A WAVELET-BASED PROCEDURE FOR MINING OF PULSE-LIKE GROUND MOTIONS FEATURES IN RESPONSE SPECTRA

S. Yaghmaei-Sabegh*

Department of Civil Engineering, University of Tabriz, P.O Box 51666-16471 Tabriz, Iran,
s_yaghmaei@tabrizu.ac.ir

*Corresponding Author

(Received: April 04, 2011 – Accepted in Revised Form: December 15, 2011)

doi: *10.5829/idosi.ije.2012.25.01b.05*

Abstract The main objective of this paper is to present a wavelet-based procedure to characterize principle features of a special class of motions called pulse-like ground motions. Initially, continuous wavelet transform (CWT) which has been known as a powerful technique both in earthquake engineering and seismology field is applied easily in automated detecting of strong pulses of earthquakes. In this procedure, BiorSpline (bior1.3) basis from biorthogonal wavelet families is applied for extracting of the largest velocity pulses from normal-fault component of selected records. The selected wavelet decomposition process aids quantification of the effect of extracted pulses on acceleration and displacement response spectra. The results on elastic spectra show that, these pulses cause a significant amplification in the region of pulse period which should be appropriately incorporated in design procedure of structures in near field area. The results also have been presented for inelastic response spectra with different ductility levels.

Keywords Wavelet analysis; Pulse-like ground motions; Elastic and inelastic response spectra; Pulse effect.

چکیده هدف اصلی این مقاله، ارائه روشی مبتنی بر تبدیل موجکها جهت بررسی خصوصیات گروه خاصی از زلزله تحت عنوان حرکتهای پالس گونه می باشد. در ابتدا تبدیل موجک پیوسته بعنوان تکنیکی قوی در مهندسی زلزله و زلزله شناسی برای تشخیص خودکار این نوع حرکتها که عموما ناشی از اثرات جهت داری در حوزه نزدیک گسل می باشند بکارگرفته می شود. بدین منظور بزرگترین پالس سرعت مربوط به مولفه عمود بر گسل زلزله های مورد مطالعه با انتخاب تابع مادر bior1.3 استخراج شده و با بخش باقی مانده از رکورد مقایسه خواهد شد. روش پیشنهاد شده دراین مقاله این فرصت را فراهم خواهد کرد تا اثرات پالس موجود در رکورد های انتخابی بر روی طیف های پاسخ شتاب و جابجایی به صورت کمی مورد مطالعه قرار گیرد. نتایج مطالعات نشان می دهد که اثرات پالس بر روی طیف های الاستیک عموما در محدوده پریود غالب زلزله متمرکز شده است که بایستی در طراحی سازه های واقع در نزدیک گسل به نوعی لحاظ گردد. همچنین، نتایج حاصل برای طیف های غیر الاستیک شتاب و جابجایی ارائه شده است.

1. INTRODUCTION

The vast domain of wavelet analysis as a powerful technique is increasing rapidly both in earthquake engineering and seismology field. Great attention from the research community has been focused on the use of wavelet analysis. Significant progress in its applications can be achieved in several studies that refer to processing of earthquake records, multi-scale analysis and simulation of earthquake motions, seismic data compression, automatic detection and rapid determination of earthquake magnitude, study of the dynamic behaviour of geotechnical structures, damage localization in structures, investigation of seismic response of frames, optimum design of structures against earthquakes, estimation of input energy during earthquakes and effect of energy concentration of earthquake ground motions on the nonlinear response of structures [1-10]. As a new application of wavelet transform, a wavelet-based procedure is applied effectively in this paper to characterize the principal features of a special class of motions called pulse-like ground motions on elastic and inelastic response spectra.

Recent seismology and earthquake engineering studies have focused on better understanding and characterization of near-fault ground motions effects on structures. Sufficient number of measurements of earthquake ground motions in near-fault area obtained in recent events: Northridge (California), 1994; Kobe (Japan), 1995; Chi-Chi (Taiwan), 1999 and Bam (Iran), 2003 provides a suitable platform to achieve new valuable detailed information about near-field ground motions features. These motions which might result in serious damage of structures typically are distinguished from ordinary far-field records with two key characteristics [11]:

i) A permanent displacement offset along the fault called fling-step effect.

ii) A distinct strong pulse in the ground velocity known as directivity effect.

Directivity effects can be classified as forward, reverse, and neutral. Forward directivity which has the most destructive effects occurs when the rupture front expands toward the site and the slip direction is aligned with the site. In this manner, when rupture spreads from the hypocenter to site, the released waves reach the site at once like a strong vibration. Figure 1 shows the location of the rupture of the Landers earthquake (Mw=7.3) along with the strike normal velocity time histories at Lucerne and Joshua-Tree stations that exhibit forward and backward directivity effect, respectively [11].

There is a great deal of evidence for severe structural damage in recent destructive earthquakes occurred in near-fault zones that have experienced these pulse-like motions. Contrasting the ordinary records that recorded from an adequate amount of sources, this kind of ground motions generally give rise to considerable velocity, displacement, energy demands, and accordingly great effect on a wide range of structures that is not expected in conventional representative measures [12-16]. Therefore as an important concern, it is necessary to consider key characteristic of this type of motions in seismic design procedure of structures.

Near-fault ground motion records used as input motions in this paper were chosen from a variety of tectonic environments obtained from the potentially destructive earthquakes of Northridge (California) 1994 (Mw 6.7), Kobe (Japan) 1995 (Mw 6.7), and Chi-Chi (Taiwan) 1999 (Mw 7.6). In the first part of this work, continuous wavelet transform (CWT) as a quantitative method is applied to make out strong near-fault velocity pulse from normal-fault component of selected motions. If the extracted pulse is large relative to remaining features in the ground motion, the ground motion is chosen as pulse-like motion [17, 18]. The period of detected velocity pulses as an effective parameter on structural demand estimation is simply determined by pseudo-period of the mother wavelets.

