Simulation of spectral-acceleration correlated and response-spectrum-compatible ground motion accelerograms

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SUMMARY:
The modelling of seismic load is a major topic that has to be addressed thoroughly in the framework of performance based seismic analysis and design. The sustained dissemination of database of recorded accelerograms along with the increasing number of strong-motion networks installed worldwide revealed that the current methodologies for simulating artificial earthquakes accelerograms do not allow for properly reproducing natural variability. As a consequence, the resulting structural response analysis can be misleading. Recently, a methodology for simulating artificial earthquake accelerograms matching mean and mean standard deviation response spectra, given either by attenuation relationships or determined by a selected strong-motion database, has been proposed by the last two authors. In this paper the method is extended to simulate high-variable ground motion accelerograms whose response spectrum will match a target response spectrum along with its prescribed variability and also a selected model of correlation of spectral acceleration values at different frequencies.

Keywords: ground motion, variability, response spectrum, correlation, evolutionary PSD

1. INTRODUCTION

Seismic analysis of ordinary structures is usually performed via the design response spectrum. For structures that exhibits nonlinear behaviour the direct integration of equation of motion in conjunction with the simulation of appropriate time-histories is usually preferred. Unfortunately, international seismic codes do not give a method for generating the earthquake time-histories furnishing only the spectrum-compatible criteria that have to be satisfied. As a consequence, several methods have been proposed in literature coping with the generation of spectrum-compatible accelerograms. Most common approaches rely on the modeling the seismic action as a realization of a stationary or quasi-stationary stochastic process. Accordingly, by modelling the seismic input as a stationary Gaussian process, the spectrum compatible power spectral density is first determined. Vanmarcke and Gasparini (1977) pointed-out the fundamental relationship between the response spectrum and the power spectral density of the input via the "first passage problem". Based on this relationship various procedures have been proposed in literature for determining the spectrum compatible power spectral density (see e.g. Vanmarcke and Gasparini, 1977; Kaul, 1978; Cacciola et al., 2004). After determining the power spectral density of the base acceleration, samples of spectrum compatible time histories can be simulated through the superposition of harmonics with random phase (Shinozuka and Deodatis, 1988). Even if the above-described approaches represent the seismic action reliably reflecting its inherent random nature, it suffers the major drawback of neglecting the nonstationary characteristics of the real records.
It is well known that the dynamic response of nonlinear structures is highly influenced by the nonstationary behavior of the input (Yeh and Wen, 1990; Wang et al. 2002; Spanos et al. 2007a; Spanos et al. 2007b). Thus, more reliable simulations have to take into account the time variability of both intensity and frequency content of the ground motion. Considering an earthquake time history as a realization of a nonstationary stochastic process, Spanos and Vargas Loli (1985) derived an approximate analytical expression of the spectrum compatible evolutionary power spectrum. The

