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A COPULA BASED STOCHASTIC MODEL FOR THE GENERATION OF ARTIFICIAL ACCELEROGRAMS

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Abstract. *A novel, stochastic methodology is proposed for generating artificial, fully non-stationary, site- and spectrum-compatible seismic accelerograms. The proposed model combines advanced signal processing techniques, like the spectral representation method and the Continuous Wavelet Transform (CWT), with data-driven parameters. The proposed methodology involves the generation of spectrum-compatible stationary artificial accelerogram signals whose non-stationarity is modeled with a time-frequency modulating function. Specifically, the non-stationary component is defined using the CWT method in order to operate in the time-frequency domain. Two approaches are explored for modeling the time-frequency modulating function: (i) a seed record-based model, where the time-frequency envelope is extracted from a representative seismic record using the CWT, and (ii) a copula-based model, where the time-frequency envelope is defined as a joint probability distribution of time and frequency modulation, allowing parametric control of energy distribution over time. Numerical examples demonstrate that the proposed models can reproduce realistic ground motions, including characteristic patterns observed in recorded accelerograms, where the high-frequency content dominates the early stages of motion and progressively shifts to lower frequencies. The copula-based model provides a flexible and data-driven approach, capable of adapting to different seismic scenarios without relying on large datasets of recorded motions.*

Keywords: copula-based modeling, artificial accelerograms, ground motion generation, non-stationary, time-frequency analysis, stochastic model.

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1 INTRODUCTION

The continuous evolution of earthquake-resistant design practices, coupled with the rapid advances of computational tools, have made Time History Analysis (THA) a prominent tool for the seismic performance assessment of structures. THA relies on the use of carefully selected ground motion records as input motions. These input ground motions can be recorded, synthetic, or artificially generated. For a successful and reliable THA, the input suites must be compatible with a predefined hazard scenario and have frequency and energy modulation characteristics that are consistent with the site of interest.

The use of artificial accelerograms in THA is particularly advantageous in cases where recorded ground motions are scarce or not available for the specific site or scenario under study. Another advantage is that they avoid excessive record scaling, since several studies have shown that it may introduce bias [1]. Various approaches have been proposed in the literature; the main categories are source-based models, which depend on seismological parameters [2], site-based models that generate ground motions using seed accelerograms [3], and spectrum-based models which comply with a target spectrum [3, 4, 5].

Artificial acceleration time-histories are typically modeled as stochastic processes and fields. The Spectral Representation Method (SRM) [6] is based on the theory of stochastic processes and, coupled with the evolutionary spectra theory [7], is one of the earliest and most widely adopted approaches in the literature. Furthermore, spectrum-compatible time-histories can be generated using the relationship of the Power Spectral Density (PSD) function values with the acceleration response spectral values of a target spectrum of given spectral damping [8, 9].

Artificial accelerograms generated using the SRM can exhibit different characteristics in terms of energy and frequency modulation. More specifically, they can be classified as stationary, quasi-stationary (or separable), or fully non-stationary (or non-separable). Stationary ground motions maintain a constant amplitude and frequency content over time, while quasi-stationary models introduce time-varying amplitude but retain a fixed frequency distribution. In contrast, fully non-stationary models capture the evolving amplitude and frequency content over time, a characteristic of real seismic records.

The Continuous Wavelet Transform (CWT) is a flexible joint time-frequency signal analysis tool that provides the time-scale representation of a signal by measuring the similarity between the signal with a mother wavelet [10, 11]. There is a direct relationship between scales and frequencies; thus, the CWT can also be expressed with a time-frequency representation. Furthermore, the mother wavelet provides a flexible time-frequency window. This window is narrowed for the detection of the rapidly changing details of high-frequency phenomena and widened for capturing the slowly changing details of signals. This localization property makes the CWT a powerful tool for analyzing signals with transient features, like earthquake ground motions. As a result, the CWT is able to provide a clear, high-resolution representation of the evolution of the signal's energy in the time-frequency plane.

