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STOCHASTIC GENERATION OF ARTIFICIAL ACCELEROGRAMS USING THE CONTINUOUS WAVELET TRANSFORM METHOD

Hera Yanni[1], **Michalis Fragiadakis**[1], **and Ioannis P. Mitseas**[1,2]

[1]National Technical University of Athens, Athens, Greece
Iroon Politechniou 9, 15780, Athens, Greece
e-mail: heragian@mail.ntua.gr; mfrag@mail.ntua.gr; Imitseas@mail.ntua.gr

[2] University of Leeds, Leeds, United Kingdom
LS2 9JT, Leeds, UK
e-mail: I.Mitseas@leeds.ac.uk

Abstract. *A new stochastic methodology for the generation of artificial, fully non-stationary, spectrum-compatible accelerograms is proposed. Time-history analysis requires the use of suites of accelerograms that can be either recorded, or artificially generated. Hazard consistency can be achieved if their mean spectrum is matched to a target design spectrum. Artificial earthquake ground motions can be easily generated at frequency bands of interest and have features compatible with desired target characteristics. The proposed model operates in the time-frequency (TF) domain using the continuous wavelet transform (CWT). The methodology follows the rationale of the techniques that use an evolutionary power spectral density function, where the temporal and spectral non-stationarity is modeled by a TF envelope function. More specifically, a zero mean stationary Gaussian stochastic process is generated using the spectral representation method and defines: the target peak ground acceleration, the frequency range, and the phase distribution. Additionally, it ensures the spectrum compatibility through the power spec-tral density function. A recorded accelerogram is consistent with the characteristics of the site of interest and models the temporal and spectral modulation. Both generated and recorded signals are analyzed in the TF domain using the CWT and their wavelet coefficients are obtained respectively. The time-frequency envelope is then extracted from the modulus of the CWT coefficients of the recorded accelerogram and modifies accordingly the stationary stochastic pro-cess in the TF domain. Energy compatibility is also imposed at each frequency, and new wavelet coefficients are produced. The simulated signal is then transformed in the time domain using the inverse CWT. The proposed methodology provides an arbitrary number of seismic accelerograms whose temporal and spectral modulation is modeled by a recorded ground motion.*

Keywords: artificial accelerogram, stochastic model, temporal and spectral non-stationarity, continuous wavelet transform, wavelets, spectrum-compatible.

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1 INTRODUCTION

The most realistic method for the assessment of the seismic response of structures is the time-history analysis. A critical stage in the process of performing this analysis is the definition of appropriate suites of acceleration time histories that represent the input ground motion. These accelerograms can be either recorded, or artificially generated. In both cases, the seismic motions must be compatible with a target design spectrum. Furthermore, they should exhibit frequency and energy characteristics that are consistent with the site of interest.

In this framework, engineers typically choose to select appropriate recorded ground motions from databases. Different approaches for selecting records without biasing the response estimates have been proposed in the literature (e.g. [1]). Historical accelerograms, however, correspond to different hazard scenarios and soil conditions as they are obtained from different sites from the site of interest. Furthermore, the lack of recorded ground motions of earthquakes with large magnitudes at small epicentral distances confines the analysis of large limit states, like the collapse limit state. To overcome these limitations, simulated artificial accelerograms are finding increased use.

Artificial earthquake ground motions can be easily generated at frequency bands of interest and have features that match desired target characteristics. Moreover, seismic codes (e.g. Eurocode 8 -EC8- [2]) establish the use of artificial or synthetic ground motions, without proposing any specific method for their simulation. Due to the random nature of seismic actions, artificial ground motion time-histories can be generated as stochastic processes. Various methods have been proposed in the literature, like methods that depend on seismological parameters (e.g. [3]), and methods that model the ground motion for a specific site by using a target recorded accelerogram, or a target spectrum (spectrum-compatible).

The latter stochastic models are more simple, thus they are the most adopted in practice. The most popular of these approaches is the spectral representation method (SRM) proposed by Shinozuka and Deodatis [4]. In this case, the ground motion time-histories are simulated mathematically as a superposition of harmonic components with random phase angles, directly related to the power spectral density (PSD) function of the process. Moreover, the relationship between the values of the PSD function and the response spectral values for a given spectral damping ratio is the basis for the generation of target spectrum compatible accelerograms [5].

The seismic time-histories simulated using the PSD function can be stationary, quasi-stationary and fully non-stationary. Natural earthquake ground motions inherently exhibit both temporal and spectral non-stationarity or in other words, they are fully non-stationary. Thus, several approaches have been proposed in order to generate fully non-stationary accelerograms using the SRM. The most popular is the use of an evolutionary power spectral density (EPSD) function, i.e. a PSD function that varies in time [6]. This may be achieved by introducing a time-frequency (TF) envelope function that modifies a stationary accelerogram both in time and in frequency in order to simulate the characteristic behavior of natural accelerograms (e.g. [7]). Another approach is the one proposed by Cacciola [8], where fully non-stationary accelerograms are produced as the superposition of a fully non-stationary counter-part modeled by a real accelerogram and a stationary process modeled with the SRM.