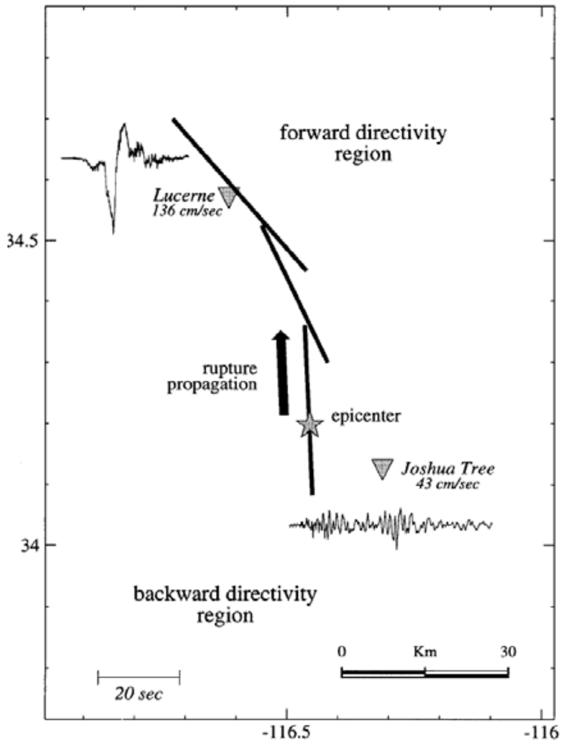


Figure 1. Strike normal velocity time histories at Lucerne and Joshua-Tree stations of the Landers earthquake (Mw=7.3) [11]

The preferred wavelet-based decomposition process aids quantification of the effect of extracted pulses on elastic and inelastic acceleration response spectra in the second part of this paper. Pseudo acceleration spectra along with the displacement spectra for selected pulse like motions are compared with the spectra of the residual motions that achieved after the pulse have been extracted. It has been long recognized that structures should be capable of withstanding substantial inelastic displacement during strong ground motions. Consequently, this paper addresses both elastic and inelastic spectra for pulse-like ground motions as a special class of motions.

2. REVIEW OF FUNDAMENTAL CONCEPTS OF WAVELET ANALYSIS

To demonstrate the ability of the proposed method in this work, a brief review of the basic concepts of wavelet analysis as a multi-resolution signal decomposition tool is presented herein. Mathematical transformations are employed greatly to signals to achieve additional information from that signal that is not available in their time domain form. For this purpose, several techniques such as the conventional Fourier transform have been proposed in the literature. The limitation of Fourier transform which is able to decompose a signal to complex exponential functions of different frequencies has been pointed out over the past few years, especially in the case of non-stationary signals. Wavelet analysis has removed the shortcoming of Fourier analysis by switching from the time-frequency to the time-scale. They are inherently better suited to the analysis of earthquakes which are known as transient and non-stationary events. Accordingly, it is able to detect more valuable information from the time series than other classical methods of analysis which is used in this study for extracting of strong pulse of the nominated records.

Wavelet analysis is breaking up of a signal but into shifted and scaled versi, ons of a wavelet prototype function, called “mother wavelet”. The basic idea behind wavelets is analysis according to scale which plays an essential role in the wavelet analysis procedure and simply means stretching (or compressing) it.

In practice, there are two types of wavelet transforms, discrete wavelet transforms (DWT) and continuous wavelet transforms (CWT) which has been used in this paper because of its higher resolution. For a given signal $f(t)$, the integral form of continuous wavelet transform with respect to mother wavelet function $\psi(\bullet)$ is defined as:

$$CWT\left[f(t);a,b\right] = \frac{1}{\sqrt{|a|}}\int_{-\infty}^{\infty} f(t)\psi^{*}(\frac{t-b}{a})dt \qquad (1)$$

where, $a \neq 0$ and b are real values called the scale and translation or location parameters, respectively and symbol * denotes complex conjugate and t is the abscissa on which the signal is analyzed. Dilation by the scale a which is inversely proportional to frequency represents the periodic nature of the signal. As results of the wavelet transform, $CWT\left[g;a,b\right]$ is representing a time-scale map (or Scalogram). If parameter a in above equation takes discrete values, the aforementioned transform is called discrete wavelet transform and is abbreviated as DWT. If not, it is named continuous wavelet transform and is abbreviated as CWT. By taking Fourier transform of $\psi(t)$, it is possible to reconstruct the signal under analysis, f(t), from its wavelet transform, $CWT\left[g;a,b\right]$, in the following form:

$$f(t) = \frac{1}{2\pi C_{\psi}}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{1}{a^{2}}CWT[f(t),a,b]\psi(\frac{t-b}{a})dadb \qquad (2)$$

$$C_{\psi} = \int_{-\infty}^{\infty}\frac{\left|\hat{\psi}(\omega)\right|^{2}}{|\omega|}d\omega \qquad (3)$$

where, $\hat{\psi}(\omega)$ is the Fourier transform of $\psi(t)$ and the coefficient of C_{ψ} depends on the selected mother wavelet.

The BiorSpline (bior1.3) basis from biorthogonal wavelet families has been adopted in this paper as a sufficient mother wavelet which was suggested recently by the author for this purpose [18]. The bior1.3 is a symmetrical, bell-shaped, piece-wise polynomial function with good local properties which originally introduced by Charles and Wang as wavelet [19]. It should be noted that biorthogonal wavelet families have been used as an appropriate alternative for some pervious applications [20, 21]. More detailed description about mathematical background of continuous wavelet transform can be found in text books of the subject [22, 23].

3. PULSE EXTRACTION PROCEDURE

In 2007, Baker has presented a novel wavelet-based method for quantitative classification of near-fault ground motions containing strong velocity pulse typically caused due to directivity effect [17]. For this purpose, the largest velocity pulse from a given ground motion is extracted by applying of CWT and then the size of original motion is compared with the residual of motion after this extraction. Comparisons were made by means of a pulse indicator (PI) which was introduced by Baker based on logistic regression analysis [17] as defined in the following form:

$$PI = (1 + \exp(-23.3 + 14.6\alpha + 20.5\beta)^{-1}) \quad (4)$$

Two predictor variables of Eq. (4) are; α that is the peak ground velocity of the residual record divided by the original record's PGV, and the second variable, β which is obtained by dividing the energy of the residual record to the original record's energy. Hereby, one pulse indicator is calculated for each record and records with score above 0.85 are classified as pulse-like motion (for more details see ref. [17]).