Copulas are versatile statistical tools that are used in order to model multivariate distributions, since they allow the separation of the marginal functions of the individual variables from their dependence structure. Introduced by Sklar [12], a copula is a mathematical function that links univariate marginal Cumulative Distribution Functions (CDFs) to form a joint multivariate distribution by providing the dependence structure. This property makes it possible to estimate the marginal distributions and the copula function independently [13], thus making copulas particularly useful when the marginals are well-characterized but the correlation structure is complex. A wide variety of copula families, including Gaussian, Clayton, and Gumbel, have been proposed to capture different types of dependence, such as symmetry, tail dependence, and asymmetry. In this study, the Gaussian copula is used in order to model the time-frequency modulation of seismic ground motions.

While several approaches have been developed for generating artificial accelerograms, many of them rely heavily on the use of individual seed records or large datasets, thus limiting their flexibility and general applicability. Nevertheless, statistical modeling of ground motion characteristics directly in the time-frequency domain provides an alternative for developing more versatile simulation tools. Building on previous work [3] of the authors where the CWT was used to model the nonstationarity, i.e. energy evolution in the time-frequency domain, using a seed record, this study introduces a copula-based framework instead. This proposed approach enables direct parameterization of the time-frequency modulating function, allowing a more broad range of spectral and temporal behaviors to be represented.

The main objectives of this work are: (i) to provide the basis of the proposed copula-based model as an extension of an established seed-record approach, (ii) to formulate a stochastic model for generating fully non-stationary, spectrum-compatible accelerograms using copulas, and (iii) to demonstrate that tuning the copula parameters enables the realistic reproduction of the spectral evolution as observed in recorded ground motions. Numerical applications are presented to illustrate and validate the methodology proposed. It should be emphasized that this work is a preliminary step in the development of a broader copula-based framework for ground motion simulation, with future efforts being directed at refining the choice of copula families, parameter calibration, and integration with hazard-consistent simulation techniques.

2 THEORETICAL BACKGROUND

2.1 Spectral representation method for spectrum-compatible stationary signals

Stationary and spectrum-compatible accelerograms can be generated following the spectral representation method (SRM) proposed by Shinozuka and Deodatis [6]. In this method, 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:

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

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, which allows for achieving compatibility with a target spectrum. Further information on this methodology can be found in [3, 9]. These ground motions are considered *stationary*, since they have no amplitude or frequency modulation in time.

2.2 The Continuous Wavelet Transform

The Continuous Wavelet Transform (CWT) is a signal processing tool that allows for transforming a time series signal to the time-frequency domain and back. The CWT is based on a set of basis functions (wavelet family) formed by dilation and translation of a prototype mother function (wavelet) $\psi(t)$. 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].

If $u(t)$ is a signal of finite energy and a piece-wise continuous function of t, then given a mother wavelet $\psi(t)$, the following integral gives the CWT of this signal:

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

where $a > 0$ is a scaling parameter that defines the dilation/compression of the mother wavelet $\psi(t)$ and b is the translation parameter related to time. The symbol $\overline{\psi}$ denotes the complex conjugate. 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.

Eq. 2 shows that the CWT transforms a one-dimensional (time domain) signal $u(t)$ to a two-dimensional representation: the time-scale plane. However, 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, $T_\psi[u](\omega, b)$. Further information on the CWT methodology can be found in [3, 15].