More recent methodologies for the generation of artificial accelerograms are based on signal processing operations (e.g. [9], [10]). This is due to their ability to analyze and synthesize the signals simultaneously in both time and frequency, thus allowing to directly model the accelerograms' evolutionary frequency content (i.e. non-stationary characteristics). The wavelet transform is a tool that allows to obtain a joint-time frequency representation of non-stationary signals. More specifically, it employs localised wave-like functions (wavelets) instead of continual harmonics as a base to decompose a signal. Different wavelet-based approaches have been proposed in the literature for generating artificial non-stationary accelerograms (e.g. [11], [12], [13]).

In this paper the first steps for a new stochastic methodology for the generation of artificial, fully non-stationa-ry, spectrum-compatible accelerograms are presented. The proposed approach uses the CWT method in order to operate in the TF domain. More specifically, the SRM is combined with the CWT in order to simulate accelerograms that are consistent with both the temporal and the frequency characteristics of seismic ground motions from the site of interest. The methodology follows the rationale of the techniques that use an EPSD function, where the temporal and spectral non-stationarity is modeled by a TF envelope function. Additionaly, a new approach is proposed for the modeling of the envelope function, based on the site's historical records. That is, a recorded accelerogram is analyzed in the TF domain using the CWT, and the TF envelope is extracted from the modulus. Therefore, the proposed methodology provides an arbitrary number of seismic accelerograms whose temporal and spectral modulation is modeled by a recorded ground motion.

2 PRELIMINARY CONCEPTS

2.1 The Continuous Wavelet Transform (CWT)

The Continuous Wavelet Transform (CWT) method is based on a set of basis functions (wavelet family) formed by dilation and translation of a prototype mother function (wavelet) $\psi(t)$ and is used to decompose a function (signal) $u(t)$ into the time-frequency domain. Definitions in the literature vary slightly and depend on the choice of normalization of the wavelets. In this study, the $L^2(\mathbb{R})$ normalization was employed [14].

Let $\psi(t)$ be a window function that fulfills the admissibility conditions. This function is called the mother (analyzing) wavelet, and the corresponding family of wavelets is the group of shifted and scaled (dilated) copies of ψ defined as:

$$\psi_{b,a}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \quad , \quad t \in \mathbb{R} \tag{1}$$

where $a > 0$ is a scaling parameter that defines the dilation of the mother wavelet $\psi(t)$ and b is the translation parameter related to time. Scale factor $a > 1$ corresponds to dilation and $0 < a < 1$ corresponds to compression. The mother wavelet is the member of the family where $b = 0$ and $a = 1$, and it can be either real or complex. The choice of the mother wavelet is dictated by the characteristics of the signal and the application. A complex wavelet function will return information about both amplitude and phase and is better adapted for capturing oscillatory behavior.

Let $u(t)$ be a signal that is of finite energy and a piece-wise continuous function of t. Given a mother wavelet $\psi(t)$, the continuous wavelet transform of this signal is given by the integral:

$$T_\psi[u](b,a) = \frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty} u(t)\overline{\psi}\left(\frac{t-b}{a}\right) dt \tag{2}$$

where $a > 0$ is a scaling parameter that defines the dilation of the mother wavelet $\psi(t)$ and b is the translation parameter related to time. The symbol $\overline{\psi}$ denotes the complex conjugate. As it is observed by Eq.2, CWT transforms a one-dimensional (time domain) signal $u(t)$ to a two-dimensional representation: the time-scale plane. When the admissibility condition is fulfilled, the original signal $u(t)$ can be reconstructed as:

$$u(t) = \frac{1}{C_\psi} \int_{-\infty}^{+\infty} \int_{0}^{+\infty} T_\psi[u](b,a)\psi\left(\frac{t-b}{a}\right)\frac{da}{a^2}db \tag{3}$$

where C_ψ is a finite constant given by the integral:

$$0 < C_\psi = \int_{-\infty}^{+\infty} \frac{|\widehat{\psi}(\omega)|^2}{|\omega|} d\omega < +\infty \tag{4}$$

As shown in the previous, the CWT is defined with scales. Scales are directly linked with frequencies: a scale a corresponds to a scaled version of the mother wavelet with center frequency ω_ψ/a, thus bringing the CWT on the time-frequency plane. Therefore, in the rest of the paper, the CWT will be used in terms of time and angular frequency, $T_\psi[u](\omega, b)$.