There is not a general systematic rule for selection of mother wavelet (or wavelet basis) and usually it depends on the type of analysis, the characteristic of function to be analyzed and the type of information one wants to emphasize. Earlier, behavior of the different types of orthogonal and biorthogonal mother wavelets on performance of pulse-like ground motion classification were discussed [18]. Estimation of pulse period for velocity time series of ground motions was also investigated by the author [18]. From the analysis, it was revealed that the choice of mother wavelets and its associated scaling function are very significant to obtain the most reliable wavelet transforms. It depends on the characteristic of velocity pulse which frequently appears in near-fault ground motions. The comparisons also showed the better performance of BiorSpline (bior1.3) basis from biorthognal wavelet families among different mother wavelets, the Haar, the Daubechies wavelet of order 4 and 7 (db4, db7), the Symlet wavelet of order 4 (Sym4), the Coiflet wavelet of order 2 (Coif2), and Reverse bi-orthogonal wavelet of order 2 and associated filter length 4 (rbio2.4) [18]. Figures 2 and 4 show the acceleration and velocity time history of original ground motions along with the associated extracted pulse using (bior1.3) for three destructive events, Northridge (California), 1994; Chi-Chi (Taiwan), 1995 and Kobe (Japan), 1995, recorded respectively at Rinaldi, CHY006 and Takarazuka stations. It should be noted that the calculated pulse indicator for all of pulse-like motions selected in this paper is close to 1.

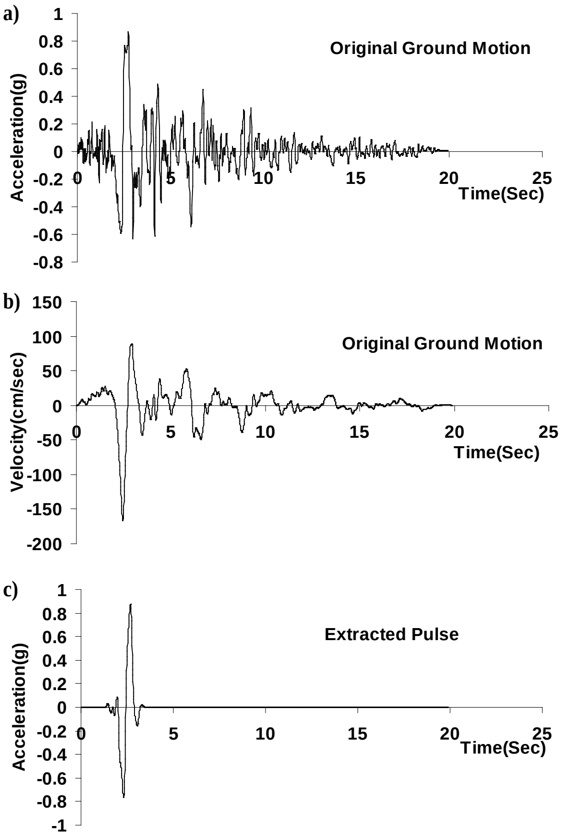


Figure 2. Acceleration, velocity and associated extracted pulse time history of Northridge (1994) event recorded at Rinaldi station

The velocity pulse period in this work also is derived based on pseudo-frequency of wavelet ($\bar{\xi}_j$) as follows:

$$\bar{\xi}_j = \frac{\xi_\psi}{j\Delta t} \quad (5)$$

where, ξ_ψ is the central frequency of wavelet ψ in Hz, j is the scale of wavelet and Δt is sampling period. Consequently, pseudo-period of the largest wavelet coefficient (Tp) is defined as the inverse of the pseudo-frequency. In order to calculate ξ_ψ, it is required to associate it with a type of mother wavelet. Therefore, the derived pulse period based on this procedure is depending to the type of selected mother wavelet.

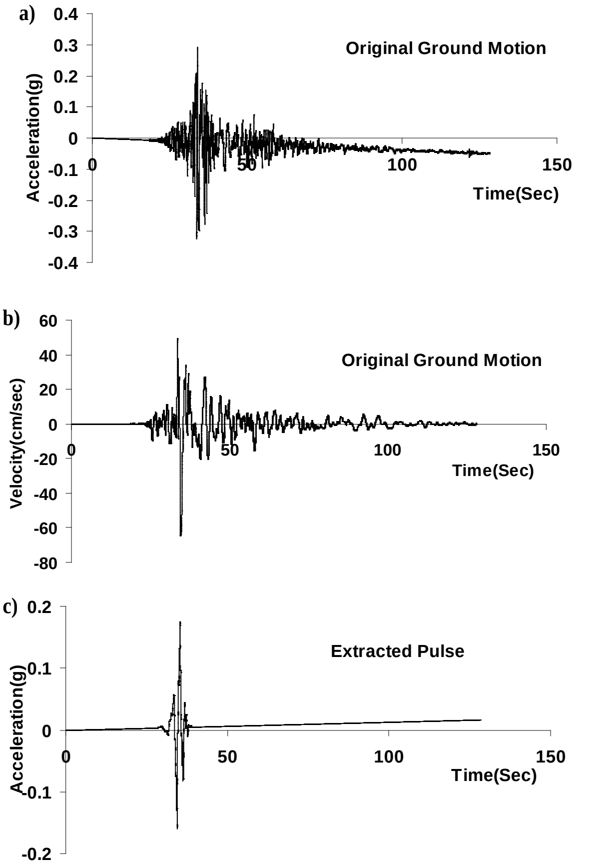
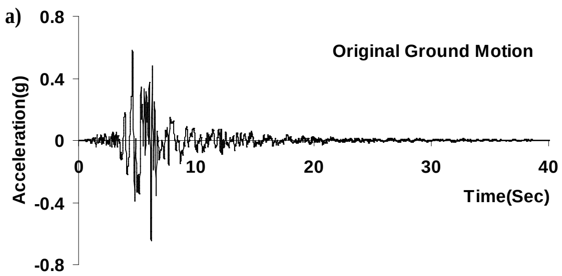


Figure 3. Acceleration, velocity and associated extracted pulse time history of Chi-Chi (1999) event recorded at CHY006 station

Based on pervious work of the author, the BiorSpline (bior1.3) basis from biorthogonal wavelet families has been adopted. Accordingly, the pulse period for ground motions of Northridge, 1994; Chi-Chi, 1999 and Kobe, 1995 events at selected stations has been summarized in Table 1. The biorthogonal wavelet function (bior1.3) is also illustrated schematically in Figure 5.



