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A METHOD FOR SIMPLIFICATION OF EARTHQUAKE ACCELEROGRAMS FOR RAPID TIME HISTORY ANALYSIS BASED ON TIME-FREQUENCY REPRESENTATIONS

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Abstract. *There are some cases, such as irregular or complex structures, in which the simplified analysis methods recommended by prevalent seismic codes are not able to yield results with acceptable precision. In such circumstances, the use of nonlinear time-history analysis (NLTHA) as the most realistic response analysis approach is mandatory. The NLTHA procedure is usually very time-consuming (due to the small size of time steps in, especially, digitized accelerograms and subsequently, large number of required time steps in the analysis algorithm). So, new methods which can reduce the computational cost, while keeping results in an acceptable range, would be desired for NLTHA users.*

There are some proposed methods in the literature to increase the size of time step and simplify the recorded accelerograms using modifications on Fourier analysis of time series. Although these methods show negligible bias in results in terms of maximum response values of simple structures, they impose some error due to the omission of some relatively high frequency components of the original signal. In other words, the Fourier based method acts as a low-pass filter the cutoff frequency of which is dependent to the target increased time step.

In this paper, first, the examples showing the importance of discussed errors are presented. Then, a new simplification procedure is introduced to overcome the drawback of previous ones. In the present study, knowing the intrinsic inability of Fourier Transform in capturing the time variation of frequency content of signals, the main goal is to apply some new time-frequency representations (TFRs), such as Short Time Fourier Transform (STFT)or wavelet transform (WT), and modify the general Fourier based simplification algorithm. The proposed method enables users to trace and compare the time-frequency variation of original and simplified signal to keep the global time-frequency pattern of signal and prevent the unwanted omissions of components. The results of analyses for a range of simple structures confirm the ability of simplified records to represent the original ones in term of response characteristics.

1 INTRODUCTION

1.1 Time-frequency representations:

Earthquake ground motions are known to have non-stationery nature, both in their amplitude and frequency content [1]. The problem of inability of conventional spectral analysis using Fourier transform to describe the evolutionary spectral characteristics of non-stationary processes can be solved by using time-frequency spectral analysis [2]. One of the first Time-Frequency representations (TFRs) providing required localization in time and frequency to establish a local spectrum for any time instant, is short time Fourier transform (STFT) [2]. Readers are referred to [4] for more details.

Shortcomings of STFT can be tackled using multiresolutional techniques based on wavelet transform. The Wavelet Transform (WT) uses a basis function that dilates and contracts with frequency. Namely, the time-frequency window can change automatically to analyze the high-frequency contents of a signal as well as low-frequency components that offers better resolution.

Stockwell *et al*. [5] have proposed a time-frequency representation called ‘S-Transform’, which can be considered as the extension of STFT and WT. Hence, we can describe the S-Transform as a frequency dependent STFT or a phase corrected Wavelet transform [3](See equation 1).

$$ST\left(f,\tau \right)=\int_{-\infty}^{\infty} x(t)g(t-\tau)e^{-i2\pi ft}dt \quad (1)$$

In the above equation, *f* denotes frequency, g is the Gaussian window and τ controls the center of gussian window in time domain. Recently, a band variable filter having the ability of acting simultaneously in frequency and time domain has been applied to the analysis of nonlinear dynamic behavior of soil and buildings [6, 7]. Also, Ghodrati Amiri and Arian Moghaddam have proposed an S-Transform-based signal decomposition technique to extract velocity pulses of near fault ground motions [3].

S-Transform based filtering of time series [8] and generation of synthetic accelerograms have been examined by some researchers [9, 10]. In this paper, we are using the suggested filtering approach in [6] to monitor the time frequency variation of input signal and extract the target part (also called shortened or filtered signal here).

