac{s(\tau)}{(t-\tau)}d\tau \tag{2.3}$$

in which, PV indicates the Cauchy principle value.

2.2. Choi-Williams distribution

The Choi-Williams distribution (CWD) is defined as follows [Boashash, 2003]:

$$CW(t,\omega)=\sqrt{\frac{2}{\pi}}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{\sigma}{|\tau|}e^{-2\sigma^2(s-t)^2/\tau^2}x(s+\frac{\tau}{2})x^{*}(s-\frac{\tau}{2})e^{-i\omega t}ds\,d\tau \tag{2.4}$$

When σ increases, CWD goes to WVD.

2.3. Pseudo Wigner-Ville distribution

To reduce cross-term interference in time-frequency plan of WVD, the Pseudo Wigner-Ville distribution (PWVD) is proposed. PWVD is described as follows [Wang et al., 2011]:

$$PWVD(t,\omega)=\int_{-\infty}^{\infty} h(\tau)x(t+\tau/2)x^{*}(t-\tau/2)e^{-i\omega\tau}d\tau \tag{2.5}$$

where, $h(\tau)$ is time smoothing window.

3. FIROOZEH RAILROAD BRIDGE

Firoozeh railroad bridge, with approximately 160 meter length, has been built near the city of Isfahan. The bridge is located in a region with 51°46´47˝ longitude and 32°34´26˝ latitude in the range of Isfahan province. The bridge has an approximately 40-year-old. A general view of the bridge is given in Figure 2.

The bridge is on a track railway line and is composed of seven simple spans. One of its spans is made of steel truss of length about 40 m long. The other spans are made of steel plate girder that each span has a total length of 20 m. Figures 3 shows a side view of the steel through truss deck of Firoozeh railroad bridge.

Figure 2. A general view of Firoozeh railroad bridge

Figure 3. A side view of steel truss deck of Firoozeh railroad bridge

The truss deck has an expansion rocker bearing and a fixed bearing at each end. The piers and abutments of Firoozeh railroad bridge are made of masonry materials.

Extensive field testing as well as analytical works were performed to assess the condition of the steel deck of the bridge in 2009. In situ measurements of member sizes, connections and support bearings and dynamic tests were conducted along with the preparation and calibration of a finite-element computer model of the steel deck. To obtain structural parameters and to define the actual behaviour of the structure, dynamic tests were conducted on the deck.

To record the vibrations of the deck, 6 accelerometers, an 8-channel dynamic data logger plus a laptop was used. The acceleration sensors were arranged in such a way that the dynamic responses of the deck are recorded as far as possible. Schematic layout of the instrumentation points is shown in Figure 4. In the figure, circle and diamond indicate out-of-plane and in-plane measurement, respectively. The dynamic data logger plus the laptop and the mounted accelerometer are displayed in Figures 5 and 6.

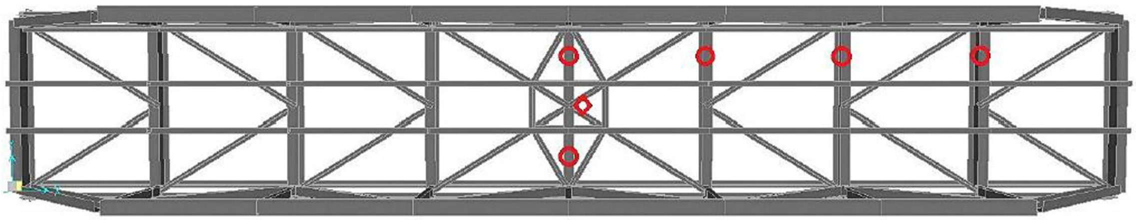


Figure 4. Schematic layout of the instrumentation points [Ahmadi et al., 2011]