authors first proposed a relationship between the target response spectrum and the evolutionary power spectrum whose parameters are then determined through an optimization procedure. The simulated time-histories are adjusted a posteriori in order to match the response spectrum. The matching has been recently improved by Giaralis and Spanos (2009) through a wavelet approach. Generation of nonseparable artificial earthquake accelerograms has been also proposed by Preumont (1985). The method assumes an empirical model of the evolutionary power spectral density function in which the high frequency components are magnified in the early part. After determining the approximate evolutionary spectrum the simulated accelerograms are then iteratively corrected. The above mentioned methods allow to simulate nonstationary artificial earthquakes whose nonstationary features are strictly related to the selected model of the evolutionary power spectral density function. Recently, a procedure for correcting recorded accelerograms through the superposition of a corrective quasi-stationary random process has been proposed by Cacciola (2010) and then extended by Cacciola and Deodatis (2011) for correcting fully non-stationary vectors of random processes. The advantage of the latter two procedures is that, after the evolutionary response-spectrum-compatible power spectral density function is determined, the simulated accelerograms do not require any further iteration.
The above methodologies for simulating artificial accelerograms possess the common drawback that the simulated time-histories do not manifest the variability observed for real earthquakes. Specifically, even if the accelerograms are simulated through a pertinent stochastic approach, the dispersion of ground motion parameters such as Peak Ground Acceleration (PGA), Arias Intensity (AI), Cumulative Absolute Velocity (CAV) as well as the spreading about the mean response spectrum are much less than those ones observed for natural accelerograms. This is mainly due to the fact that recorded accelerograms, even if they possess the same magnitude and distance epicentral, have strongly different energy distributions, with different ground motion parameters. On the other hand, the simulated accelerograms are generally determined from a unique power spectral density function leading to ground motion time histories with very similar joint-time frequency distribution. This problem has been recently addressed by Pousse et al. (2006) for simulating accelerograms through a stochastic approach by using the K-Net Japanese database. The basic idea of this approach is to define an evolutionary power spectral density function possessing random variables determined through empirical attenuation equations. Recently, Rezaeian and Der Kiureghian (2010) proposed a method for simulating synthetic ground motion time histories through a parameterized stochastic model based on a modulated filtered white-noise process. The parameters of the model are random variables calibrated on a set of recorded earthquakes. These models cannot be used directly for design purpose since they in general do not satisfy the spectrum-compatible criteria imposed by seismic codes and to this aim they need a proper calibration or filtering. In this regard very few contributions have been proposed to determine the evolutionary response-spectrum-compatible power spectral density function (see e.g. Spanos and Vargas Loli, 1985; Preumont, 1985; Cacciola 2010; Cacciola and Deodatis, 2011, Cacciola and Zentner, 2012). Moreover, various studies (Inoue and Cornell 1990, Baker and Cornell 2005, Baker and Jayaram 2008, Wang 2011), showed that recorded accelerograms manifest a certain correlation among the spectral acceleration values and the importance of this quantity in the reliability of structures has been also pointed out (see e.g. Baker and Cornell 2005). Recently, Wang (2011) used the correlation of spectral acceleration as a further criteria to select natural accelerograms compatible with a given response spectrum. Up to now, such correlation has not been taken into account in the simulation of artificial earthquakes. In this paper a procedure to simulate fully non stationary accelerograms that are compatible with given target mean and mean+standard deviation response spectral and also consistent with a selected correlation of spectral accelerations is proposed. To this aim an evolutionary power spectral density function with random correlated coefficients is introduced. The statistics of the random coefficients are determined by the knowledge of the mean+standard deviation response and prescribed correlation coefficients of acceleration spectral values.

2. SIMULATION OF FULLY NON-STATIONARY RESPONSE-SPECTRUM-COMPATIBLE ACCELEROGRAMS

Let consider ground motion time-history as a realization of a zero-mean Gaussian process fully defined by the evolutionary spectrum (Priestley, 1981)

$$G_{\ddot{u}_g}(\omega,t) = \left|A(\omega,t)\right|^2 G(\omega) \tag{2.1}$$

where $A(\omega,t)$ is the non-separable frequency dependent modulating function and $G(\omega)$ is the stationary power spectral density function. In the case in which $A(\omega,t) = A(t)$ the process is called uniformly modulated or quasi-stationary and possesses the feature that only the amplitude varies with respect to time, while the zero-crossing rate is constant over the time. Although, various models of non-separable evolutionary power spectral density functions have been proposed in literature, see e.g. Cacciola (2011) they cannot be used for design purpose since they do not satisfy the prescriptions imposed by the seismic codes. Therefore, evolutionary models have to be corrected to become response-spectrum-compatible. Recently, Cacciola and Zentner (2012) extended the procedure proposed by Preumont (1985) to modify any evolutionary spectrum leading to the simulation of fully non-stationary response-spectrum-compatible accelerograms. The procedure requires the definition of the non-separable frequency dependent modulating function $A(\omega,t)$ and the evaluation of the stationary spectrum compatible power spectral density function $G^S(\omega)$. The non-separable frequency dependent modulating function can be selected among the available models proposed in literature. Among these, probably the simplest reliable model is the Evolutionary Clough-Penzien model, successfully adopted for representing different kind of non-stationarities of recorded earthquakes (see e.g Yeh and Wen, 1991; Deodatis and Shinozuka, 1988; Deodatis, 1996). Alternative models based on more physical approach involving geophysical parameters such us that one proposed by Sabetta and Pugliese (1996) and by Pousse et al. (2006) can be also suitably used. The stationary spectrum compatible power spectral density function $G^S(\omega)$ can be determined through various procedures generally based on the solution of the first crossing problem (Vanmarcke and Gasparini, 1977). Specifically, for a given damping ratio ζ_0 and circular frequency ω_0 , the mean pseudo-acceleration response spectrum $RSA(\omega_0,\zeta_0)$ under the hypothesis that mean and median can be considered coincident is given by the equation