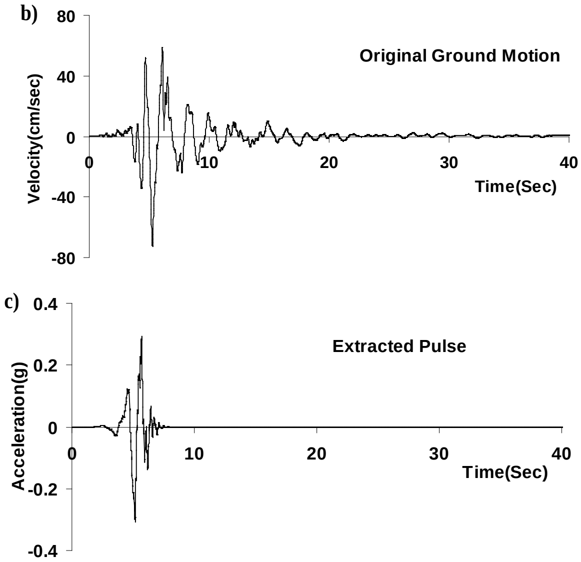


Figure 4. Acceleration, velocity and associated extracted pulse time history of Kobe (1995) event recorded at Takarazuka station

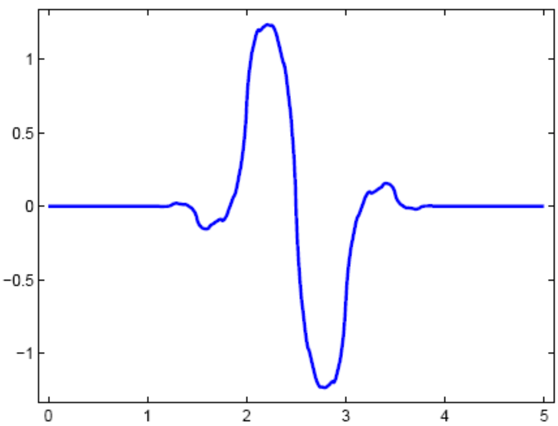


Figure 5. Schematic representation of biorthogonal wavelets bior 1.3

4. PULSE EFFECTS ON ACCELERATION AND DISPLACEMENT RESPONSE SPECTRA

4.1. Elastic Response Spectra The response spectrum as a straightforward tool in earthquake engineering is widely used for characterization of earthquake ground motion features on seismic design of structures. In design of a structure that has been located in near-fault zones, the effect of special nature of such motions (see section 1 for more detail) on elastic response spectra should be considered.

Application of continuous wavelet transform for extracting pulse portion of pulse-like ground motions could provide a suitable platform for quantifying of this effect that has not systematically included in the development of seismic design code. In this paper, great capability of continuous wavelet transform (CWT) is used to clearly identify sudden jumps in time history of earthquake records by considering contribution of different levels of frequency. Figures 6 to 8 illustrate elastic acceleration and displacement response spectra for three pulse-like motion (named as original) along with the spectra of motions while the pulses have been extracted and named residual motions herein. As an example, residual ground motion for Northridge, 1994, event in Rinaldi station has been shown in Figure 9.

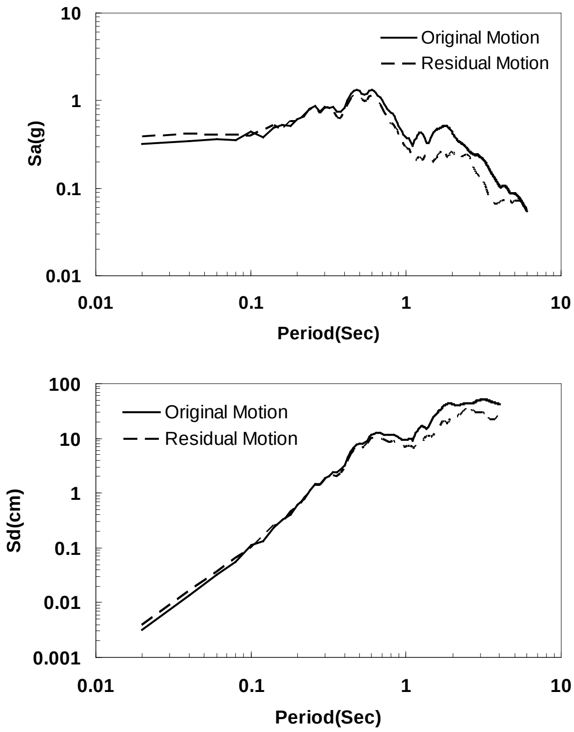


Figure 7. Acceleration and displacement response spectra of original and residual ground motion of Chi-Chi (1999) event recorded at CHY006 station

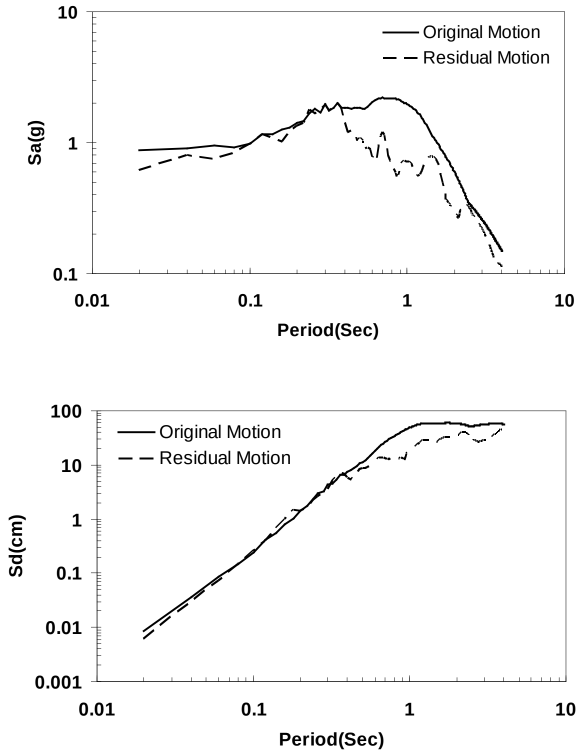


Figure 6. Acceleration and displacement response spectra of original and residual ground motion of Northridge (1994) event recorded at Rinaldi station