2.2 Generation of stationary, spectrum compatible artificial accelerograms

Stationary and target spectrum-compatible accelerograms are simulated following the spectral representation method (SRM) proposed by Shinozuka and Deodatis [4]. The signal is modeled as a zero mean stationary Gaussian stochastic process $a_s(t)$ of finite duration T_s and is generated as the superposition of harmonic functions with random phase angles:

$$a_s(t) = \sum_{i=1}^{N} \sqrt{2G_s(\omega_i)\Delta\omega}\cos(\omega_i t + \theta_i) \tag{5}$$

where N is the number of harmonics to be superimposed, ω_i is the angular frequency of the i^{th} harmonic, $\Delta\omega$ is the constant integration step, and θ_i are random phase angles uniformly distributed over the interval $[0, 2\pi]$. Furthermore, the amplitude of each component is related to the one-sided PSD function $G_s(\omega_i)$ of the stochastic process. Compatibility with a target spectrum is achieved by the evaluation of $G_s(\omega_i)$ based on the random vibration analysis approach proposed by Cacciola et al. [15]:

$$G_s(\omega_i) = \begin{cases} \dfrac{4\zeta}{\omega_i\pi - 4\zeta\omega_{i-1}}\left(\dfrac{{S_a}^2(\omega_i,\zeta)}{\eta^2_{X_i}} - \Delta\omega\displaystyle\sum_{k=1}^{i-1} G_s(\omega_k)\right), & \omega_i > \omega_0 \\ 0, & \omega_i \leq \omega_0 \end{cases} \tag{6}$$

where $S_a(\omega_i, \zeta)$ is the target spectral acceleration at frequency ω_i, ζ is the target spectrum's damping ratio, and η_{X_i} is the peak factor. According to the hypothesis of a barrier outcrossing in clumps [16], the peak factor is evaluated as:

$$\eta_{X_i}(T_s, p) = \sqrt{2\ln\left\{2N_{X_i}\left[1 - \exp\left(-\delta_{X_i}^{1.2}\sqrt{\pi\ln(2N_{X_i})}\right)\right]\right\}} \tag{7}$$

where N_{X_i} is the mean zero crossing rate and δ_{X_i} is the spread factor of the stochastic response process $X_i(t)$, evaluated approximately with reference to a white-noise input [15] as:

$$N_{X_i} = \frac{T_s}{2\pi}\omega_i(-\ln p)^{-1} \tag{8a}$$

$$\delta_{X_i} = \sqrt{1 - \frac{1}{1-\zeta^2}\left(1 - \frac{2}{\pi}\arctan\frac{\zeta}{\sqrt{1-\zeta^2}}\right)^2} \tag{8b}$$

The range of ω_i is defined in the interval $[\omega_0, \omega_u]$, where ω_u is an upper cut-off frequency beyond which the PSD function $G_s(\omega_i)$ is assumed to be zero for either mathematical or physical reasons and ω_0 is the lowest frequency bound of the existence domain of Eq.7. For Eq.8 in particular, $\omega_0 = 0.36$ rad/s. It should be noted that, for $i = 1$, $G_s(\omega_1) = 0$. The accelerograms generated combining Eqs.5 and 6 have all the same duration T_s and are stationary, i.e. amplitude and PSD function are not a function of time.

3 THE PROPOSED METHODOLOGY

The proposed methodology generates artificial, fully non-stationary, and spectrum-compatible accelerograms. Furthermore, the model produces accelerograms that reflect the temporal and frequency characteristics of seismic ground motions from the site of interest by combining spectral representation techniques with signal processing operations. The proposed model employs the CWT in order to operate in the time-frequency (TF) domain.

First, the desired target spectrum and frequency range $[\omega_0, \omega_u]$ are defined. The temporal and spectral modulation (i.e. the non-stationarity) is modeled by a TF envelope function that is extracted from a historical ground motion. Therefore, a recorded accelerogram from the site of interest is selected and analyzed in the time-frequency domain using the CWT. The TF envelope function is then obtained from the normalized modulus of the obtained CWT coefficients, leading to realistic modeling of the time-varying spectral energy distribution.

A zero mean stationary Gaussian stochastic process is then generated using the SRM and defines the target peak ground acceleration, the frequency range, and the phase distribution. In this step, spectrum compatibility is also ensured by proper computation of the power spectral density function (PSD). The generated signal is then analyzed in the TF domain using the CWT.

The TF envelope then modifies accordingly the stationary stochastic process in the time-frequency domain, and new wavelet coefficients are obtained. The simulated signal is transformed in the time domain using the inverse CWT and the desired new artificial accelerogram is obtained. Corrective iterations in the frequency domain may also be required in order to achieve enhanced spectrum matching. The proposed methodology provides seismic accelerograms whose temporal and spectral modulation is modeled by a historical ground motion.

