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A stochastic approach for generating spectrum compatible fully nonstationary earthquakes

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ABSTRACT

Simulation of artificial earthquakes in agreement with the provision of international seismic codes is addressed. Due to the importance of nonstationary frequency content on the seismic assessment of structures, in this paper a new method for generating spectrum compatible fully nonstationary earthquakes is proposed. The method assumes that the ground motion is modeled by the superposition of two contributions: the first one is a fully nonstationary counterpart modeled by a recorded earthquake; the second one is a corrective random process adjusting the recorded earthquake in order to make it spectrum compatible. Several examples show the accuracy of the proposed method.

1. Introduction

For a number of applications connected with the seismic assessment of structures it is necessary to generate accelerograms which are compatible with a design response spectrum. To date, international seismic codes [1,2] do not give a method for generating the time-histories imposing only the matching of the mean simulated response spectrum with the target one according to certain spectrum compatible criteria. As a consequence, several methods have been proposed in literature coping with the generation of spectrum compatible accelerograms. Earlier contributions on this subject can be found in [3]. Based on either a deterministic or stochastic approaches two main parallel strategies are usually adopted for defining suitable earthquake time histories. Namely, based on a deterministic approach the spectrum compatible accelerogram is usually determined via an iterative alteration of the frequency content of synthetic or recorded time-histories. In Ref. [4] a single spectrum compatible accelerogram using an artificial deterministic signal resulting by the superposition of a number of harmonics with amplitude scaled so as to mach the target response spectrum has been determined. Neural network based approach for generating accelerograms through the knowledge of the inverse mapping from response spectra to earthquake accelerograms is proposed in [5]. Wavelet-based methods modifying recorded accelerograms such that those are compatible with a given response spectrum can be found in [6–8].

Deterministic-based approach possesses the advantage to lead generally to spectrum compatible accelerograms nonstationary in both amplitude and frequency; on the other hand it suffers the major drawback to produce a single spectrum compatible accelerogram from and individual recorded signal. Therefore, since for design purpose it is required [1,2] the use of a number of accelerograms the application of a deterministic approach could be prohibitive whereas few records are allowable.

Furthermore, being the response spectrum determined smoothing and averaging the response spectra pertinent to a number of recorded signals and due to the widely recognized random nature of the seismic action, stochastic approach appears more attractive. In this regard, many common approaches rely on modeling the seismic action as a realization of a stationary or quasi-stationary stochastic process. Moreover, in the framework of stochastic dynamics, spectral representation of random processes is usually preferred. Accordingly, by modeling the seismic input as a stationary Gaussian process, the spectrum compatible power spectral density is first determined. Vanmarcke and Gasparini [9] pointed-out the fundamental relationship between the response spectrum and the power spectral density of the input via the so-called "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. Refs. [9–18]). An iterative scheme to generate seismic ground motion time histories at several location on the ground surface that are compatible with prescribed response spectra correlated according to a given coherence function has been proposed in [19]. 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 [20]. Even if the above described approaches

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represent the seismic action reliably reflecting its inherent random nature, it suffers the major drawback of neglecting the nonstationary characteristics of the real records. Remarkably, it is well known that the dynamic response of nonlinear structures is highly influenced by the nonstationary behavior of the input [21,22]. 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 [23] derived an approximate analytical expression of the spectrum compatible evolutionary power spectrum. The simulated time-histories are iteratively adjusted a posteriori in order to match the response spectrum. Generation of nonseparable artificial earthquake accelerograms has been also proposed in [24]. The method assume an empirical model of the evolutionary power spectral density function possessing the feature that high frequency component are magnified in the early part of the process and the iterative correction of the simulated accelerograms. Nonstationary characteristics from recorded earthquakes have been taken into account in [25] by means of phase spectrum for generating spectrum compatible signals. Ensemble of spectrum compatible accelerograms using stochastic neural networks has been proposed in [26]. Recently, the procedure originally established in Spanos and Vargas Loli [23] has been modified by Giaralis and Spanos [27] by means of the use of harmonic wavelets transform for iteratively improve the matching between the target and the simulated response spectra.

In this paper a method based on the spectral representation of stochastic processes is proposed. The method assumes that the ground motion is modeled by the superposition of two contributions: the first one is a fully nonstationary counterpart modeled by a recorded earthquake, that takes into account the time variability of both intensity and frequency content; the second one is a corrective term represented by a quasi-stationary process adjusting the response spectrum of the nonstationary signal in order to make it spectrum compatible. Remarkably, the simulated earthquakes do not require any further iterative correction leading the proposed procedure very handy and competitive from a computational point of view. Therefore, the influence of the corrective term on the nonstationary behavior of the original recorded signal has been scrutinized via a pertinent study of the mean instantaneous energy and frequency of the spectrum compatible earthquakes. Various examples show the accuracy and the efficiency of the proposed method.