Figure 5. Used dynamic data logger and laptop

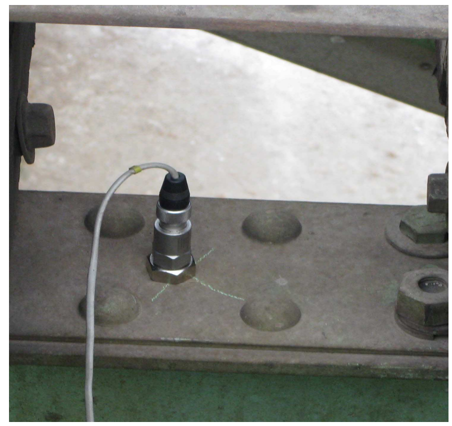


Figure 6. A vertical accelerometer mounted at the truss deck

Firoozeh railroad bridge is a very important bridge that transform raw materials and also products for plants specially Mobarakeh Steel Plant and Isfahan Steel Company. In addition, passenger trains cross the bridge. Therefore, regarding high volume of traffic passing over the bridge, it is difficult to close the traffic. However, some trains with specified weight and speed, were moved over the bridge. Dynamic loading on the deck was accomplished by three trains, which have been passed through the bridge. In figure 7, the trains passing over the bridge and recording of dynamic responses of the truss deck, are shown.

Figure 7. Dynamic loading induced by train passages

Using the results of tests, the finite-element model of Firoozeh railroad bridge was created. To model bridge members, the frame elements were defined and used in the analytical model. The frames were defined according to plans and as built measures. The bridge model has 1307 nodes, 162 frame elements and 1029 shell elements. Figures 8 shows a side view of the finite-element model of the truss deck.

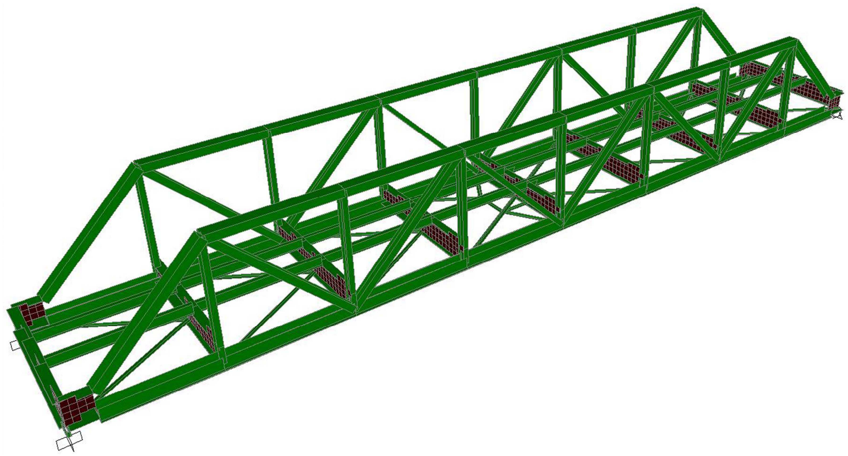


Figure 8. Finite-element model of the truss deck of Firoozeh railroad bridge

4. USED METHODOLOGY FOR ASSESSMENT AND COMPARISON OF TFRs

To assess and evaluate the TFRs, capability of the TFRs in seismic signal processing of the truss deck was studied. For this purpose, the deck model has been excited by ground motion records, and its responses were recorded. The response signals are processed by the TFRs and related time-frequency plans are calculated. Then, with comparison and evaluation the plans, the optimal TFR for signal processing of steel truss deck under seismic loads is identified.

To record seismic signals of the steel truss deck, three ground motion records based on site classification were selected and perform to the analytical model of the deck. The ground motions are far field, and the location where they have been recorded is according to the site classification of Firoozeh railroad bridge. Correspondingly, Borrego Mountain, Big Bear and Chi Chi records which recorded on the class C of site classification, were selected to perform the time history analysis of Firoozeh railroad bridge. According to the base design acceleration of the Iranian standard 2800 seismic code, these ground motion records were scaled to the base acceleration of 0.3g. Properties of the records could be found in Table 4, and the records in time domain are shown in Figures 9, 10 and 11.