$$RSA(\omega_0,\zeta_0) = \omega_0^2 \eta_U\left(T, p, \lambda_{0,U}, \lambda_{1,U}, \lambda_{2,U}\right)\sqrt{\lambda_{0,U}} \tag{2.2}$$

where T is the duration of the time observing window, assumed equal to the strong motion phase of the uniformly modulated ground motion process, $p = 0.5$ is the not exceeding probability, η_U is the peak factor of the response given by the following equation

$$\eta_U\left(T, p = 0.5; \lambda_{0,U}, \lambda_{1,U}, \lambda_{2,U}\right) = \sqrt{2\ln\left\{2N_U\left[1-\exp\left[-\delta_U^{\;1.2}\sqrt{\pi\ln\left(2N_U\right)}\right]\right]\right\}} \tag{2.3}$$

with

$$N_U = \frac{T}{2\pi}\sqrt{\frac{\lambda_{2,U}}{\lambda_{0,U}}}\left(-\ln p\right)^{-1} \tag{2.4}$$

and

$$\delta_U = \sqrt{1-\frac{\lambda_{1,U}^2}{\lambda_{0,U}\lambda_{2,U}}} \tag{2.5}$$

Furthermore, $\lambda_{i,U}$ ($i = 0,1,2$) are the response spectral moments given by the following equation

$$\lambda_{i,U} = \int_0^\infty \omega^i \left|H(\omega)\right|^2 G^S(\omega)\,d\omega \tag{2.6}$$

in which $\left|H(\omega)\right|^2=\left(\left(\omega^2-\omega_0^2\right)+4\zeta_0^2\omega_0^2\omega^2\right)^{-1}$ is the energy transfer function and $G^S(\omega)$ is the unilateral stationary power spectral density function of the ground acceleration process. The evaluation of the stationary power spectral density function $G^S(\omega)$ can be pursued through different strategies. The recursive relationship proposed by Cacciola et al. (2004) will be adopted in the following to determine $G^S(\omega)$. That is

$$
\begin{aligned}
&G^S(\omega_i)=0; \qquad 0\le\omega_i\le\omega_1 \\
&G^S(\omega_i)=\frac{4\zeta_0}{\omega_i\pi-4\zeta_0\omega_{i-1}}\left(\frac{RSA(\omega_i,\zeta_0)^2}{\eta(\omega_i,\zeta_0,T,p)^2}-\Delta\omega\sum_{j=1}^{i-1}G^S(\omega_j)\right); \quad \omega_i>\omega_1
\end{aligned}
\tag{2.7}
$$

where $RSA(\omega,\zeta_0)$ is the target pseudo-acceleration response spectrum for a given damping ratio ζ_0 and circular frequency ω, $\eta(\omega,\zeta_0,T,p)$ is the peak factor given by the following equation

$$
\eta(\omega_i,\zeta_0,T,p)=2\ln\left\{\frac{T\omega_i}{\pi}\left(-\ln p\right)^{-1}\left[1-\exp\left[-\left(4\frac{\zeta_0}{\pi}\right)^{0.6}\sqrt{\pi\ln\left(\frac{T}{\pi}\omega_i\left(-\ln p\right)^{-1}\right)}\right]\right]\right\}^{1/2}
\tag{2.8}
$$

T is the duration of the time observing window, assumed equal to the duration of the strong motion phase of the ground motion process and $p=0.5$ is the not-exceeding probability. In Eqn.2.7 $\omega_1\cong 1\ rad/s$ is the lower frequency of the domain of existence of the peak factor defined in Eqn.2.7. Following the procedure proposed by Preumont (1985) the stationary counterpart of Eqn.2.1, $G(\omega)$ is determined by equating for each frequency the energy of the separable spectrum compatible model and that of the non-separable process defined in Eqn. 2.1. That is

$$
G(\omega)\int_0^\infty\left|A(\omega,t)\right|^2dt=G^S(\omega)\int_0^\infty\phi^2(t)dt
\tag{2.9}
$$