1.2 Simplification of accelerograms:

In seismic evaluation and design of structure, there are several cases in which the simplified seismic analysis procedures suggested by design code, are not applicable. In these cases such as irregular buildings, tall buildings and many special structures or critical facilities, most seismic codes recommend time history analysis (THA). THA can be very time-consuming, especially, when user needs to estimate collapse capacity of target structure and NLTHA becomes necessary. Although the idea of accelerogram simplification is not uncommon in earthquake engineering [11], recently and coincidentally with increase in application of THA, some researchers have tried to develop efficient methods to overcome limitations of simplification. The main goal of these researches focuses on decrease of computational time without losing much precision. One approach suggests application of larger time steps using different algorithms proposed by some researchers like Soroushian[12], Hosseini & Mirzaei[13] and Faroughi & Hosseini[14]. Main shortcoming of these methods is related to the disturbance in frequency content of original signal. Another available method is to define significant duration of ground motion and shorten the accelerogram such that the criteria controlling response parameters are satisfied. The superiority of last method is due to the preservation of original components of accelerogram. In other words, any part of accelerogram cannot be omitted qualitatively. Figure 1 compares time-frequency content of an artificial accelerogram (as the representative of rich frequency content) before and after changing time step size from 0.01s to 0.05 s. The highlighted zones, the most of which are located in high frequency part, are affected by the procedure.

The chief goal of our work is to propose a simplified accelerogram and subsequently reduce the computational cost of NLTHA, while the disorderliness in the time variation of frequency content is minimized. So, we are going to simplify the input signal by reduction of duration and simultaneously keep the response characteristic in an acceptable tolerance. Auteurs, after rather wide search, have selected the S-Transform as the TFR used in filtering procedure. There is sufficient scientific evidence confirming the superiority of S-Transform compared to other alternatives [3]. The general steps of method are:

- Calculate the TFR of accelerogram by S-Transform.
- Find the most sever (showing larger amplitude based on equation 1) region in time and frequency domains.
- Define a quantitative (based on normalized ratio of amplitude, for example) or qualitative (by visual judgment) criterion to select the target parts of original signal and extract the wanted portion.
- Combine extracted signals to reconstruct a shortened (filtered) signal in TF domain.
- Compute the inverse transform of filtered signal from last step to yield the output in time domain.

Figure 2 shows time frequency variation of acceleration time history of R1 (Table 1 presents characteristics of ground motion recording used in this paper).

It is worth mentioning that it is possible to use a predefined intensity measure (IM) to check the precision of the method and repeat the whole steps so as to satisfy threshold criteria. Also, it should be noted that although there are many definitions of strong motion duration in the literature, almost none of them allow a drastic reduction of duration as what we are proposing. To have a legible comparison between response characteristics of input and output signals, readers should keep in mind that the filtered signal consists of some real components of original signal which are not scaled (See Table 2). In coming sections, a brief discussion about scaling is presented. Furthermore, it is possible to combine other simplification methods, such as increased time step size, with current duration reduction method, while it is not in the scope of present study.

2 NUMERICAL EXAMPLE

In this section, to evaluate the effectiveness of proposed method, response history and spectra of original and shortened accelerogram are calculated. For this purpose, elastic and inelastic displacement, velocity and acceleration response spectra for a 5% damping SDOF and displacement response history for both the original and filtered signals of Imperial Valley, event is compared. Inelastic analyses are carried out using "Constant-ductility" method (the value of ductility is $\mu=4$), while readers can find other simplified proposals in the literature [15, 16]. It should be noted that the peak values of shortened accelerogram (as the output of proposed procedure) differ from those of input ground motion.