Table 4.1. Table 4: Characteristics of the ground motions applied to the model

Row	Record Name	Event Time	Record Station	PGA (g)
1	Borrego Mountain	1968	El Centro Array	0.057
2	Big Bear	1992	San Bernardino	0.101
3	Chi Chi	1999	CHY036	0.294

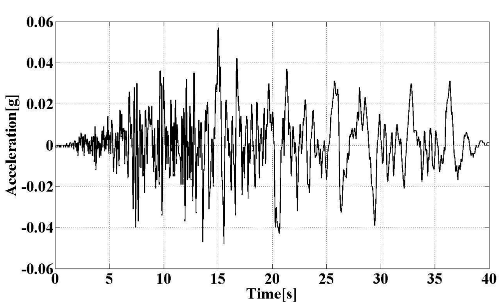


Figure 9. Acceleration time history of Borrego Mountain

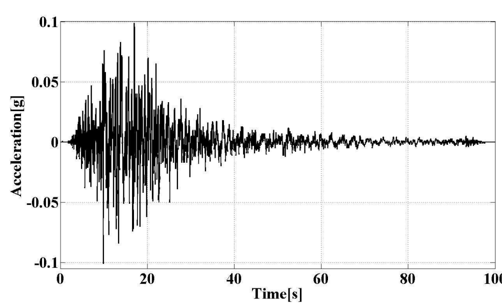


Figure 10. Acceleration time history of Big Bear

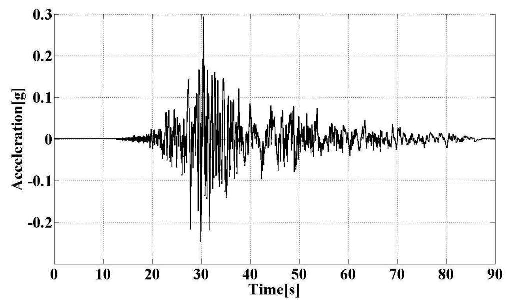


Figure 11. Acceleration time history of Chi Chi

To calculate the bridge model responses under seismic load, the model has been analyzed based on the linear time history method.

5. SIGNAL PROCESSING

As already mentioned, the response signals of the truss deck under the effect of earthquake load were processed by three well known time-frequency representations consisting of WVD, CWD and PWVD and related time-frequency plans were calculated. The time-frequency plans are shown in figures 12 to 14. In order to enable efficient evaluation and assessment between the TFRs, along with the time-frequency plans, related signal in time domain and its energy spectral density in frequency domain are displayed.