2.3 Copula theory

Copulas are statistical tools that describe/model the dependence (inter-correlation) between n random variables; thus, copulas can be n-dimensional [13]. Bivariate copulas help to model the dependency between two variables. In this study, these variables will be the amplitude and the frequency modulation over time. A bivariate copula is a function C defined on $I^2 = [0,1]^2$ with values in $I = [0,1]$, satisfying the following conditions:

- For every $u, v \in [0,1]$,

$$C(u,1) = u \ , C(1,v) = v \ , C(u,0) = C(0,v) = 0 \tag{4}$$

- For every $u_1, u_2, v_1, v_2 \in [0,1]$, such that $u_1 \leq u_2$ and $v_1 \leq v_2$

$$C(u_2,v_2) - C(u_2,v_1) - C(u_1,v_2) + C(u_1,v_1) \geq 0 \tag{5}$$

In probabilistic terms, a copula is a Cumulative Distribution Function (CDF) with uniform marginals. Sklar's theorem [12] provides the theoretical foundation for using copulas to model joint distributions. If $F \in \mathcal{F}(F_1, F_2)$ is the joint CDF of a bivariate distribution, where $u = F_X$ and $v = F_Y$ are univariate marginals, there exists a bivariate copula $C : [0,1]^2 \to [0,1]$ such that:

$$F(x,y) = C(F_X(x), F_Y(y)), \quad (x,y) \in \mathbb{R}^2 \tag{6}$$

If the marginal CDFs F_X and F_Y are continuous, then C is unique. If the bivariate distribution has a joint Probability Density Function (PDF) f and univariate marginal PDFs f_X and f_Y, then f can be estimated as:

$$f(x,y) = c(u,v) f_X(x) f_Y(y) \tag{7}$$

where $c(u,v)$ is the PDF of C. This formulation allows the joint PDF f to be constructed by separately specifying the marginal PDFs and the copula that captures their dependency structure. There are various types of copulas. In this preliminary study we consider only the "Gaussian" copula.

3 PROPOSED METHODOLOGY

The proposed methodology generates *fully non-stationary* artificial accelerograms that are site- and spectrum-compatible. The method relies on the combination of spectral representation techniques with signal processing operations. Specifically, the model produces accelerograms that effectively simulate the temporal evolution of the amplitude and frequency characteristics of seismic ground motions representative of the site of interest. The proposed framework operates directly in the time-frequency domain using the CWT in order to impose this non-stationary behavior by using a time-frequency modulating function to model the amplitude and frequency modulation. The CWT method is chosen because the modulus of the CWT is a robust representation of the signal's energy evolution in time.

The proposed methodology relies on two main steps: first, a zero mean stationary Gaussian and spectrum-compatible base signal is generated using the SRM. The stationary signal is then transformed into a fully non-stationary artificial ground motion through the introduction of a time-frequency modulating function $\Phi(\omega, t)$. Therefore in Eq. 1 $G(\omega_i)$ becomes $G(\omega_i, t)$ in order to denote that the one-sided evolutionary power spectral density is modeled as the combination of the PSD function $G_s(\omega_i)$ with the time-frequency modulating function $\Phi(\omega, t)$. The CWT method helps to work directly in the time-frequency domain in order to model $G(\omega_i, t)$, by expressing it as wavelet coefficients $T_\psi[a_g](\omega, b)$.

Two alternative approaches are proposed in order to define the time-frequency modulating function: either using a seed ground motion record [3], or the function can be mathematically modeled using a copula. In the first approach, a seed ground motion record is selected from the site of interest. Next, the time-frequency envelope of the seed record is extracted using the CWT. Specifically, the time-frequency modulating function is obtained from the $L^2(\mathbb{R})$ normalized modulus of the seed record's CWT coefficients. This procedure produces artificial accelerograms that not only match the target spectrum but also reflect the temporal evolution of the frequency content as observed in the seed record.

In the second approach, the time-frequency modulating function is defined statistically using a copula model. More specifically, the time-frequency modulation is decomposed into two marginal functions, one describing the target amplitude modulation in time and one describing the target frequency content. In order to model the statistical dependence between these two marginal functions, a bivariate copula is employed. In this study, the Gaussian copula is adopted as a first implementation due to its flexibility and analytical tractability. It is worth noting that the copula approach eliminates the dependence on a specific seed record and offers a parametric framework that can be adapted to different seismic scenarios through calibration of the copula parameters. The above steps are presented and analyzed in the following sections.