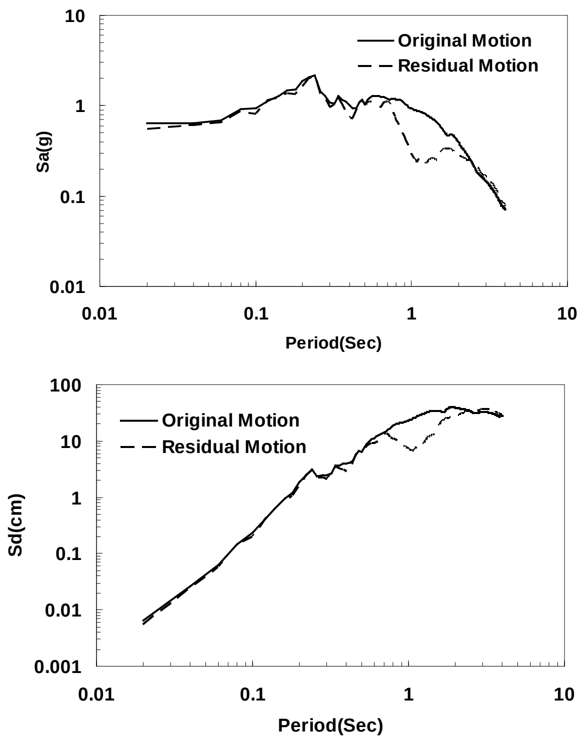


Figure 8. Acceleration and displacement response spectra of original and residual ground motion of Kobe (1995) event recorded at Takarazuka station

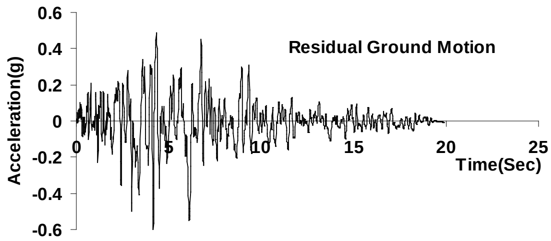
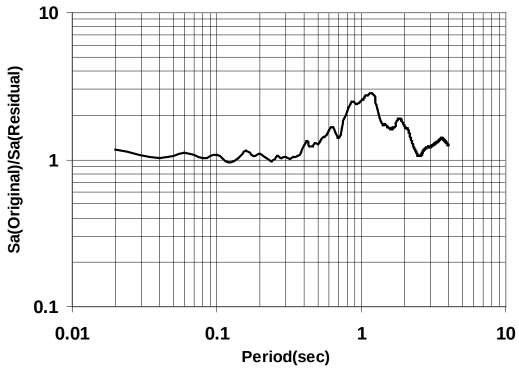


Figure 9. Residual ground motion for Northridge (1994) event in Rinaldi station

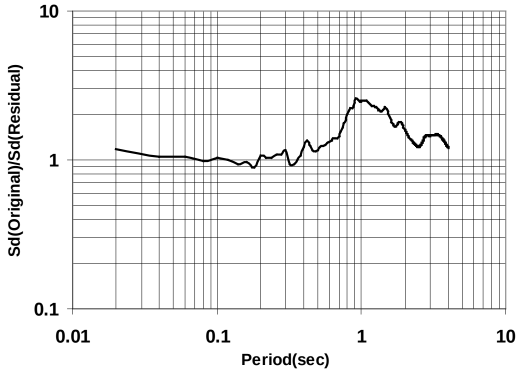
It is obvious that the pulses cause significant amplification of acceleration spectra, in the region of the pulse period (see Figures 6, 7 and 8). This parameter is known as a main characteristic in structural engineering, because the ratio of pulse period to fundamental period of structure (Tp/T) can effect on the structure response significantly [24].

As a final consideration, the average response including all of records has been considered in this section. For this purpose, the acceleration and displacement spectral ratio of observed to residual motions at each individual station, averaged over all stations, have been evaluated in Figure 10. It can be appreciated that, the pulse-like ground motions which induced normally by forward rupture directivity are able to amplify the spectral scaling differently in a wide range of periods from 0.6 to 2.3 second which should be considered in seismic design of structures.

4.2. Inelastic Response Spectra Following the developments of the last 15 years, performance-based earthquake engineering (PBEE) needs reliable approaches to estimate earthquake demands for the design, evaluation and rehabilitation of structures, to make sure that particular performance criteria are met and they are within satisfactory limits. It has been long recognized that structures should be capable of withstanding substantial inelastic displacement during strong ground motion which can be represented by means of inelastic acceleration and displacement spectra.



a)



b)

Figure 10. a) Acceleration b) displacement spectral ratio of observed to residual motions, averaged over 3 stations

The previous studies often address the comparative effects of near-fault vs. far-field ground motions. The contribution of pulse portion of motion on inelastic displacement of a system has not been systematically studied in the past. In this work, the influence of the pulse-like ground motions on inelastic acceleration and displacement spectra were investigate. These spectra for two sets of ground motions, original pulse-like motions and residual ground motions, corresponding to three ductility levels 2, 4, and 6 are computed and have been also presented in Figure 11 to13.

TABLE 1. Pulse-like ground motions used in this study

#	Event	Station	Mw	Epicentral Distance (km)	Soil Classification (NEHRP)	Tp (sec)
1	Northridge, 1994	Rinaldi Receiving	6.7	10.9	D	1.1
2	Chi-Chi, Taiwan, 1999	CHY006	7.6	40.5	D	4.4
3	Kobe, Japan, 1995	Takatori	6.9	13.1	D	1.7