The modulating function $\phi(t)$, among those proposed in literature, have to be selected and calibrated in such a way to exhibits a strong motion phase equal to the duration of the time observing window *T*. The model proposed by Jennings et al. (1969) will be used to this purpose, specifically

$$
\phi(t)=\begin{cases}\left(\dfrac{t}{t_1}\right)^2 & t\le t_1\\ 1 & t_1\le t\le t_1+T\\ \exp\left[-\beta\left(t-t_2\right)\right] & t>t_1+T\end{cases}
\tag{2.10}
$$

t_1 and β being positive parameters. Once defined $G^S(\omega)$ and $\phi(t)$ Eqn. 2.9 provides the direct relationship for determining $G(\omega)$, that is

$$
G(\omega)=\frac{\int_0^\infty\phi^2(t)dt}{\int_0^\infty\left|A(\omega,t)\right|^2dt}G^S(\omega)
\tag{2.11}
$$

The simulation of fully non-stationary spectrum compatible earthquake can be then performed through the superposition of N_h harmonics with random phases (Shinozuka, and Deodatis 1988)

$$\ddot{u}_g^{(r)}(t) = \sum_{k=1}^{N_h} \sqrt{2\left|A(k\Delta\omega,t)\right|^2 G(k\Delta\omega)\Delta\omega} \cos\left(k\Delta\omega t + \varphi_k^{(r)}\right) \tag{2.12}$$

where $\varphi_k^{(r)}$ are independent random phases uniformly distributed in the interval $[0, 2\pi]$. Even if the spectrum compatible quasi-stationary model guarantees the matching within a certain tolerance of the simulated and target response spectra, depending by the kind of non-stationarity embedded in the term $A(\omega,t)$, the difference between simulated and target response spectra could be relevant. In this regard, the matching can be achieved by adopting the following iterative scheme applied to the stationary component $G(\omega)$

$$G^{(j)}(\omega) = G^{(j-1)}(\omega)\left(\frac{RSA(\omega,\zeta_0)}{\overline{RSA}^{(j-1)}(\omega,\zeta_0)}\right)^2 \tag{2.13}$$

where $G^{(j)}(\omega)$ is the stationary power spectral density and $\overline{RSA}^{(j)}(\omega,\zeta_0)$ the simulated mean response spectrum both determined at the j-th iteration.

3. SIMULATION OF HIGH VARIABLE FULLY NON-STATIONARY RESPONSE-SPECTRUM-COMPATIBLE ACCELEROGRAMS

The procedure described in previous sections provides very accurate results for matching an individual target mean response spectrum. It could be applied for structural design according to current seismic regulation. Nevertheless, a thorough investigation of the results reveals the necessity to include in the simulation of artificial earthquakes the natural variability of relevant ground motion parameters (Pousse et al. 2006, Viallet et al. 2007, Cacciola and Zentner, 2012). To this aim the procedure propes by Cacciola and Zentner (2012) is herein extended to taking into account the correlation among the spectral acceleration values. Let consider the following random evolutionary spectrum

$$G_{\ddot{u}_g}(\omega,t,\alpha) = \alpha(\omega)^2 \left|A(\omega,t)\right|^2 G(\omega) \tag{3.1}$$

in which for fixed ω_j, $\alpha(\omega_j) = \exp\left[\beta(\omega_j)\right]$ $j = 1,...,n$ as a set of lognormal distributed random variable, $\beta(\omega_j)$, $j = 1,...,n$ being a set of correlated Gaussian random variables possessing mean value $\mu_\beta = \mu_\beta(\omega_j)$, standard deviations $\sigma_\beta = \sigma_\beta(\omega_j)$ and correlation $\rho_{\beta(\omega_i)\beta(\omega_j)}$. Also $\mu_\alpha = \mu_\alpha(\omega_j)$ and $\sigma_\alpha = \sigma_\alpha(\omega_j)$ are the mean value and standard deviation of $\alpha(\omega_j)$ respectively. The values of μ_β, σ_β and $\rho_{\beta(\omega_i)\beta(\omega_j)}$ can be determined by the meaning of the following relationship (Cacciola and Zentner, 2012)