3.1 Seed record-based model

A seed ground motion record can be used in order to extract the time-frequency evolution of the seismic energy, which is then imposed on a stationary spectrum-compatible signal. The procedure begins by generating a stationary signal $a_s(t)$ via the spectral representation method (SRM), ensuring compatibility with a target response spectrum.

A representative recorded accelerogram $a_r(t)$ is chosen from the site of interest, and its time-frequency characteristics are extracted using the continuous wavelet transform (CWT). The normalized modulus of the CWT coefficients defines the modulation function as follows:

$$\Phi(\omega, t) = \frac{|T_\psi[a_r](\omega, b)|}{\max\left(|T_\psi[a_r](\omega, b)|\right)} \tag{8}$$

where $T_\psi[a_r](\omega, b)$ are the wavelet coefficients of the seed record. The envelope $\Phi(\omega, b)$ models the temporal variation of the amplitude and the dominant frequencies of the signal.

The generated stationary signal $a_s(t)$ is projected into the time-frequency domain and is modified in order to become fully non-stationary as:

$$T_\psi[a_g](\omega_i, b) = T_\psi[a_s](\omega_i, b)\Phi(\omega_i, t)\frac{A_s(\omega_i)}{\lambda A_r(\omega_i)} \tag{9}$$

where $T_\psi[a_s](\omega, b)$ are the wavelet coefficients of the stationary signal and $A_s(\omega_i)$, $A_r(\omega_i)$, and λ are spectrum compatibility parameters. The fully non-stationary artificial accelerogram $a_g(t)$ is generated through the inverse CWT transform of Eq. 3. Finally, corrective iterations may also be applied in the frequency domain in order to improve the compatibility with the target spectrum, especially at long periods. More information about the methodology can be found in [3] and an online tool is freely available at [16].

3.2 Copula-based model

While the seed record-based model is simple and produces realistic ground motions, its features are confined to a chosen seed record. In order to create a more flexible parametric framework, the time-frequency modulation can be modeled statistically using copulas.

In this case, the time-frequency modulating function is produced as the joint PDF of Eq. 7, thus, full non-stationarity can be deconstructed in terms of two marginal PDFs and a copula. Specifically, one marginal describes the amplitude evolution in time $\varphi(t)$, and the other describes the range and variation of frequency content, thus $G_s(\omega)$ is appropriate. Furthermore, in this study, the Gaussian copula PDF is used:

$$c_\rho(u, v) = \frac{1}{\sqrt{1-\rho^2}} \exp\left(-\frac{1}{2}\begin{bmatrix}\Phi_{\mathcal{N}}^{-1}(u) & \Phi_{\mathcal{N}}^{-1}(v)\end{bmatrix}\left(\begin{bmatrix}1 & \rho\\ \rho & 1\end{bmatrix}^{-1} - \begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}\right)\begin{bmatrix}\Phi_{\mathcal{N}}^{-1}(u)\\ \Phi_{\mathcal{N}}^{-1}(v)\end{bmatrix}\right) \tag{10}$$

where ρ is the correlation coefficient, and $\Phi_{\mathcal{N}}^{-1}(\cdot)$ denotes the quantile function (inverse CDF) of the standard normal distribution, not to be confused with the time–frequency modulating function $\Phi(\omega, t)$. Once $c_\rho(u, v)$ is defined, a joint distribution can model the shape of the time-frequency modulating function by applying Eq. 7 as:

$$\Phi(\omega_i, t) = c_\rho(u, v)\varphi(t)G_s(\omega) \tag{11}$$

$\Phi(\omega_i, t)$ is then applied to generated stationary signals $a_s(t)$ in order to produce the fully non-stationary accelerograms as:

$$T_\psi[a_g](\omega_i, b) = T_\psi[a_s](\omega_i, b)\Phi(\omega_i, t) \tag{12}$$

The fully non-stationary artificial accelerogram $a_g(t)$ is generated through the inverse CWT transform Eq. 3. By adjusting the marginal PDFs and the copula parameters, the methodology can reproduce different shapes of the time-frequency modulation, thereby enabling the generation of suites of motions that are independent of seed records.