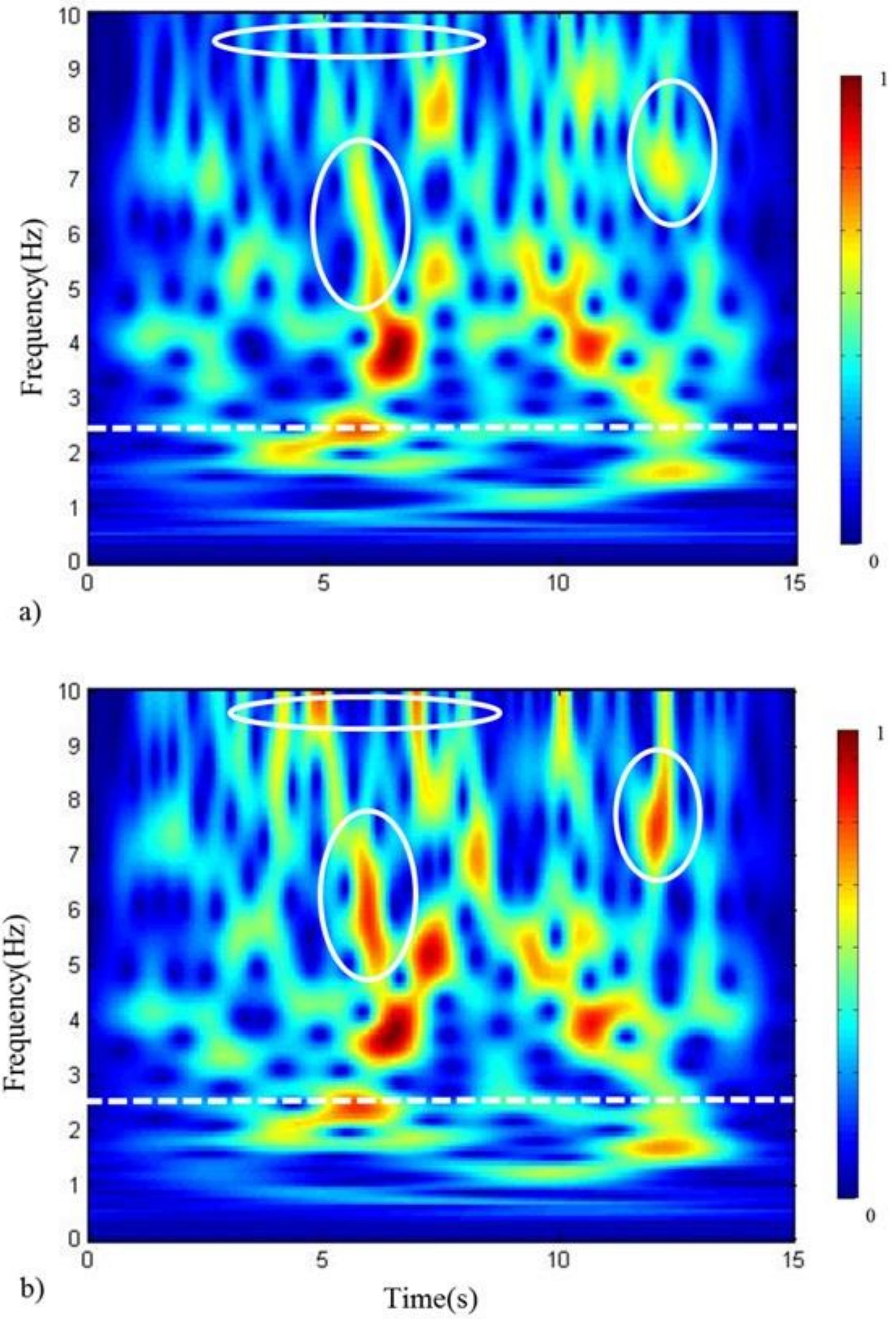

Figure 1: Time-frequency content of an artificial signal, before (a) and after (b) changing time step size from 0.01 to 0.05 s.