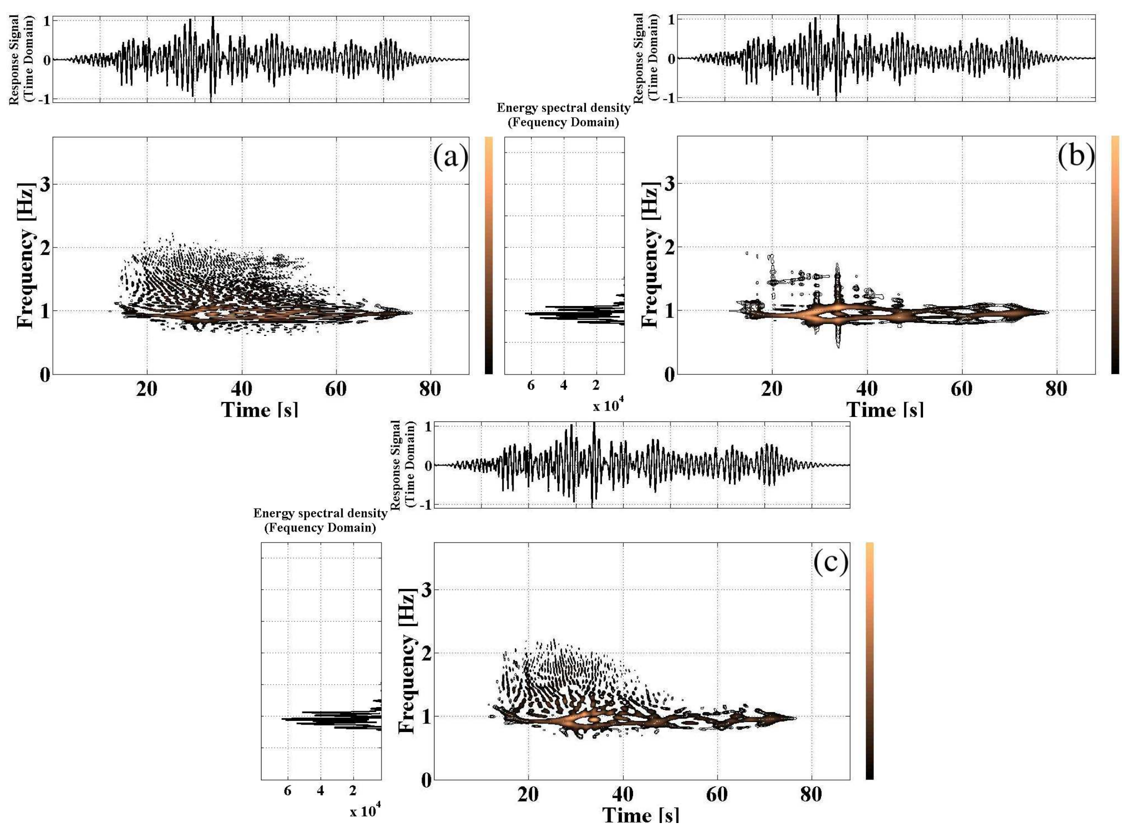


Figure 12. Time-frequency plans of a) WVD, b) CWD and c) PWVD of the deck responses under Borrego Mountain

As can be seen in the figures, important information of the structure about changing frequency content over time is visible. Based on the results, WVD produce interference terms. The interference terms are unsupported in both time and frequency domain. In other words, WVD suggests energy at a frequency while according to energy spectral density, there is known to be no energy. In addition, it shows a temporal onset at an instant when there is not transient signal.

PWVD in comparison with WVD, has partly better resolution and produces fewer interference terms. However, the number of interference terms is considerable in time-frequency plans and the interpretations are made difficult, consequently. According to the results, CWD significantly could eliminate the interference terms. Furthermore, very good resolution can be seen in the time-frequency plans of CWD.