4 NUMERICAL APPLICATIONS

4.1 First application: Generation of fully non-stationary motions following the seed record-based model

The site of interest is a region in central Greece, with soil conditions of $V_{S30} \approx 700$ m/s. Moreover, the target spectrum is obtained using the BSSA 14 Ground Motion Model (GMM)

[17]. The considered seismic hazard scenario corresponds to moment magnitude $M_w = 6.5$, Joyner-Boore distance $R_{JB} = 10$ km, and $\varepsilon = 1$. The fault type is normal, for damping ratio $\zeta = 5\%$. The frequency range is chosen $[\omega_0, \omega_u] = [1, 125]$ rad/s, with frequency step $\Delta\omega = 0.12$.

A recorded accelerogram $a_r(t)$ is selected from the site of interest as the seed record. The Kozani-Grevena 1995 time-history (Kozani station, Greece, 1995, L-component) is chosen from the PEER NGA-West 2 database [18] and is shown in Figure 1. The seed record $a_r(t)$ is analyzed in the time-frequency domain, and the modulus of the CWT coefficients $|T_\psi[a_r](\omega, b)|$ is obtained and shown in Figure 1(b). Following Eq. 8, the time-frequency modulating function is determined from $|T_\psi[a_r](\omega, b)|$ and it is shown in Figure 2(b). As observed, the time and frequency locations of the dominant features of the recorded accelerogram are preserved within the time-frequency modulating function.