$$RSA(\omega_j,\zeta_0,\alpha) = \alpha(\omega_j) RSA(\omega_j,\zeta_0) \tag{3.2}$$

where $RSA(\omega_j,\zeta_0,\alpha)$ is the response spectrum pertinent to the proposed evolutionary power spectrum given in Eqn. 2.1. Taking the mathematical expectation of Eqn. 3.2

$$E\left[RSA(\omega_j,\zeta_0,\alpha)\right] = RSA(\omega_j,\zeta_0) E[\alpha(\omega_j)] \tag{3.3}$$

and imposing the coincidence between the target response spectrum $RSA(\omega_j,\zeta_0)$ and the mean value $E\left[RSA(\omega_j,\zeta_0,\alpha)\right]$ it follows that

$$\mu_\alpha = E[\alpha(\omega_j)] = 1 \quad \forall \omega_j \in [0,\infty] \tag{3.4}$$

Since also the following relationship holds

$$\mu_\alpha = e^{\mu_\beta + \frac{\sigma_\beta^2}{2}} \tag{3.5}$$

it follows that

$$\mu_\beta = -\frac{\sigma_\beta^2}{2} \qquad \forall \omega_j \in [0,\infty] \tag{3.6}$$

The value of the standard deviation $\sigma_\alpha = \sigma_\alpha(\omega_j)$ can been determined (Cacciola and Zentner, 2012) using a target mean+standard deviation response spectrum, $RSA^{+\sigma}(\omega_j,\zeta_0)$, that is

$$\sigma_\alpha(\omega_j) = \frac{RSA^{+\sigma}(\omega_j,\zeta_0)}{RSA(\omega_j,\zeta_0)} - 1 \qquad \forall \omega_j \in [0,\infty] \tag{3.7}$$

Since the following relationship holds

$$\sigma_\alpha^2 = \left(e^{\sigma_\beta^2} - 1\right) e^{2\mu_\beta + \sigma_\beta^2} \tag{3.8}$$

therefore, taking into account Eqn. 3.6 it follows that

$$\sigma_\beta(\omega_j) = \sqrt{\ln\left(1 + \sigma_\alpha^2(\omega_j)\right)} \qquad \forall \omega_j \in [0,\infty] \tag{3.9}$$

Since the correlation of spectral accelerations $\rho_{\ln RSA(\omega_i)\ln RSA(\omega_j)}$ is generally defined through empirical relationships based on log-response spectra (see e.g. Inoue and Cornell 1990, Baker and Jayaram 2008,), taking the logarithm of Eqn. 3.2, it reads

$$\ln RSA(\omega_j,\zeta_0,\alpha) = \ln \alpha(\omega_j) + \ln RSA(\omega_j,\zeta_0) \tag{3.10}$$

After simple algebra, the correlation coefficients $\rho_{\beta(\omega_i)\beta(\omega_j)}$ can be shown to be coincident with the selected correlation of spectral accelerations $\rho_{\ln RSA(\omega_i)\ln RSA(\omega_j)}$, that is

$$\rho_{\beta(\omega_i)\beta(\omega_j)} = \rho_{\ln\alpha(\omega_i)\ln\alpha(\omega_j)} = \rho_{\ln RSA(\omega_i)\ln RSA(\omega_j)} \qquad \forall \omega_j \in [0,\infty] \tag{3.11}$$

Moreover, the simulation formula given in Eqn. 2.12 is modified as follows

$$\ddot{u}_g^{(r)}(t) = \sum_{k=1}^{N_h} \sqrt{\alpha^{(r)}(k\Delta\omega)^2 \left|A(k\Delta\omega,t)\right|^2 G(k\Delta\omega)\Delta\omega} \cos\left(k\Delta\omega t + \varphi_k^{(r)}\right) \tag{3.12}$$

the value of the to the stationary component $G(\omega)$ is updated through Eqn. 2.13, while the standard deviation $\sigma_\alpha(\omega)$ is updated through the following iterative scheme

$$\sigma_\alpha^{(j)}(\omega_k) = \sigma_\alpha^{(j-1)}(\omega_k) \frac{RSA^{+\sigma}(\omega_k,\zeta_0)}{\overline{RSA}^{+\sigma(j-1)}(\omega_k,\zeta_0)} \tag{3.13}$$

where $\sigma_\alpha^{(j)}(\omega)$ is the standard deviation and $\overline{RSA}^{+\sigma(j)}(\omega,\zeta_0)$ is the simulated mean+standard deviation response spectrum both determined at the *j*-th iteration.