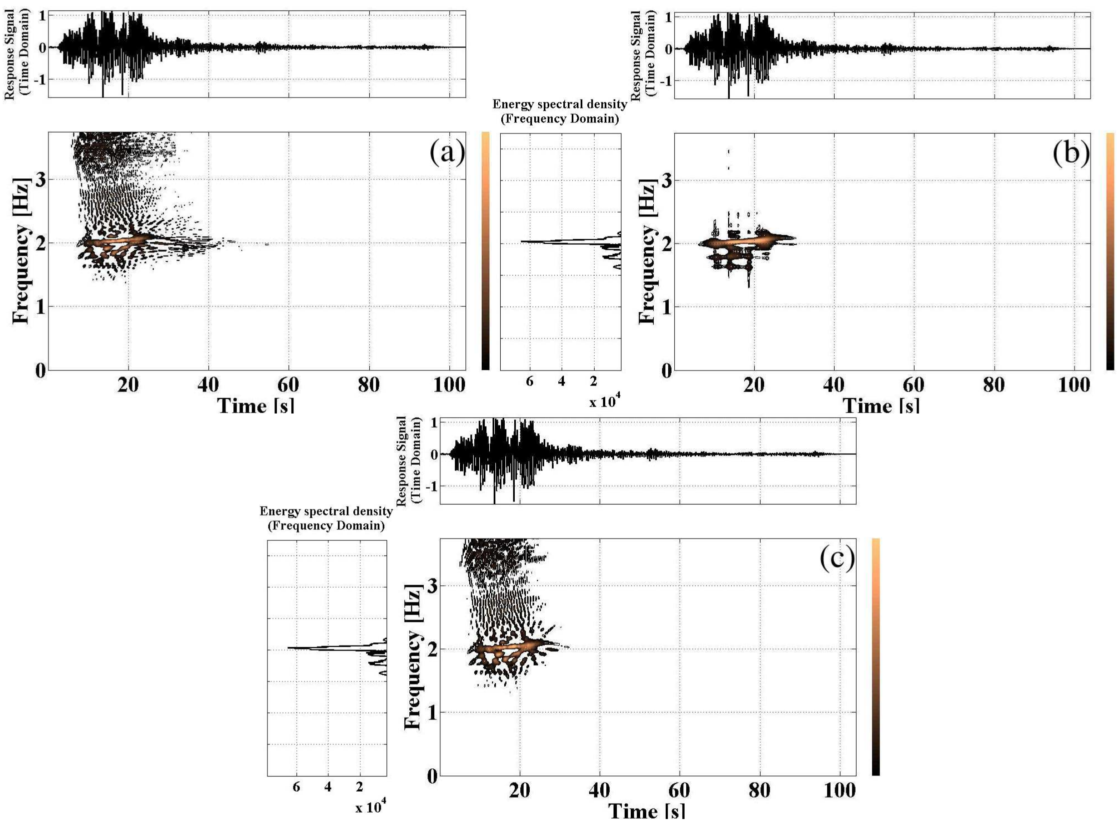


Figure 13. Time-frequency plans of a) WVD, b) CWD and c) PWVD of the deck responses under Big Bear

6. CONCLUSION

For the first time, three well known square time-frequency representations consisting of Wigner-Ville distribution, Choi-Williams distribution and pseudo Wigner-Ville distribution were evaluated and assessed for extraction of dynamic properties from steel truss deck of a railroad bridge under the effect of earthquake load. To identify the best square TFR, steel truss deck of Firoozeh railroad bridge which has an approximately 40-year-old was selected as the structural sample. To create the finite-element model according to the current condition of the Firoozeh railroad bridge, extensive in-situ measurements were performed. In addition, dynamic tests were conducted on the bridge to obtain structural parameters.

To assess and evaluate the TFRs, the deck model has been excited by three ground motion records, and its responses were registered. The response signals are processed by the TFRs and related time-frequency plans are calculated. Then, with comparison and evaluation the plans, the optimal TFR for signal processing of steel truss deck under seismic loads is identified.

According to the results, WVD shows good resolution in time and frequency, but the presences of interference terms are significant obstacles to using the WVD.