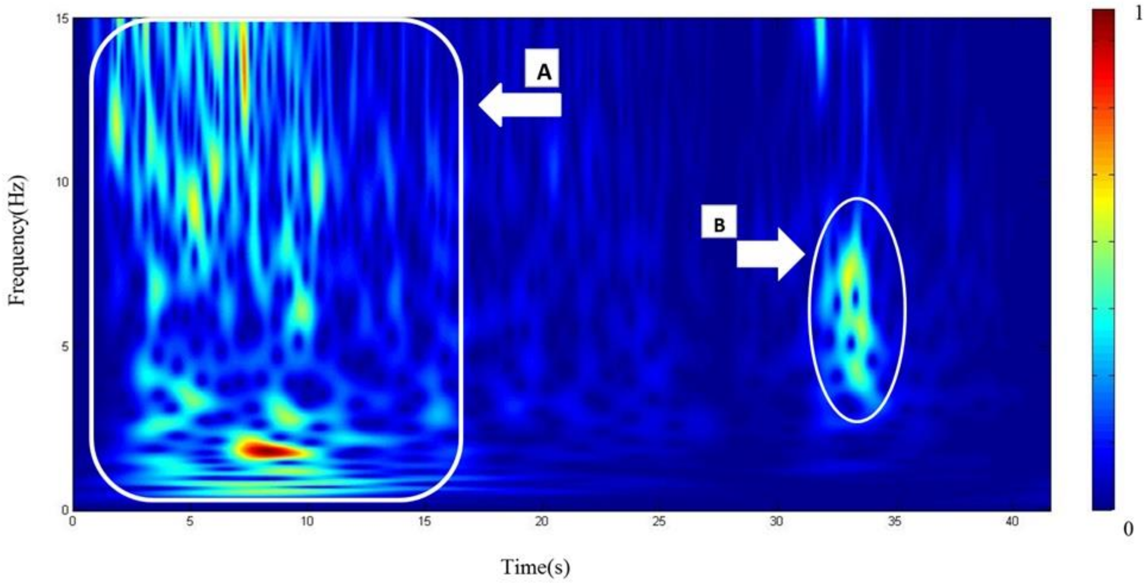

Figure 2: Time-frequency variation of recording 1, selected part (A) and portion chosen to be omitted (B).

event	label	Year	M_w	PGA(g)	PGV (cm/s)	PGV/PGA (sec)	recorded duration (sec)	AI* (m/s)	CAV** (cm/s)
Imperial Valley	R1	1979	6.5	0.311	53.79	0.176	40.8	1.57	1140

* Arias Intensity[17]
** Cumulative Absolute Velocity[17]

Table 1. General features of recording used in this study

Table 1 presents general features of recording used in current study. Figures 3 to 5 illustrate displacement, velocity and acceleration elastic response spectra of shortened and original accelerogram of Imperial Valley (R1, RF1), respectively. It is obvious that there is a rather good match between spectral coordination of two accelerogram.

label	PGA(g)	PGV(cm/s)	PGV/PGA(sec)	Duration(sec)	AI(m/s)	CAV(cm/s)
RF1	0.266	48.5	0.186	16	0.894	666