4. NUMERICAL RESULTS

In this section the proposed method for generating fully nonstationary spectrum compatible earthquakes is applied to the target response spectrum defined in Eurocode 8. Specifically, for a 5% damping ratio the response spectrum is given by the equations

$$\begin{aligned} RSA(T) &= a_g S\left[1+\frac{T}{T_B}(1.5)\right] && 0 \le T \le T_B \\ RSA(T) &= 2.5 a_g S && T_B \le T \le T_C \\ RSA(T) &= 2.5 a_g S\left[\frac{T_C}{T}\right] && T_C \le T \le T_D \\ RSA(T) &= 2.5 a_g S\left[\frac{T_C T_D}{T^2}\right] && T_D \le T \le 4s \end{aligned} \tag{4.1}$$

The parameters defined for ground Type A have been used for the applications. Namely, $S=1$, $T_B = 0.1s$, $T_C = 0.4s$ and $T_D = 3.0s$; furthermore, the maximum ground acceleration a_g it has been set equal to $1\,m/s^2$. According to Eurocode 8, consistency is considered to be achieved if the condition

$$\max\left\{\frac{\widetilde{RSA}(T)-RSA(T)}{RSA(T)}\times 100\right\} \le 10\% \tag{4.2}$$

is satisfied over the range of periods between $0.2T_1$ to $2T_1$; T_1 being the fundamental period of the structure under study in the direction where the accelerogram is applied; and if

$$\widetilde{RSA}(0) > a_g S, \tag{4.3}$$

$\widetilde{RSA}(T)$ being the mean response spectrum from at least three simulated earthquakes. To illustrative purpose the variability of the response spectrum has been set as

$$RSA^{+\sigma}(T) = 1.5 RSA(T) \tag{4.4}$$

Therefore

$$\sigma_\beta(\omega_j) = \sqrt{\ln(1.25)} = 0.4724\ ;\ \mu_\beta(\omega_j) = -0.1116 \qquad \forall \omega_j \in [0,\infty] \tag{4.5}$$

The correlation of spectral accelerations $\rho_{\ln RSA(\omega_i)\ln RSA(\omega_j)}$ proposed by Inoue and Cornell (1990) has been also selected, that is

$$\rho_{\beta(\omega_i)\beta(\omega_j)} = \rho_{\ln RSA(T_i)\ln RSA(T_j)} = 1-0.33\left|\ln\left(\frac{T_i}{T_j}\right)\right| \qquad 0.1 \le T_i, T_j \le 4s, \tag{4.6}$$

In order to apply the proposed procedure the evolutionary Clough-Penzien model has been selected

$$G_{\ddot{u}_g}(\omega,t) = a_1 t^{a_2} \exp(-a_3 t^{a_4}) \times \frac{1+4\zeta_g^2(t)\left(\frac{\omega}{\omega_g(t)}\right)^2}{\left\{1-\left(\frac{\omega}{\omega_g(t)}\right)^2\right\}^2 + 4\zeta_g^2(t)\left(\frac{\omega}{\omega_g(t)}\right)^2} \frac{\left(\frac{\omega}{\omega_f(t)}\right)^4}{\left\{1-\left(\frac{\omega}{\omega_f(t)}\right)^2\right\}^2 + 4\zeta_f^2(t)\left(\frac{\omega}{\omega_f(t)}\right)^2} \quad (4.7)$$

in which it has been assumed for illustrative purpose

$$\omega_g(t) = \pi\left(3+19.01\left(e^{-0.0625t} - e^{-0.15t}\right)\right) \quad (4.8)$$

proposed by Ahmadi and Fan (1990), for representing the non-stationary features of the El Centro earthquake, and $\omega_f(t) = 0.1\omega_g(t)$, $\zeta_g = \zeta_f = 0.6$. Therefore, the parameters $a_1 = 2.2064$ $a_2 = 1.85$ $a_3 = 0.13$ $a_4 = 1.58$ have been used.