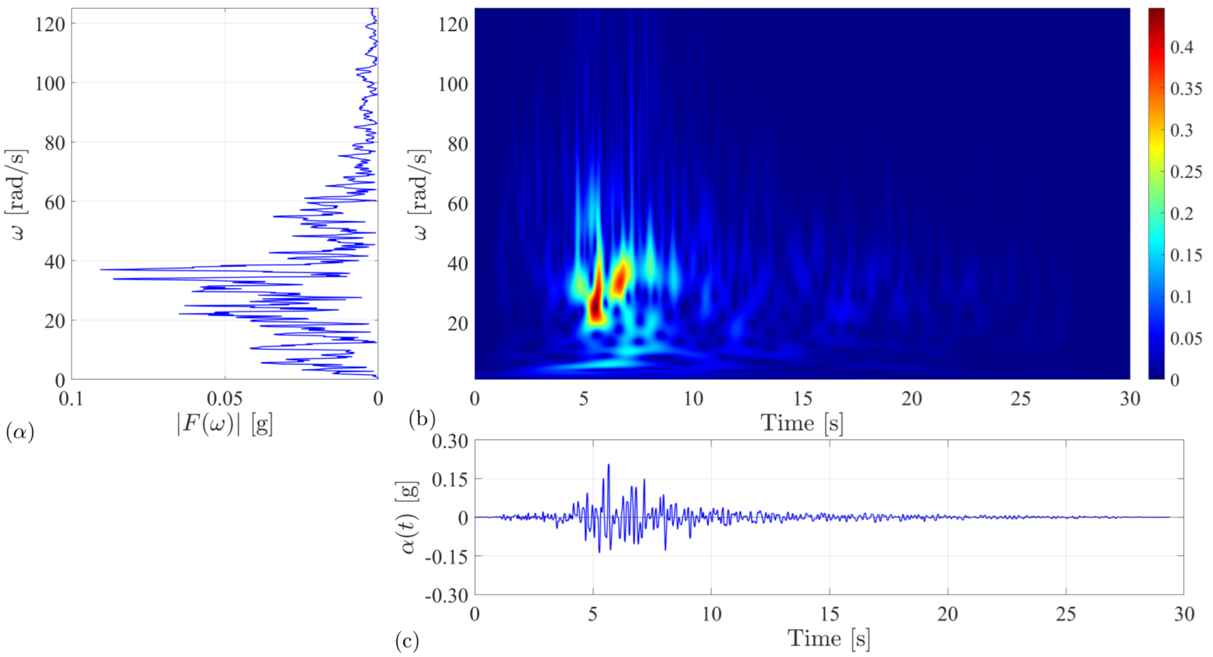

Figure 1: The selected seed record: Kozani-Grevena 1995 earthquake, Greece, Kozani station, L-component: (α) Fourier amplitude spectrum $|F(\omega)|$ plot, (b) CWT modulus $|T_\psi[a_r](\omega, b)|$ two-dimensional plot, (c) seed record acceleration time-history.

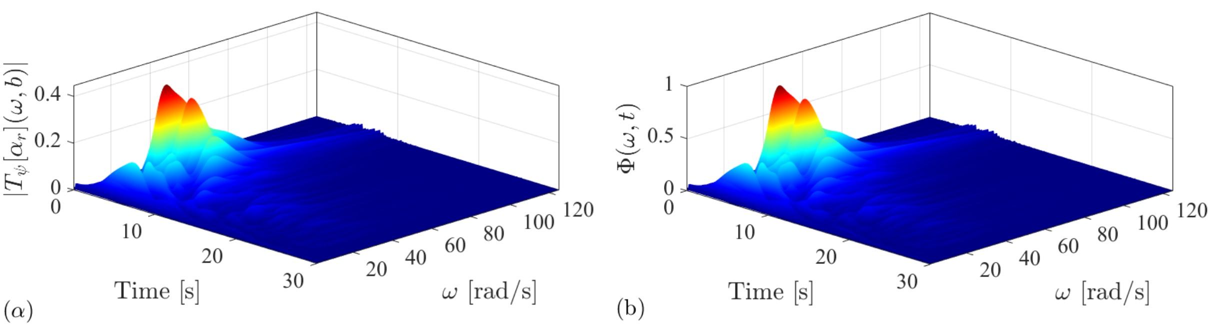

Figure 2: (α) $|T_\psi[a_r](\omega, b)|$ three-dimensional plot, (b) the time-frequency modulating function $\Phi(\omega_i, t)$ extracted from the seed record.

For the next step, a stationary and spectrum-compatible accelerogram $a_s(t)$ is generated following the procedure presented in Section 2.1. The generated signal is then analyzed in the time-frequency domain, with the same filterbank used for the CWT analysis of the recorded accelerogram. The parameters λ, $A_s(\omega_i)$ and $A_r(\omega_i)$ that ensure spectrum compatibility are subsequently estimated and Eq. 12 is applied. Finally, the updated CWT coefficients $T_\psi[a_g](\omega, b)$ for the generated ground motion are obtained, and $a_g(t)$ is produced by applying the inverse CWT on $T_\psi[a_g](\omega, b)$, following Eq. 3. An example of a generated accelerogram is shown in Figure 3, along with its FT amplitude plot $|F(\omega)|$ and the modulus of the CWT coefficients $|T_\psi[a_g](\omega, b)|$. As shown in Figure 3, $a_g(t)$ is fully non-stationary, as both temporal amplitude and frequency modulation are evident.