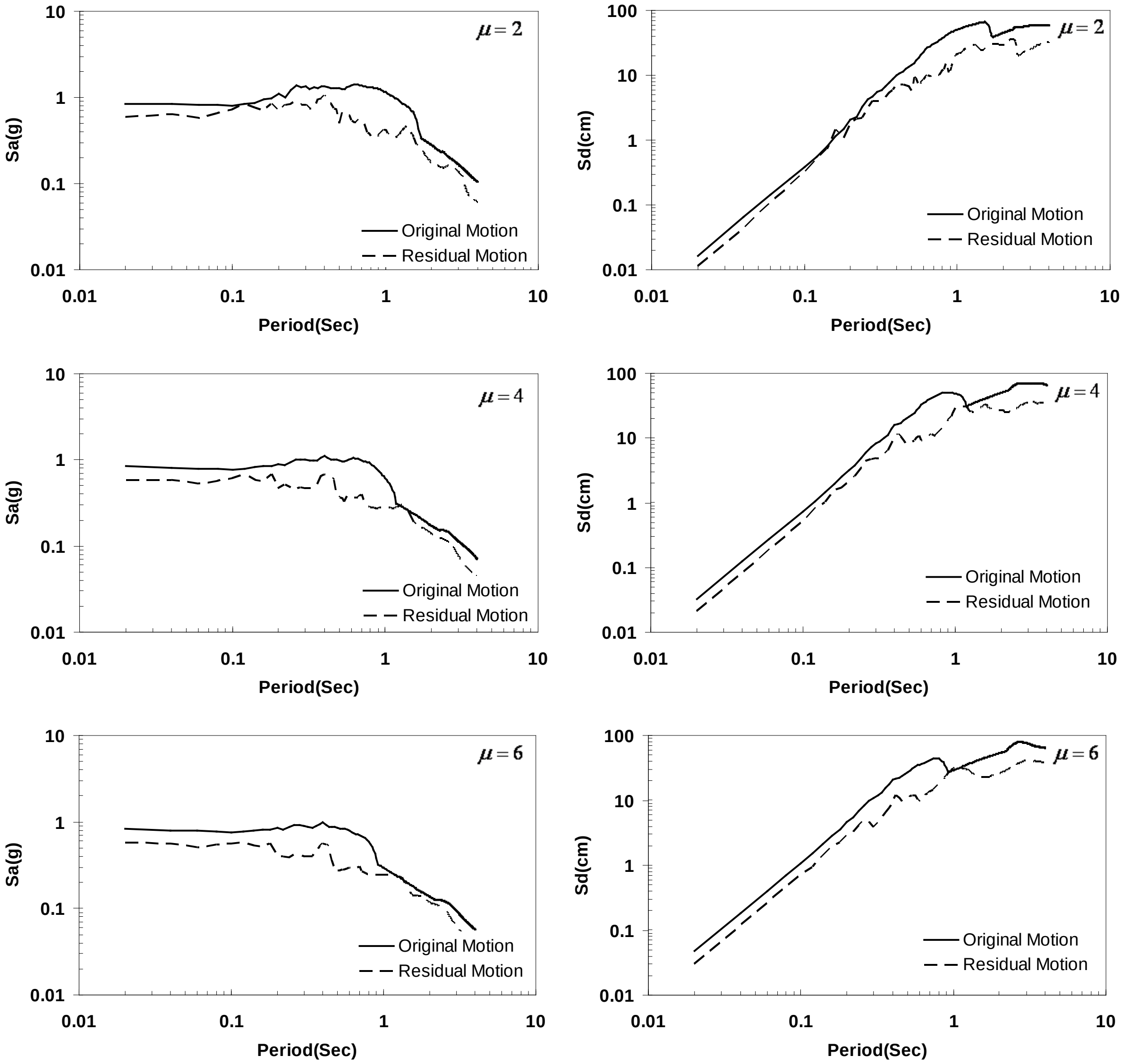


Figure 11. Inelastic response spectra of ground motion of Northridge (1994) event recorded at Rinaldi station

The provided spectra in this paper follow the similar method used for deriving an elastic response spectrum with the addition of an iterative approach which is needed to reach the desired ductility level. These spectra describing constant-ductility inelastic spectral ordinates and will provide a useful tool for estimating maximum inelastic demand of SDOF systems. Here, the force-displacement relationship of system is elastic-perfectly plastic. Damping ratio is assumed 5% of critical damping and inelastic ratios were computed for three different levels of ductility ($\mu = 2$, 4 and 6).

Important observation can be made from Figure 11 to 13 which highlight the need to more fully understand this effect on demand estimation. Figure 11 to 13 show that how the inelastic acceleration spectral values change as the ductility level grows. Based on these figures, the influence of pulse on inelastic acceleration response is decreased with increasing of ductility level. Unlike elastic cases; the main effect of pulses has not focused merely in the region of the pulse period. Also the effect of pulse portion of motions on acceleration response spectra is clearer than displacement response spectra with different ductility levels.