Table 2. General features of shortend recordings

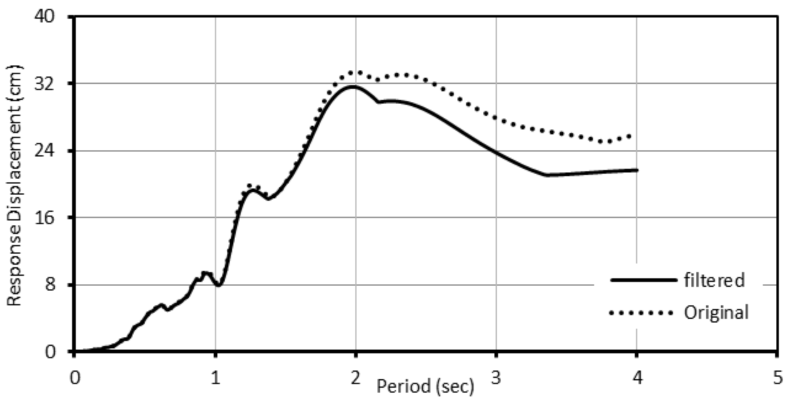

Figure 3: Displacement elastic response specrtum

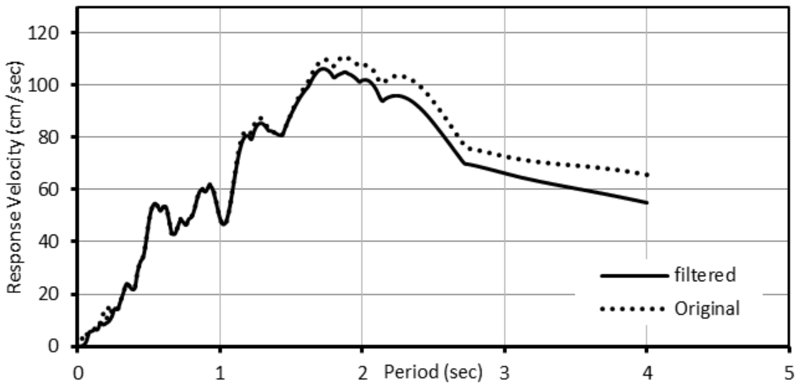

Figure 4: Velocity elastic response specrtum

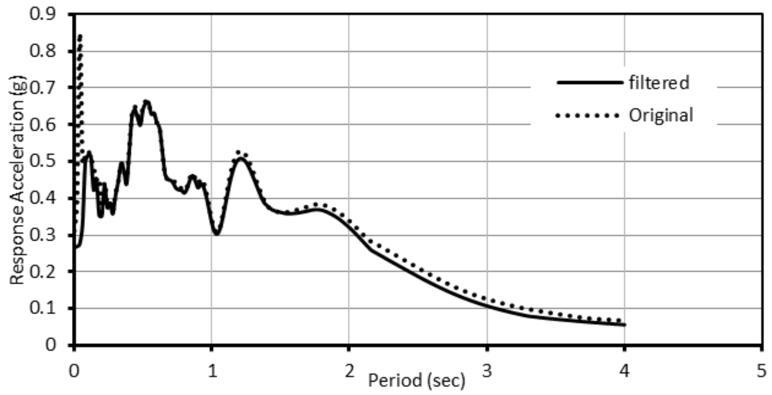

Figure 5: Acceleration elastic response specrtum

Inelastic response spectra of original and filtered earthquake are shown in figures 6 to 8. Focusing on inelastic results, it is concluded that shortened signal can be an acceptable alternative for original accelerogram (as it is expected from elastic results).