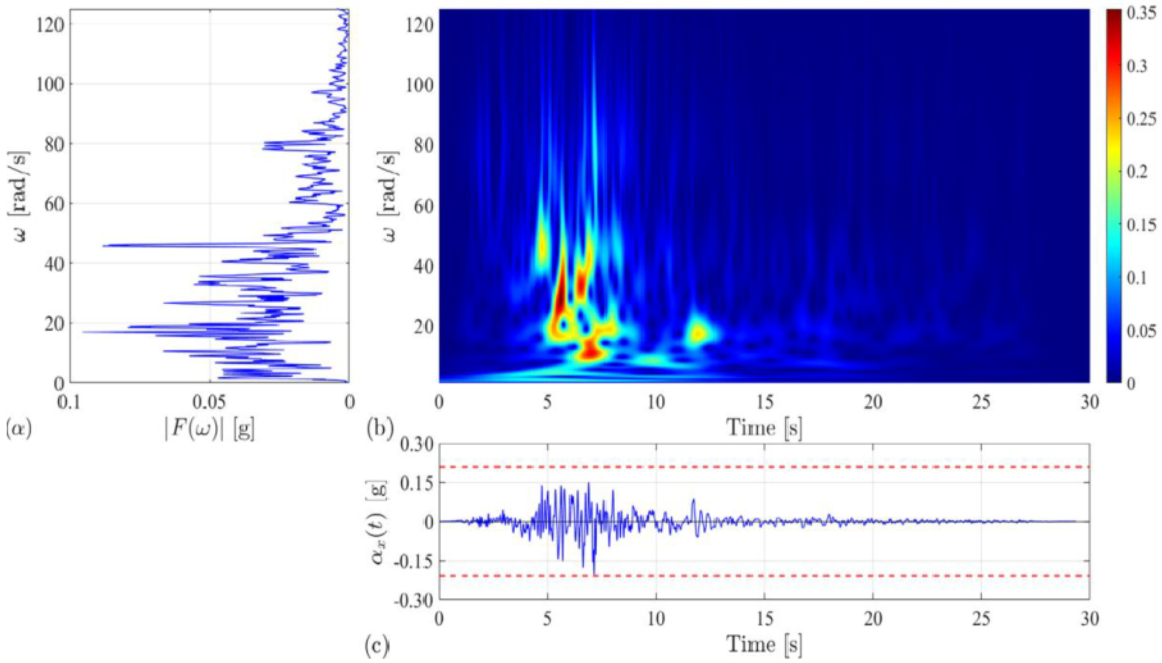

Figure 3: The ground motion generated with the Seed record-based model: (α) Fourier amplitude spectrum $|F(\omega)|$ plot, (b) CWT modulus $|T_\psi[a_g](\omega, b)|$ two-dimensional plot, (c) generated acceleration time-history.

4.2 Second application: Copula-based model parameter investigation

There are various types of copulas which can be used in Eq. 11. This model is in an initial stage; thus, the bivariate Gaussian copula is selected (Eq. 10), and a realization of it is shown in Figure 4.

Mathematically, ρ is the correlation coefficient describing the dependence of the two random variables. The values of ρ greatly influence the shape of the time-frequency modulating function, thus the energy distribution in time. This can be observed in Figure 5, where three realizations of the Gaussian copula PDF are plotted for (α) $\rho = -0.8$, (b) $\rho = 0.1$, and (c) $\rho = 0.9$. It is observed that when ρ is strongly negative, the density elongates along the x and y axes, creating a spread distribution that emphasizes separation between time and frequency characteristics. At near-zero correlation, the density becomes almost circular, indicating a uniform spread without dominant orientation. Finally, with strongly positive ρ, the density contracts along the diagonal, concentrating energy in a narrow band that couples time and frequency evolution. Consequently, by tuning ρ, a wide range of time-frequency modulating function shapes

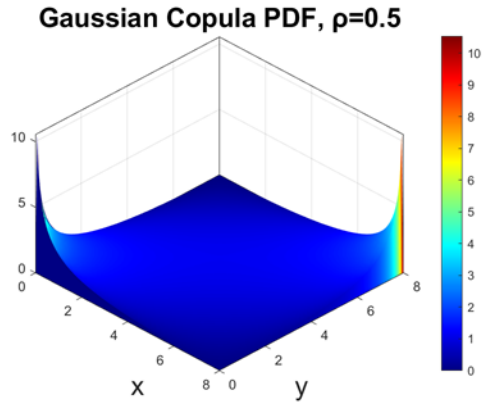

Figure 4: Representative visualization of the bivariate Gaussian copula PDF.

can be reproduced, allowing the generated accelerograms to resemble the spectral evolution of real seismic records, and reflect the physical sequence of P-waves, S-waves, and surface waves. Therefore, it can be observed that values of ρ below approximately 0.1–0.2 are able to produce ground motions where high-frequency components dominate the initial part of the record and gradually diminish as time progresses, leading to a motion that is dominated by low-frequency components in the later stages of the acceleration time series, which is consistent with the characteristics of real ground motions.