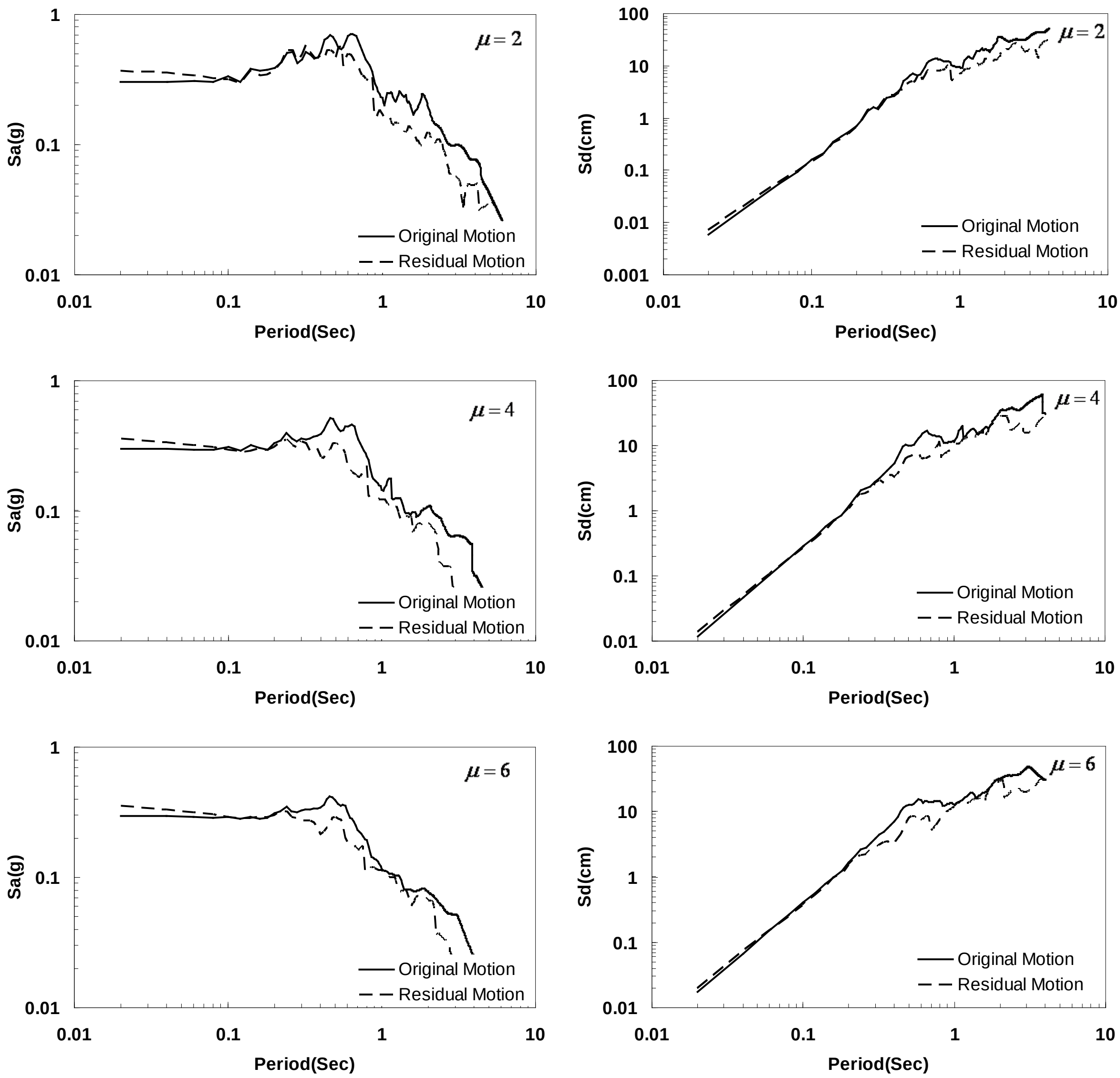


Figure 12. Inelastic response spectra of ground motion of Chi-Chi (1999) event recorded at CHY006 station

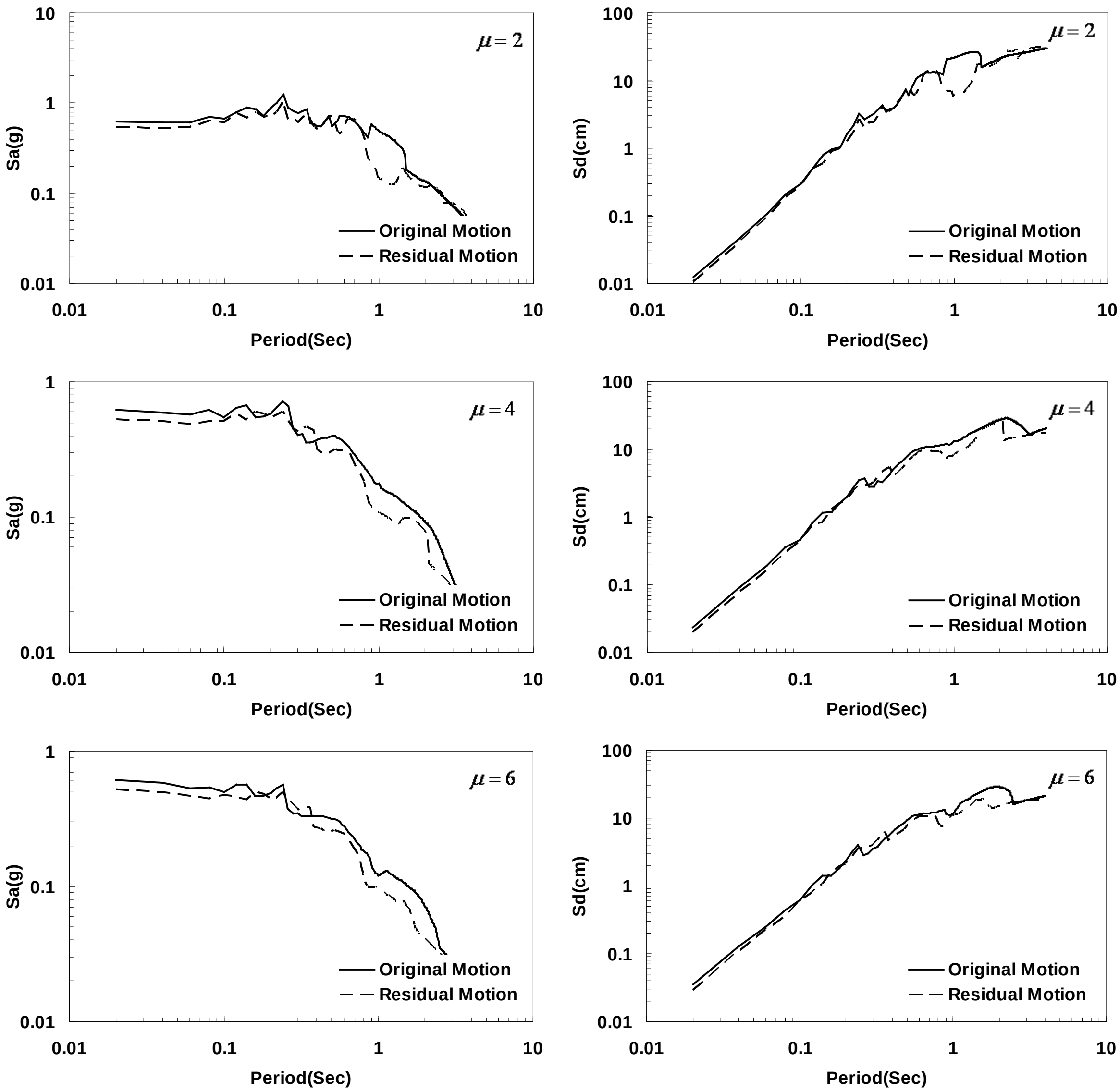


Figure 13. Inelastic response spectra of ground motion of Kobe (1995) event recorded at Takarazuka station

5. CONCLUSION

a) This study was aimed on studying the new application of continuous wavelet transforms as a powerful technique for identification of special feature of pulse-like ground motions on both elastic and inelastic acceleration; displacement spectra.

b) This work highlights some new important features of pulse-like ground motions for earthquake engineering in seismic performance evaluation of structures.

c) In the preferred procedure of this paper, continuous wavelet transform (CWT) as a quantitative approach is applied to extract strong near-fault velocity pulse of selected motions. The BiorSpline (bior1.3) basis from biorthognal wavelet families has been applied as a suitable mother wavelet. The period of velocity pulses as a key parameter was simply determined by pseudo-period of the mother wavelets.

d) The results of this study showed that pulses cause significant amplification of records acceleration spectra, in the region of the pulse period.

e) The results also reveal that how the inelastic acceleration spectral values changes as the ductility level grows. The experimental results depict that the influence of pulse on inelastic acceleration response is decreased with increasing of ductility level. Unlike of elastic cases, the main effect of pulses has not focused merely in the region of the pulse period.

f) The effect of pulse portion of motions on acceleration response spectra is clearer than displacement response spectra for different ductility levels.

g) It can be appreciated that, the pulse-like ground motions which induced normally by forward rupture directivity are able to amplify the spectral scaling differently in a wide range of periods from 0.6 to 2.3 second. It should be considered in seismic design of structures.