3.1 Time-Frequency envelope extraction

Once the desired target spectrum and frequency range $[\omega_0, \omega_u]$ are defined, a recorded accelerogram $\ddot{u}(t)$ is selected from the site of interest, and its total duration t_f and peak ground acceleration $pga_{\ddot{u}}$ are obtained. Then the signal is analyzed with the CWT at frequency range $[\omega_0, \omega_u]$, with fine frequency resolution, and the wavelet coefficients $T_\psi[\ddot{u}](\omega, b)$ are calculated using Eq.2. The complex Morlet wavelet (see Fig.1) is chosen as a mother wavelet, as it also has a a wave-like shape with an increased number of oscillations. Next, the time-frequency envelope $\Phi(\omega, t)$ is defined as the normalized modulus of the CWT coefficients $T_\psi[\ddot{u}](\omega, b)$, so that the peak of the envelope to be equal to one:

$$\Phi(\omega, t) = \frac{|T_\psi[\ddot{u}](\omega, b)|}{\max\left(|T_\psi[\ddot{u}](\omega, b)|\right)} \tag{9}$$

3.2 Generation of the non-stationary accelerograms with the CWT method

Having the desired target spectrum, the same frequency range $[\omega_0, \omega_u]$, and the same total duration t_f, a stationary, spectrum-compatible, artificial accelerogram $a_s(t)$ is generated following Eqs.5-8, by setting T_s=t_f. Then its peak acceleration value pga_s is obtained and the following coefficient is calculated:

$$a_{sc} = \frac{pga_s}{pga_{\ddot{u}}} \tag{10}$$

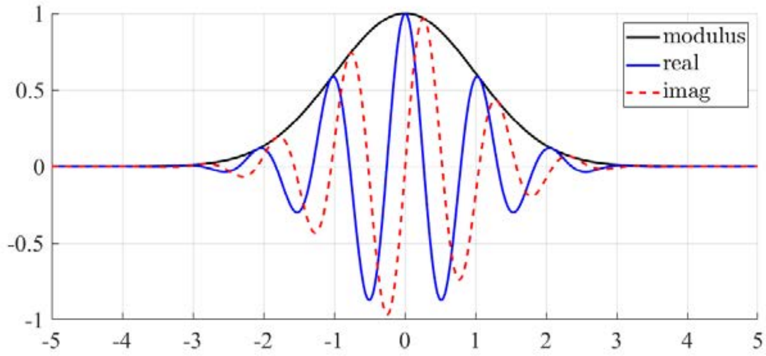

Figure 1: The Complex Morlet Wavelet.

The generated signal $a_s(t)$ is then analyzed with the CWT, following Eq.2 with the same filterbank as the recorded accelerogram, and the wavelet coefficients $T_\psi[a_s](\omega, b)$ are calculated. In order to ensure energy compatibility for every frequency from f_0 to f_u

$$A_s(\omega) = \int_0^{t_f} |T_\psi[a_s](\omega, b)| dt \tag{11}$$

$$A_{\ddot{u}}(\omega) = \int_0^{t_f} |T_\psi[\ddot{u}](\omega, b)| dt \tag{12}$$

Finally, new wavelet coefficients are produced, that correspond to the artificially generated accelerogram:

$$T_\psi[a(t)](\omega, b) = T_\psi[a_s](\omega, b)\Phi(\omega, t)\frac{A_s(\omega)}{a_{sc}A_{\ddot{u}}(\omega)} \tag{13}$$

Finally, the generated accelerogram $a(t)$ is obtained by applying the inverse CWT on $T_\psi[a(t)](\omega, b)$, by following Eqs.3-4.

3.3 Post processing

If further spectrum compatibility is desired, corrective iterations are carried out in the frequency domain, by using the Fourier Transform. That is, and the new signal is transformed back in the time domain by using the inverse Fourier Transform [17].

Moreover, in order to be able to obtain realistic velocity and displacement time-histories through numerical integration of the acceleration signals, baseline correction is applied. A simple quadratic curve for polynomial fitting is employed in this study.

4 NUMERICAL APPLICATION

The efficiency of the proposed methodology is demonstrated through a numerical application. Let the site of interest be a region in central Greece, that has soil conditions that correspond to type C soil according to EC8 [2] ($V_{S30} \approx 360$ m/s). Moreover, the target spectrum is the elastic EC8 spectrum, for peak ground acceleration (PGA) equal to 0.24g and damping ratio $\zeta = 5\%$. The target frequency range is $[\omega_0, \omega_u] = [1, 150]$ rad/s.

The first step is to select a recorded accelerogram $\ddot{u}(t)$ from the site of interest. The Corinth earthquake (Corinth, Greece, 2/24/1981, Corinth, T, see Fig.2) is chosen from the PEER NGA-West 2 database [18], with $V_{S30} = 361$ m/s. The total duration of the accelerogram is $t_f = 40.93$ s and $pga_{\ddot{u}} = 0.30$ g. Next, the recorded ground motion $\ddot{u}(t)$ is analyzed in the TF domain using the CWT method (see section 2.1), and the modulus of the CWT coefficients are obtained (see Fig.3). Following Eq.9, the TF envelope is extracted from the modulus (see Fig.4). As it is observed, the time and frequency locations of the dominant energetic features of the recorded accelerogram are preserved within the envelope.