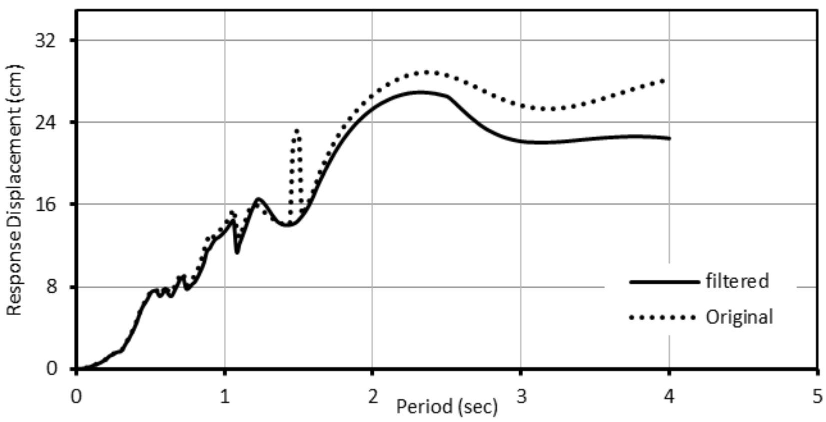

Figure 6: Displacement inelastic response specrtum

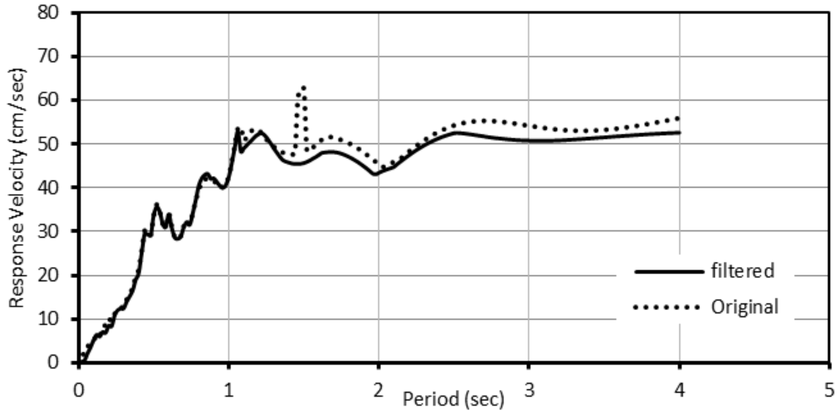

Figure 7: Velocity inelastic response specrtum

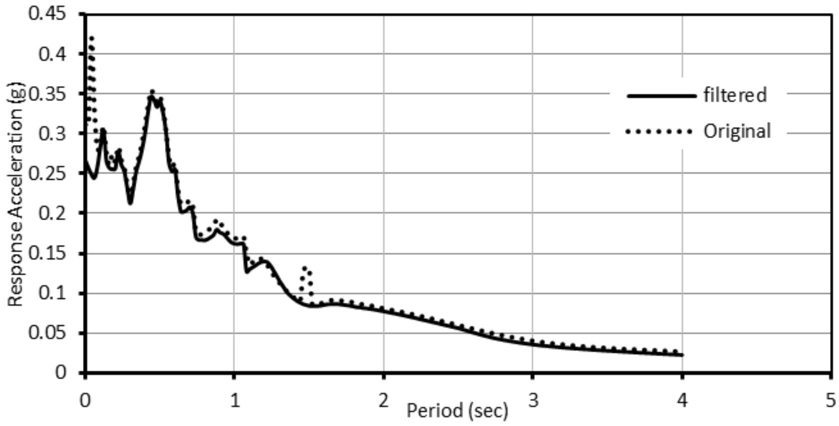

Figure 8: Acceleration inelastic response specrtum

To evaluate result in more details, displacement response histories for 5% damping SDOF system having fundamental period of 1sec, are presented in figures 9 and 10.

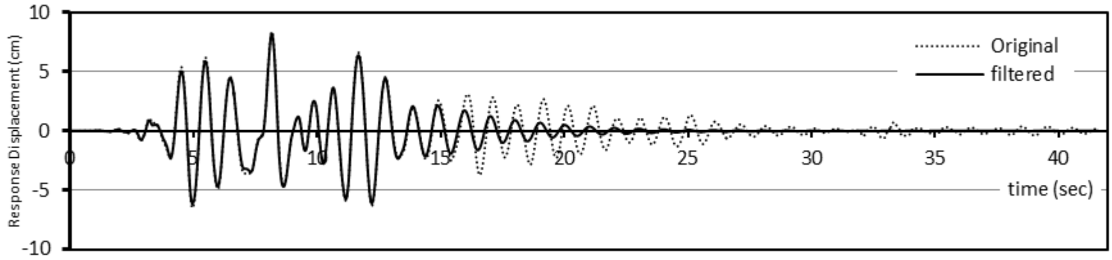

Figure 9: elastic response T=1.0 s

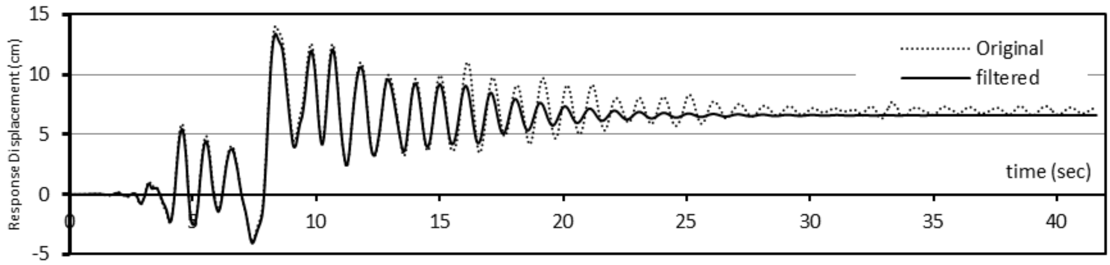

Figure 10: inelastic response T=1.0 s

3 CONCLUSION

Detailed results of applying proposed method in section 1 have been presented in pervious section. Here, we are going to evaluate the effectiveness of shortened time histories in representing original accelerogram in term of response characteristics.