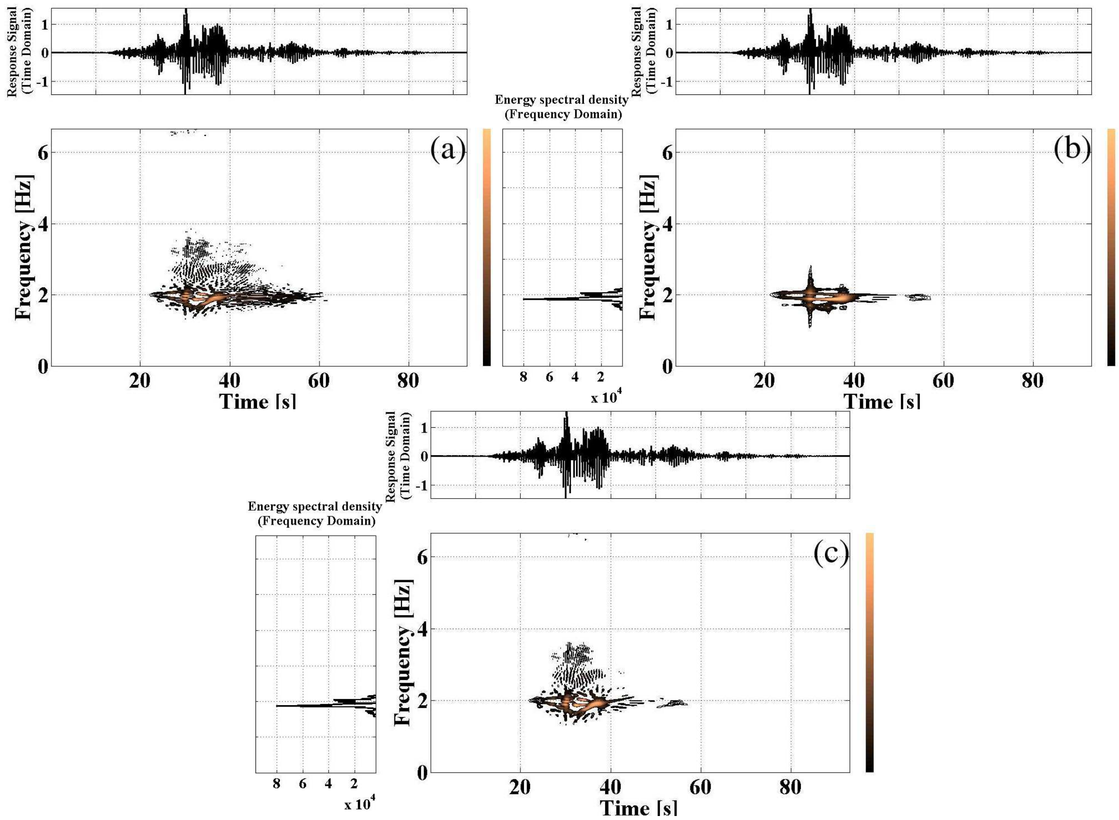


Figure 14. Time-frequency plans of a) WVD, b) CWD and c) PWVD of the deck responses under Chi Chi

PWVD has partly better resolution and produces fewer interference terms in comparison with WVD. However, the number of interference terms is considerable in time-frequency plans of PWVD and the interpretations are made difficult. Based on the results, CWD not only shows very good resolution in time-frequency plans and eliminates the interference terms, but also provides good temporal resolution compared with WVD and PWVD. Therefore, CWD is nearly optimal TFR for processing and feature extraction of seismic response signals of steel truss deck.

REFERENCES

Ahmadi, H.R. and Daneshjoo, F. (2012). A harmonic vibration, output only and time-frequency representation based method for damage detection in concrete piers of complex bridges. accepted in *International Journal of Civil and Structural Engineering.*

Ahmadi, H.R., Daneshjoo, F. and Gharighoran, A.R. (2011). The sensor network design for health monitoring of bridges, 6^{th} national congeress on civil engineering, Semnan University, Semnan, Iran.

Boashash, B. (2003). Time Frequency Signal Analysis and Processing; A Comprehensive Reference, Elsevier Ltd, Oxford, UK.

Bradford, S.C. (2006). Time-frequency analysis of systems with changing dynamic properties, Ph.D. thesis, Department of Civil Engineering, California Institute of Technology, California, USA.

Cohen, L. (1989). Time-frequency distributions-A review. *Proceeding of the IEEE* **77:7**, 941-981.

De Stefano, A., Ceravolo, R., and Sabia, D. (2001). Output Only Dynamic Identification in Time-Frequency Domain. *American Control Conference*, 447-449.

Guo, Z., Durand, L.G. and Lee, H.C. (1994). Comparison of Time-Frequency Distribution Techniques for Analysis of Simulated Doppler Ultrasound Signals of the Femoral Artery. *IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING* **41:4**, 332–342.

Hlawatsch, F. and Boudreaux-Bartels, G.F. (1992). Linear and Quadratic Time-Frequency Signal Representations. *IEEE Signal Processing Magazine*.

Ljung, L. (1999). System Identification: Theory for the User, Prentice Hall, Upper Saddle River, NJ, USA.

Mertin, A. (1999). Signal Analysis (Wavelets, Filter Bank, Time-Frequency Transforms and Applications, John Wiley & Sons Ltd, England.

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.

Papandreou-Suppappola, A. (2003). Application in Time-Frequency Signal Processing, CRC Press, Florida, USA.

Qiao, L. (2009). Structural damage detection using signal-based pattern recognition, Ph.D. thesis, Department of Civil Engineering, Kansas State University, Kansas, USA.

Roshan-Ghias, A., Shamsollahi, M.B., Mobed, M. and Behzad, M. (2007). Estimation of modal parameters using bilinear joint time–frequency distributions. *Mechanical Systems and Signal Processing* **21**, 2125-2136.

Ville, J. (1948). Theorie et applications de la notion de signal analytique. *Cables et Transmissions* **2.A**, 61-74, Translated from French by Selin, I. (1958). Theory and applications of the notion of complex signal. RAND Corporation, Santa Monica, USA.

Wang, H. and Chen, P. (2011). Fuzzy Diagnosis Method for Rotating Machinery in Variable Rotating Speed. *IEEE Sensors Journal* **11:1**, 23-34.

Wigner, E. (1932). On the quantum correction for thermodynamic equilibrium. *Physics Review* **40**, 749–759.

Zhang, Z., Hua, H., Xu. X. and Huang, Z. (2003). Modal parameter identification through Gabor expansion of response signals. *Journal of Sound and Vibration* **266**, 943-955.