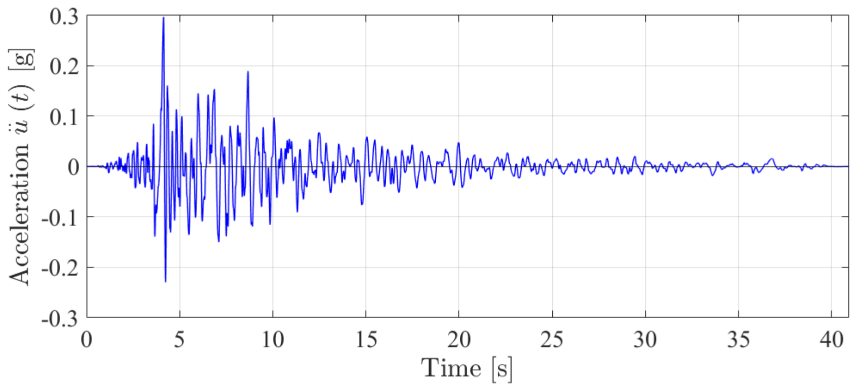

Figure 2: The selected recorded accelerogram: Corinth, Greece, 2/24/1981, Corinth, T.

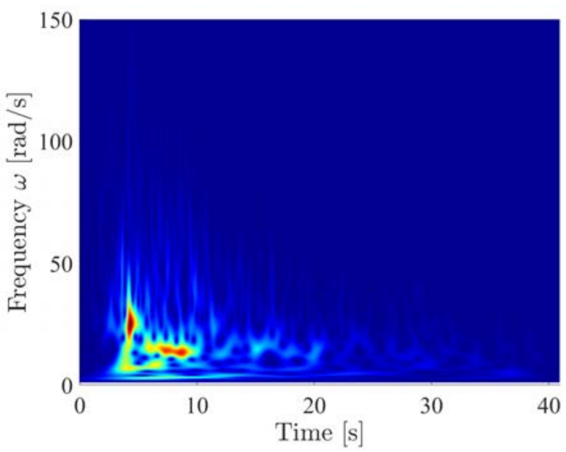

Figure 3: CWT modulus Scalogram of the recorded ground motion.

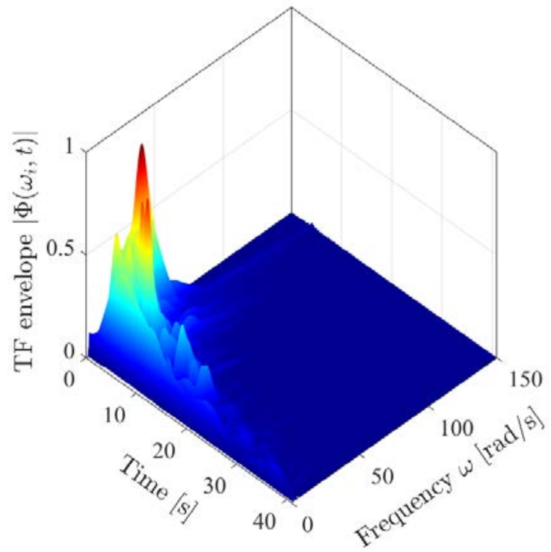

Figure 4: The respective extracted and normalized time-frequency envelope.

It should be noted that for the implementation of the CWT, the MATLAB Wavelet Toolbox of the MATLAB R2018b version [19] was used. The MATLAB Wavelet Toolbox has its own built in "cwt" command, which employs a discretized version of the CWT and computes the coefficients as a convolution product. In this paper, the new "cwt" command was used, with several modifications in order to adopt the $L^2(\mathbb{R})$ normalization.

For the next step, a stationary, target spectrum-compatible accelerogram $a_s(t)$ is generated following the procedure presented in section 2.2, for frequency range $[\omega_0, \omega_u] = [1, 150]$ rad/s, total duration $T_s = t_f = 40.93$ s. The generated accelerogram is shown in Fig.5. This component ensures the compatibility of the final accelerogram with the target spectrum, as its response spectral values match the target ones. To highlight this, Fig.6 shows the target EC8 elastic spectrum and the response spectrum of the generated stationary accelerogram.