- Elastic response spectra of SDOF systems:

  As it is clear in figure 2 to 4, elastic response spectra computed for filtered time histories of Imperial Valley event can represent those of original accelerogram adequately. It should be emphasized that the filtered signal is not scaled to any predetermined value. In other words, the peak ground values of filtered accelerogram differ from those of original one.

- Elastic & Inelastic response histories:

  Referring to figure 8, one can simply conclude that filtered signals are acceptable representatives of their original counterparts in term of peak response values (it is expected from spectral results) and the overall pattern in time domain. But the effectiveness of method is highly dependent to the natural period of SDOF system.

  Nonlinear displacement history of SDOF system with natural period of 1sec is presented in figure 9. The general structure of nonlinear behavior is similar to linear one, although, the period elongation as a result of nonlinear effects magnifies differences in response of SDOFs having longer natural periods. It should be stated that the appropriate scaling may alleviate the problem.

REFERENCES

[1] S. Mukherjee and V. K. Gupta, "Wavelet-based characterization of design ground motions," *Earthquake Engineering & Structural Dynamics*, vol. 31, pp. 1173–1190, 2002.

[2] K. Gurley and A. Kareem, "Applications of wavelet transforms in earthquake, wind and ocean engineering," *Engineering Structures*, vol. 21, pp. 149–167, 1999.

[3] G. Ghodrati Amiri and S. Arian moghaddam, "Extraction of forward-directivity velocity pulses using S-Transform-based signal decomposition technique", *Bulletin of the Earthquake Engineering, article in press,* 2013.

[4] L. Cohen, *Time-frequency analysis: theory and applications*. Upper Saddle River, New Jersey: Prentice-Hall, 1995.

[5] R. G. Stockwell, *et al.*, "Localisation of the complex spectrum: the S transform," *IEEE Trans. Signal Processing*, vol. 44, pp. 998-1001, 1996.

[6] R. Ditommaso, *et al.*, "S-Transform based filter applied to the analysis of nonlinear dynamic behaviour of soil and buildings," presented at the 14th European conference on earthquake engineering, Ohrid, Republic of Macedonia, 2010.

[7] R. Puglia, *et al.*, "Frequency variation in site response as observed from strong motion data of the L'Aquila (2009) seismic sequence," *Bulletin of Earthquake Engineering,* vol. 9, pp. 869-892, 2011.

[8] S. Parolai, "Denoising of Seismograms Using the S Transform," *Bulletin of the Seismological Society of America,* vol. 99, pp. 226-234, 2009.

[9] J. Fan and P. Dong, "Simulation of artificial near-fault ground motions based on the S-transform " presented at the Congress on Image and Signal Processing, 2008.

[10] G. GhodratiAmiri and S. Arian moghaddam, "New method for generation of synthetic near-fault earthquake records based on S-Transform," presented at the 15wcee, Lisbon, 2012.

[11] W. Wang, "Structural instability during earthquakes and acceleration simplification," Ph.D, Michigan University, Ann Arbor, USA, 1975.

[12] A. Soroushian, "A technique for time integration analysis with steps larger than the excitation steps," *Communications in Numerical Methods in Engineering,* vol. 24, pp. 2087-2111, 2008.

[13] M. Hosseini and I. Mirzaei, "Simplification of earthquake accelerograms for rapid time history analysis based on the impulsive load concept."

[14] A. Faroughi and M. Hosseini, "Simplification of Earthquake Accelerograms for Quick Time History Analyses by using Their Modified Inverse Fourier Transforms," *Procedia Engineering,* vol. 14, pp. 2872-2877, 2011.

[15] A. K. Chopra, *Dynamics of structures: Theory and applications to earthquake engineering* vol. 2: Prentice Hall Saddle River^ eNY NY, 2001.

[16] R. W. Clough and J. Penzien, *Dynamics of structures* vol. 634: McGraw-Hill New York, 1993.

[17] Elnashai, Amr, and Luigi Di Sarno. *Fundamentals of earthquake engineering*. Wiley, 2008.