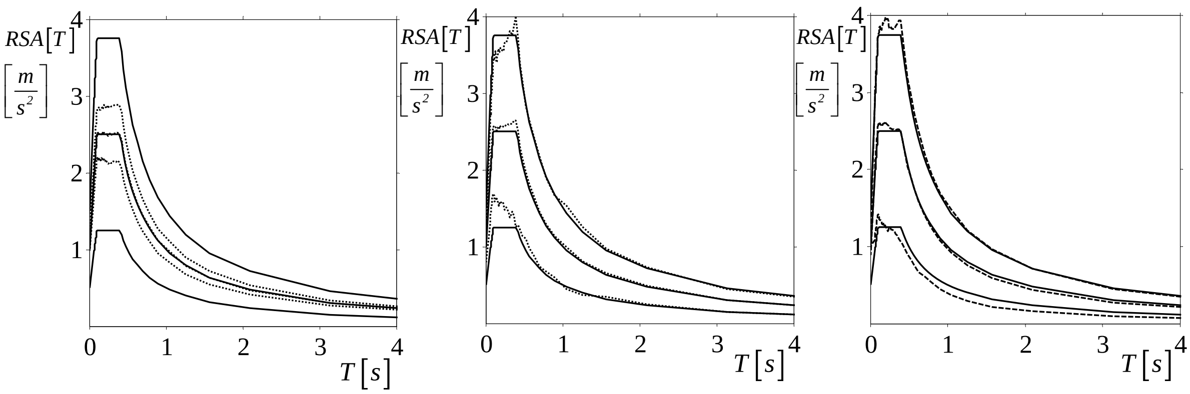

Figure 1. Comparison between simulated and target response spectra: a) $\alpha(\omega_j)=1$, b) $\alpha(\omega_j)$ uncorrelated; c) $\alpha(\omega_j)$ correlated.

The proposed procedure has been then applied for simulating artificial accelerograms compatible with mean and mean ± standard deviation response spectra and compared with the procedure proposed by Cacciola and Zentner (2012), considering either $\alpha(\omega_j)=1$, i.e. no imposed variability, $\alpha(\omega_j)$ lognormal uncorrelated random variables.

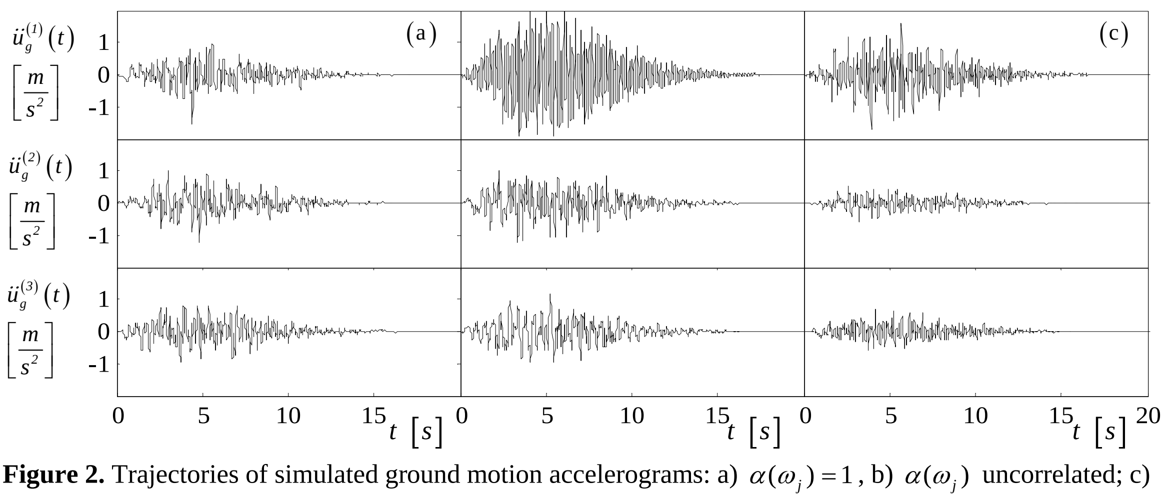

Figure 2. Trajectories of simulated ground motion accelerograms: a) $\alpha(\omega_j)=1$, b) $\alpha(\omega_j)$ uncorrelated; c) $\alpha(\omega_j)$ correlated.