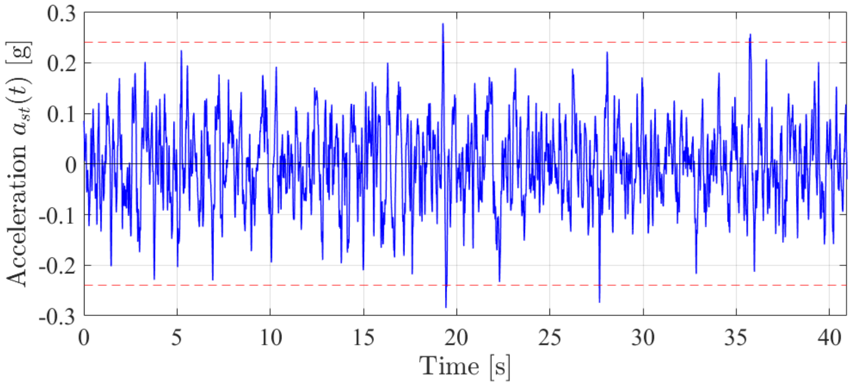

Figure 5: The generated with the SRM stationary accelerogram.

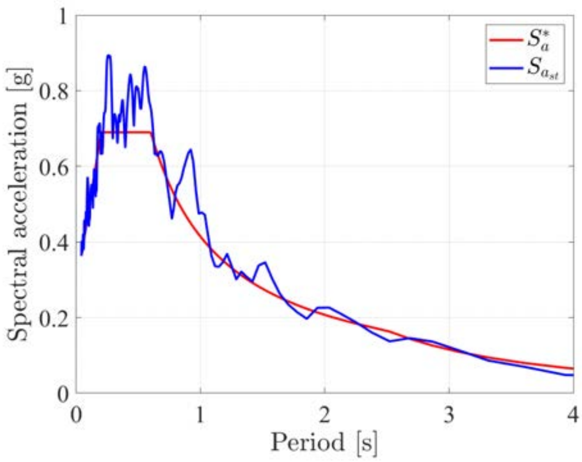

Figure 6: Comparison of the matching between the target EC8 elastic response spectrum S_a^* with the generated stationary accelerogram's response spectrum $S_{a_{st}}$.

The generated stationary accelerogram is then analyzed in the TF domain by applying the CWT method presented in section 2.1, with the same filterbank used for the CWT analysis of the recorded accelerogram. Fig.7 shows the one-sided PSD function of the stationary accelerogram, with its dominant frequency highlighted. Fig.8 shows the modulus of the CWT coefficients of the same signal. As it is observed, the dominant frequency is evident through the energy concentration region of the Scalogram. This is a direct result of the $L^2(\mathbb{R})$ normalization that was applied in the CWT definition.

Next, the PGA value of the stationary accelerogram is obtained, equal to $pga_s = 0.28$g and the coefficient $a_{sc} = 0.96$ is calculated, according to Eq.10. Moreover, the areas $A_s(\omega)$ and $A_{\ddot{u}}(\omega)$ are computed, following Eqs.11 and 12 respectively.

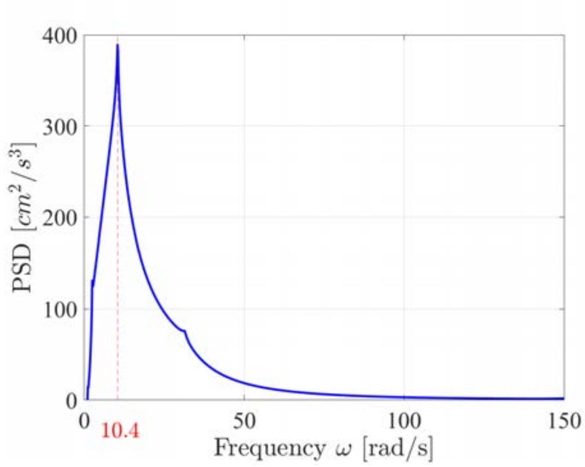

Figure 7: The one-sided PSD function $G(\omega)$ of the stationary accelerogram and its dominant frequency.

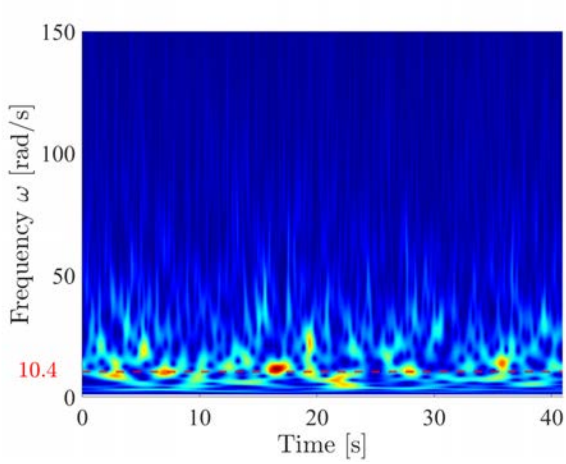

Figure 8: CWT modulus Scalogram of the stationary accelerogram. The dominant frequency of the one-sided PSD function $G(\omega)$ is clearly distinguishable.