2. Generating quasi-stationary spectrum compatible earthquakes

Assume that a target pseudo-acceleration response spectrum $RSA(\omega_0,\zeta)$ (for a given natural frequency, ω_0, and damping ratio, ζ) is specified. The problem of simulating spectrum compatible earthquakes is addressed on a probabilistic basis under the assumption that an earthquake time history is considered as a realization of a random process. In this section the simplest hypothesis of zero-mean stationary Gaussian random process, fully defined by the so-called power spectral density function, is assumed. Accordingly, the problem is recast to determine the power spectral density function whose response spectrum matches the target one. This can be pursued via the following first crossing problem [9]

$$RSA(\omega_0,\zeta)=\omega_0^2\eta_U(T_s,p=0.5;\lambda_{0,U}(\omega_0,\zeta),\lambda_{1,U}(\omega_0,\zeta),\lambda_{2,U}(\omega_0,\zeta))\sqrt{\lambda_{0,U}(\omega_0,\zeta)},\tag{1}$$

where η_U is the peak factor given by the equation

$$\eta_U=\sqrt{2\ln\left\{2N_U\left[1-exp\left[-\delta_U^{1.2}\sqrt{\pi\ln(2N_U)}\right]\right]\right\}}\tag{2}$$

with

$$N_U=\frac{T_s}{2\pi}\sqrt{\frac{\lambda_{2,U}(\omega_0,\zeta)}{\lambda_{0,U}(\omega_0,\zeta)}}(-\ln p)^{-1}\tag{3}$$

and

$$\delta_U=\sqrt{1-\frac{\lambda_{1,U}(\omega_0,\zeta)^2}{\lambda_{0,U}(\omega_0,\zeta)\lambda_{2,U}(\omega_0,\zeta)}},\tag{4}$$

where T_s is the time observing window, and p is the not-exceeding probability. Furthermore, $\lambda_{i,U}(\omega_0,\zeta)(i=0,1,2)$ are the response spectral moments defined as

$$\lambda_{i,U}(\omega_0,\zeta)=\int_0^\infty\omega^i|H(\omega,\omega_0,\zeta)|^2G_{\ddot{u}_g}(\omega)\,d\omega\tag{5}$$

in which $|H(\omega,\omega_0,\zeta)|^2=\left((\omega_0^2-\omega^2)^2+4\zeta^2\omega_0^2\omega^2\right)^{-1}$ is the energy transfer function and $G_{\ddot{u}_g}(\omega)$ is the unilateral power spectral density function of the ground acceleration process that have to be determined. It is noted also that in Eq. (1) the 50% fractile has been approximated by the mean value of the peak values.

A handy recursive expression determining the power spectral density compatible with a given response spectrum has been proposed in Ref. [18]. Specifically,

$$G_{\ddot{u}_g}(\omega)=0\quad 0\le\omega\le\omega_l,\tag{6}$$

$$G_{\ddot{u}_g}(\omega_i)=\frac{4\zeta}{\omega_i\pi-4\zeta\omega_{i-1}}\left(\frac{RSA(\omega_i,\zeta)^2}{\eta_U^2(\omega_i,\zeta)}-\Delta\omega\sum_{j=1}^{i-1}G_{\ddot{u}_g}(\omega_j)\right),\quad \omega>\omega_l,\tag{7}$$

where the peak factor η_U is given by Eq. (2) along with the following approximate parameters:

$$N_U=\frac{T_s}{2\pi}\omega_i(-\ln p)^{-1},\tag{8}$$

$$\delta_U=\left[1-\frac{1}{1-\zeta^2}\left(1-\frac{2}{\pi}\arctan\frac{\zeta}{\sqrt{1-\zeta^2}}\right)^2\right]^{1/2},\tag{9}$$

determined assuming that the input PSD possess a smooth shape and $\zeta << 1$. Moreover $\omega_l \cong 1$ rad/s is the lowest bound of the existence domain of η_U. The accuracy of Eqs. (6) and (7) can be also improved via the following iterative scheme [9]:

$$G_{\ddot{u}_g}^{(j)}(\omega)=G_{\ddot{u}_g}^{(j-1)}(\omega)\left[\frac{RSA(\omega,\zeta)^2}{\widetilde{RSA}^{(j-1)}(\omega,\zeta)^2}\right],\tag{10}$$

$\widetilde{RSA}^{(j)}$ being the approximate pseudo-acceleration spectrum determined at the jth iteration through Eqs. (1)–(5).

After determining the spectrum compatible power spectral density $G_{\ddot{u}_g}(\omega)$ the simulation of spectrum compatible ground acceleration earthquakes is performed via the superposition of N_a harmonics with random phases. Specifically, the kth artificial earthquake is given by the equation

$$\ddot{u}_g^{(k)}(t)=\varphi(t)\sum_{i=1}^{N_a}\sqrt{2G_{\ddot{u}_g}(i\Delta\omega)\Delta\omega}\cos\left(i\Delta\omega t+\phi_i^{(k)}\right),\tag{11}$$

where $\phi_i^{(k)}$ are independently random phases uniformly distributed in the interval $[0,2\pi)$ and $\varphi(t)$ is a modulating function. In order to preserve the stationary condition of the response process within a segment of duration T_s (i.e. the time-observing window), the modulating function proposed in [28] is selected. That is,