6. REFERENCES

1. yama, J., "Estimate of input energy for elastoplastic SDOF systems during earthquakes based on discrete wavelet coefficients", ***Earthquake Engineering & Structural Dynamics***, Vol. 34, No. 15, (2005), 1799–1815.
2. Iyama, J. and Kuwamura, H., "Application of wavelet to analysis and simulation of earthquake motions", ***Earthquake Engineering & Structural Dynamics***, Vol. 28, No. 3, (1999), 255–72
3. Xi-zhen, W., Yun-tian, T., Meng-tan, G. and Hui, J., "Seismic data compression based on integer wavelet transform", ***Acta Seismol Sin***, Vol. 17, (2004), 123–128.
4. Yan, G., Duan, Z., Oua, J. and Stefano, A., "Structural damage detection using residual forces based on wavelet transform", ***Mechanical Systems and Signal Processing***, Vol. 24, (2010), 24–239.
5. Zhou, Z. and Adeli,H., "Time-frequency signal analysis of earthquake records using Mexican Hat wavelets", ***Computer Aided Civil and Infrastructure Engineering,*** Vol. 18, No. 5, (2003), 379–389.
6. Cao, H.andFriswell,M.I.,"The effect of energy concentration of earthquake ground motions on the nonlinear response of RC structures", ***Soil Dynamic and Earthquake Engineering,*** Vol. 29, (2009), 292–299.
7. Simons, F.J., Dando,B.D. and Allen, R.M., "Automatic detection and rapid determination of earthquake magnitude by wavelet multiscale analysis of the primary arrival", ***Earth and Planetary Science Letters***, Vol. 250, (2006), 214–223.
8. Haigh, S.K., Teymur, B., Madabhushi, S.P.G. and Newland, D.E., "Applications of wavelet analysis to the investigation of the dynamic behavior of geotechnical structures", ***Soil Dynamics and Earthquake Engineering***, Vol. 22, No. 9, (2002), 995-1005.
9. Goggins, J., Broderick, B.M., Basu, B.Y. and Elghazouli, A.Y., "Investigation of the seismic response of braced frames using wavelet analysis", ***Structural Control and Health Monitoring***, Vol. 14, (2007), 627–648.
10. Salajegheh, E., Heidari, A. and Saryazdi, S. "Optimum design of structures against earthquake by a modified genetic algorithm using discret wavelet transform," ***International Journal for Numerical methods in Engineering***, Vol. 62, (2005), 2178-2192.
11. Somerville, P.G., Smith, N.F., Graves, R.W. and Abrahamson, N.A., "Modification of empirical strong ground motion attenuation relations to include the amplitude and duration effects of rupture directivity", ***Seismological Research Letters***, Vol. 68, No. 1,(1997), 199–222.
12. Akkar, S., Yazgan,U. and P. Gulkan, "Drift estimates in frame buildings subjected to near-fault ground motions", ***Journal of Structural Engineering***, Vol. 131, No.7, (2005), 1014–1024.
13. Luco, N. and Cornell, C.A., "Structure-specific scalar intensity measures for near-source and ordinary earthquake ground motions", ***Earthquake Spectra***, Vol. 23, No.2, (2007), 357–392.
14. Mavroeidis, G.P., Dong, G. and Papageorgiou, A.S., "Near fault ground motions, and the response of elastic and inelastic single degree of-freedom (SDOF) systems", ***Earthquake Engineering & Structural Dynamics***, Vol. 33, No.9, (2004), 1023–1049.
15. Yaghmaei-Sabegh, S. , "Stochastic finite fault modeling for the 16 September 1978 Tabas, Iran, earthquake", ***International Journal of Engineering, Transactions A: Basics,*** Vol. 24, No. 1, (2011), 15-24.
16. Yaghmaei-Sabegh, S. and Tsang, H.H., "An Updated Study on Near-Fault Ground Motions of 1978 Tabas, Iran, Earthquake (Mw=7.4)", ***Scientia Iranica***, ***Transaction A: Civil Engineering,*** Vol. 18, (2011), 895-905.
17. Baker, J.W., "Quantitative Classification of Near-Fault Ground Motions Using Wavelet Analysis", ***Bulletin of the Seismological Society of America***, Vol. 97, (2007), 1486-1501.
18. Yaghmaei-Sabegh, S., "Detection of pulse-like ground motions based on continues wavelet transform", ***Journal of seismology***, (2010), 14:715–726.
19. Charles, K.C, Wang, J., "On compactly supported spline wavelets and a duality principle", ***Transactions of the American Mathematical Society***, Vol. 330, No. 2, (1992), 903–915.
20. Chanerley, A.A., Alexander, N.A.,"Obtaining estimates of the low-frequency 'fling', instrument tilts and displacement time series using wavelet decomposition", ***Bulletin of Earthquake Engineering***, Vol. 8, No. 2, (2009), 231-255.
21. Ovanesova, A.V. and Suarez, L.E., "Application of wavelet transform to damage detection in frame structures", ***Engineering Structures***, Vol. 26, (2004), 39–49.
22. Newland, D.N., "An introduction to random vibrations, spectral and wavelet analysis", Harlow: Longman, (1997).
23. Walnut, D.F., "An Introduction to Wavelet Analysis",

2nd printing, Springer, (2003).
24. Alavi, B. and Krawinkler, H., “Effects of near-fault ground motions on frame structures”, ***Blume Center Reports***, Vol. 138, Stanford, California, (2001), 301.