Finally, Eq.13 is applied and the new wavelet coefficients are obtained. The new accelerogram $a(t)$ is simulated by applying the inverse CWT on $T_\psi[a(t)](\omega, b)$, by following Eqs.3-4. One corrective iteration is applied for greater spectrum matching, and the new accelerogram is obtained, shown in Fig.9. As it is observed, the PGA values correspond to the target. The produced accelerogram is spectrum-compatible as it is seen in Fig.10, where its response spectral values are compared to the target EC8 elastic spectrum.

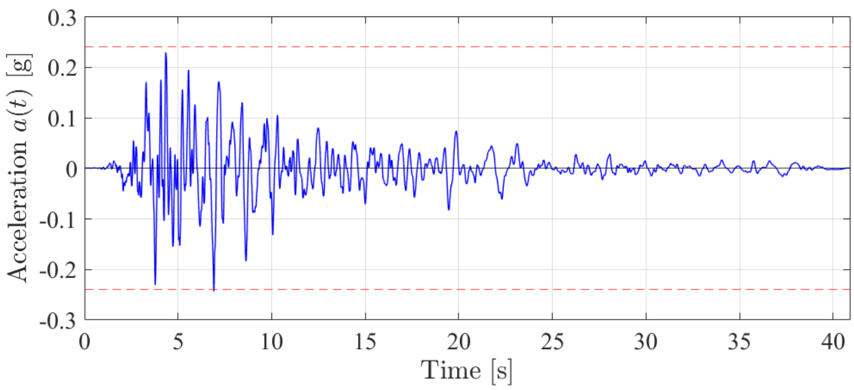

Figure 9: The new accelerogram, generated with the proposed method.

The produced accelerogram is fully non-stationary. This is observed in Fig.11, where the signal is analyzed in the TF domain with the CWT. Both temporal and frequency modulation are evident. Also, in comparison with Fig.3, it is obvious that the energy localisation is modeled after the recorded accelerogram. As it is seen, the frequency range of the generated accelerogram matches target. Furthermore, the influence of the recorded accelerogram to the temporal non-stationarity is observed in Fig.12, where the Husid function plot of both of the signals are shown. This is also seen by defining and calculating the significant duration as the interval between 5% and 95% of the total energy. The recorded accelerogram has a strong motion duration of 13.94 s, whereas for the produced accelerogram it is equal to 16.62 s. These two values are very close, and the Husid plots are in good agreement.

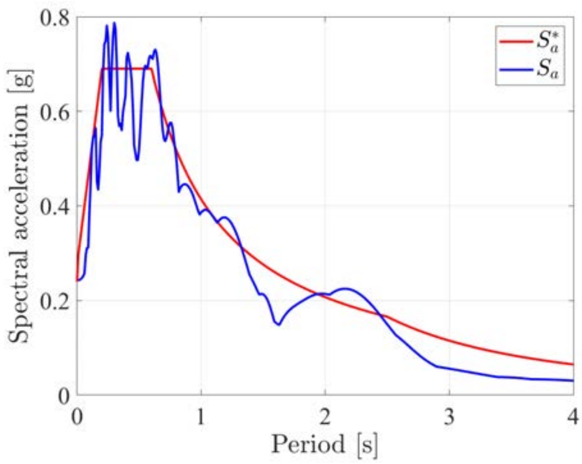

Figure 10: Comparison of the matching between the target EC8 elastic response spectrum S_a^* with the produced accelerogram's response spectrum S_a.

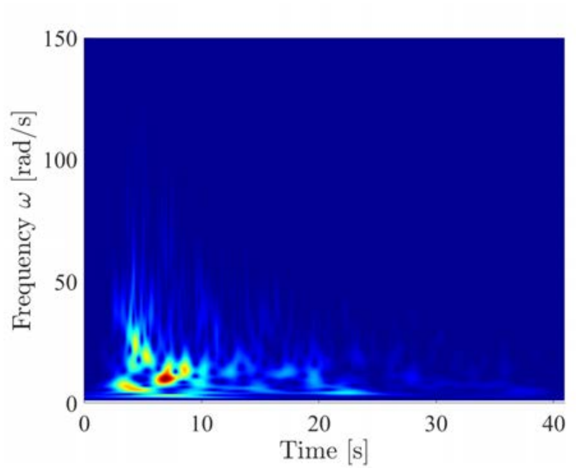

Figure 11: CWT modulus Scalogram of the new generated accelerogram.