The accuracy of the proposed procedure is manifested in Figure 1 by the positive matching between simulated and target response spectra. Interestingly, it can be noted in all the case considered the mean target response spectra in perfectly matched, so to satisfy the response-spectrum compatibility criteria imposed by the seismic Eurocodes. Fig. 1b and 1c show that also the imposed target mean+standard deviation response spectra is matched confirming the accuracy of the convergence criteria defined by Eqn. 2.13. Pertinent trajectories are reported in Fig. 2. It can be seen as the case in which $\alpha(\omega_j)=1$ the accelerograms are very similar, while by considering a random evolutionary spectrum it can be observed not only large variability in the peak values, but also in the frequency content.

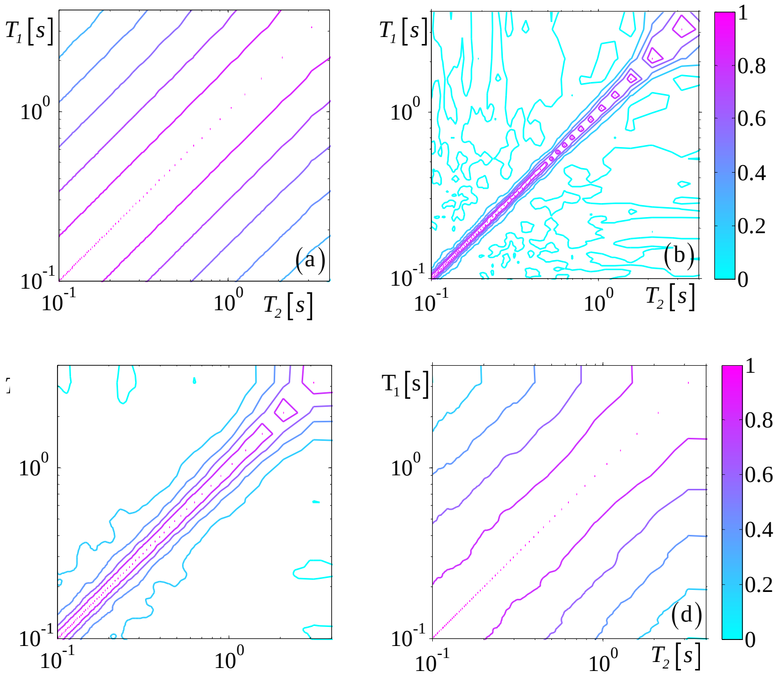

Figure 3. Correlations of the log-response spectral acceleration values: a) Inoue and Cornell (1990) target correlation; b) $\alpha(\omega_j)=1$, c) $\alpha(\omega_j)$ uncorrelated; d) $\alpha(\omega_j)$ correlated.

Lastly correlations of the log-response spectral acceleration values are compared. Fig. 3a shows the target one defined in Eqn. 4.6. Figure 3b, 3c, and 3d shows the correlation coefficient in the case of $\alpha(\omega_j)=1$, $\alpha(\omega_j)$ uncorrelated and correlated respectively.

4. CONCLUDING REMARKS

The modelling of seismic load is a major topic still open in the scientific community. The sustained dissemination of database of recorded accelerograms along with the increasing number of strong-motion networks installed worldwide provide valuable information to calibrate and eventually modify theoretical models up to now used to simulate artificial accelerograms. The main drawback of most of the available procedure is that the simulated accelerograms do not manifest the observed natural variability of the recorded ones. As a consequence, the resulting structural response analysis can be misleading. In this paper a procedure for simulating fully non-stationary response-spectrum-compatible accelerograms has been proposed. The procedure is aimed at reproduce features observed by the analysis of database of recorded earthquakes. Specifically the procedure is able to reproduce the variability of the acceleration response spectra along with a prescribed correlation of spectral acceleration values. The procedure is versititle and various seismological models can be embedded. As shown in the numerical applications.

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