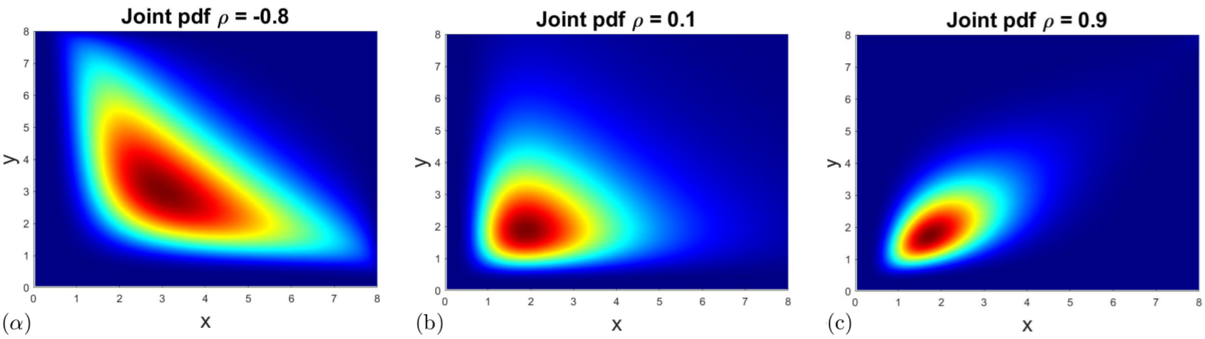

Figure 5: Effect of the Gaussian copula PDF correlation parameter ρ in a derived joint PDF shape: (α) $\rho = -0.8$, (b) $\rho = 0.1$, (c) $\rho = 0.9$. Shape control for time-frequency modulating function design.

5 CONCLUSIONS

The paper presented a stochastic framework for generating fully non-stationary, site-specific, and spectrum-compatible seismic accelerograms using two complementary approaches: a seed-record-based model and a copula-based model. The seed-record method effectively models the amplitude and frequency evolution in time directly in the time-frequency domain using a selected seed ground motion while achieving compatibility with a target spectrum, thus offering a straightforward solution when high-quality site-specific recordings are available.

The copula-based model introduces a parametric framework for the modeling of the time-frequency modulating function, where the dependence between time and frequency modulation is explicitly modeled through a copula. Numerical applications demonstrate that varying the Gaussian copula correlation parameter ρ allows direct control over energy distribution patterns. Therefore, a realistic simulation of the progression from high-frequency to low-frequency content as observed in recorded earthquake motions is possible to be achieved in the produced ground motions. Preliminary results confirm that this methodology can produce realistic energy evolution patterns in the time-frequency domain. However, the methodology is still under development, and several areas for further research have been identified.

The results confirm that both methods can produce artificial accelerograms that accurately capture essential non-stationary features of real ground motions. The seed-record approach provides strong physical fidelity, while the copula-based model offers flexibility and independence, making it possible to generate hazard-consistent suites of motions without the need to rely on large databases of records. Together, these approaches aim to offer a practical tool for engineering applications in a consistent and code-compliant manner, as well as for stochastic dynamics problems.

Future work will focus on expanding beyond the Gaussian copula, which was chosen here for its simplicity and analytical tractability, and alternative copula families will be investigated. Furthermore, a comprehensive calibration procedure will be developed for generating the fully non-stationary artificial ground motions coupled with GMMs, in order to ensure consistency with probabilistic seismic hazard scenarios. Finally, the copula-based model will be extended to produce multi-component ground motion simulations.

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