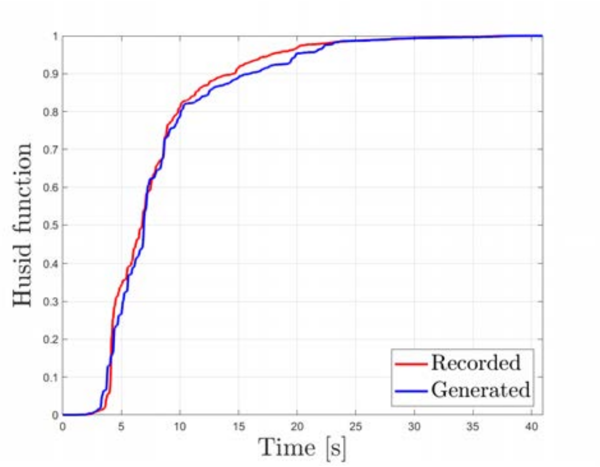

Figure 12: Comparison of the Husid function plot of the recorded ground motion with the generated accelerogram.

5 CONCLUSIONS

A novel stochastic methodology for the generation of artificial accelerograms by combining the Spectral Representation Method with the Continuous Wavelet Transform method is proposed. The temporal and frequency non-stationarity is modeled after a recorded accelerogram from the site of interest. The methodology produces good results by generating accelerograms that are are fully non-stationary and spectrum-compatible. However, the model is in the early stages of development, thus issues concerning better energy preservation for modeling the temporal non-stationarity and a probabilistic treatment using more historical records will be addressed in future work.

REFERENCES

[1] M. Georgioudakis, M. Fragiadakis, Selection and scaling of ground motions using multi-criteria optimization. *Journal of Structural Engineering*, **146**(11):04020241, 2020.

[2] CEN (European Committee for Standardization), *EN1998-1: Design of structures for earthquake resistance. Part I: General rules, seismic actions and rules for buildings*. Brussels, Belgium, 2004.

[3] D. M. Boore, Simulation of ground motion using the stochastic method. *Pure applied geophysics*, **160**, 635—676, 2003.

[4] M. Shinozuka, G. Deodatis, Simulation of stochastic processes by spectral representation. *Applied Mechanics Reviews (ASME)*, **44**(4), 191–204, 1991.

[5] E. H. Vanmarcke, *Developments in Geotechnical Engineering, volume 15, Chapter 8: Structural Response to Earthquakes*, Elsevier, 1976.

[6] P.D. Spanos, L.M. Vargas Loli, A statistical approach to generation of design spectrum compatible earthquake time histories. *International Journal of Soil Dynamics and Earthquake Engineering*, **4**(1), 2–8, 1985.

[7] A. Preumont, The generation of non-separable artificial earthquake accelerograms for the design of nuclear power plants. *Nuclear Engineering and Design*, **88**(1) 59–67, 1985.

[8] P. Cacciola, A stochastic approach for generating spectrum compatible fully nonstationary earthquakes. *Computers and Structures*, **88**, 889–901, 2010.

[9] J. Liang, S. R. Chaudhuri, M. Shinozuka, Simulation of nonstationary stochastic processes by spectral representation. *Journal of Engineering Mechanics*, **133**(6), 616–627, 2007.

[10] T. Huang, M. Lou, H. Chen, N. Wang, An orthogonal Hilbert-Huang transform and its application in the spectral representation of earthquake accelerograms. *Soil Dynamics and Earthquake Engineering*, **104**, 378–389, 2018.

[11] P.D. Spanos, G. Failla, Evolutionary spectra estimation using wavelets. *Journal of Engineering Mechanics*, **130**(8), 952–960, 2004.

[12] L.E. Suárez, L. A. Montejo, Generation of artificial earthquakes via the wavelet transform. *International Journal of Solids and Structures*, **42**(21–22), 5905-5919, 2005.

[13] D. Wang, F. Yu, F. Kong, J. Xu, Simulation of fully nonstationary random processes using generalized harmonic wavelets. *Mechanical Systems and Signal Processing*, **181**, 109468, 2022.

[14] C.K. Chui, R.C. Taylor, *An Introduction to Wavelets, Vol. I.* Academic Press, 1992.

[15] P. Cacciola, P. Colajanni, G. Muscolino, Combination of Modal Responses Consistent with Seismic Input Representation. *Journal of Structural Engineering*, **130**(1), 47–55, 2004.

[16] E. H. Vanmarcke, Properties of Spectral Moments with Applications to Random Vibration. *Journal of the Engineering Mechanics Division*, **98**(2), 425–446, 1972.

[17] H. Yanni, M. Fragiadakis, I. P. Mitseas, A novel method for the stochastic generation of artificial accelerograms. *5th Panhellenic Conference on Earthquake Engineering and Engineering Seismology*, Athens, Greece, 2022.

[18] PEER (Pacific Earthquake Engineering Research Center). "Shallow crustal earthquakes in active tectonic regimes." Accessed December 14, 2022. http://ngawest2.berkeley.edu.

[19] MathWorks, MATLAB version 2018b [Computer Program].