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An evolutionary power spectrum model of fully nonstationary seismic ground motion

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ABSTRACT

A parametric evolutionary power spectrum model of fully nonstationary seismic ground motion is developed based on the evolutionary spectrum estimation method via generalized harmonic wavelets. The model consists of a frequency-domain energy distribution function and a series of normalized time-dependent envelop functions for different frequencies. The frequency-domain energy distribution function describes the spectral characteristics of the seismic ground motion. The nonstationarity is achieved by the normalized time-dependent envelope functions. For a specific seismic ground motion record, the evolutionary power spectral density (EPSD) is estimated via generalized harmonic wavelets. The parameters are identified by letting the model approximate to the estimated EPSD of the realistic ground motion. By using the spectral representation method, the proposed EPSD model can be used to synthesize the artificial seismic ground motion time histories for engineering purposes.

1. Introduction

Nonstationary characteristics of seismic ground motions have been of interest to seismologists and earthquake engineers for a long time. Generally, the realistic seismic ground motion exhibits two types of nonstationarities, namely temporal and spectral nonstationarities [1]. The temporal nonstationarity refers to the time variation of the intensity of the ground motion in the time domain and the spectral nonstationarity refers to the time variation of the energy distribution of the ground motion in the frequency domain. The physical factors causing the nonstationarity of the seismic ground motion are complex, including the onset and end of the earthquake fault rupture process, the seismic wave propagation through the random earth medium and the local site effect. As well known, both of the temporal and spectral nonstationarities of the earthquake ground motion may have significant effect on the response of nonlinear structure [2,3]. Hence, for the seismic response analysis of nonlinear structure, there has been a number of work regarding the modeling and the simulation of nonstationary seismic ground motion [1,4–6].

Due to the complexity and randomness of the realistic earthquake time history, seismic ground motion is usually treated as stochastic process [7]. For engineering purposes, seismic ground motion is usually modeled as filtered white noise with amplitude modulation in time. Several amplitude envelope functions have been proposed to achieve the temporal nonstationarity of the filtered white noise model [8–11]. However, the amplitude-modulated filtered white noise model can not reflect the spectral nonstationarity of the realistic seismic ground motion. In 1965, Priestley defined the evolutionary power spectral density (EPSD) to describe the time variation of the frequency-domain energy distribution of the fully nonstationary stochastic process [12]. The EPSD was introduced to model the seismic ground motion by Liu in 1970 [13]. At present, several EPSD models of fully nonstationary seismic ground motions have been proposed [2,14–18]. For simulating stochastic process samples by power spectra, the spectral representation method, which was first presented by Shinozuka [19,20], has been developed in recent decades [21–23]. Applying the spectral representation method, the EPSD models are available to synthesize the artificial nonstationary and spectrum-compatible ground motion processes for structural nonlinear response analysis and seismic reliability evaluation.

Modeling of the EPSD of nonstationary seismic ground motion is based on the EPSD estimation of realistic ground motion record. With the development of the time-frequency analysis technology, especially the wavelet transforms, several EPSD estimation methods have been presented [24–26]. In 1994, Spanos and Failla proposed a general method to estimate the EPSD of nonstationary stochastic process using wavelets. Further, the harmonic wavelets (HW) and the generalized harmonic wavelets (GHW), which were both proposed by Newland [27,28], have been applied in the EPSD estimation of the nonstationary stochastic process [25]. The development of the wavelet-based EPSD

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estimation technology has provided a basis for the EPSD modeling of the nonstationary seismic ground motion.

In this article, an evolutionary power spectrum model of fully nonstationary seismic ground motion is proposed, including: a). Within the framework of evolutionary spectra estimation given by Spanos and Failla [24], an EPSD estimation formula for nonstationary process is derived based on the GHW. This EPSD estimation formula is expressed by the GHW coefficients. For a realistic ground motion record at station C00, the SMART-1 array, the GHW coefficients are computed and the corresponding EPSD is obtained. b). An parametric EPSD model of nonstationary seismic ground motion is proposed, consisting of a frequency-domain energy distribution function and a series of normalized time-dependent envelop functions for different frequency components. c). The parameter identification method is given. The parameters of the normalized time-dependent envelop functions should be respectively identified for different frequencies. In order to simplify the model, the parameters of the normalized envelop functions are treated as function of frequency. d). Based on the spectral representation method, the seismic ground motion acceleration samples are synthesized by using the proposed EPSD model.

2. EPSD estimation via GHW

As defined by Priestley [12], a zero mean nonstationary process $f(t)$ can be expressed as

$$f(t) = \int_{-\infty}^{+\infty} A(\omega, t)\cdot e^{i\omega t}\cdot \mathrm{d}Z(\omega) \tag{1}$$

in which $A(\omega, t)$ is a deterministic modulating function and $Z(\omega)$ is a spectral process with orthogonal increments. The evolutionary power spectral density of $f(t)$ is defined as

$$S_{ff}(\omega, t) = |A(\omega, t)|^2\cdot S_{\bar{f}\bar{f}}(\omega) \tag{2}$$

in which $S_{\bar{f}\bar{f}}(\omega)$ is the power spectral density of the associated stationary process

$$\bar{f}(t) = \int_{-\infty}^{+\infty} e^{i\omega t}\cdot \mathrm{d}Z(\omega) \tag{3}$$

and satisfies

$$E[|\mathrm{d}Z(\omega)|^2] = S_{\bar{f}\bar{f}}(\omega)\cdot \mathrm{d}\omega \tag{4}$$

In Eq. (4), $E[\cdot]$ represents the expectation operator. The EPSD reflects the time-varying frequency-domain energy distribution of the nonstationary stochastic process and is a powerful tool to describe the nonstationary properties of a realistic signal. For engineering applications, according to the algorithm in [22], the EPSD is available to simulate the fully nonstationary process by spectral representation by the following series as $N \to \infty$

$$f_0(t) = \sqrt{2}\sum_{n=0}^{N-1}[2S_{ff}(\omega_n, t)\cdot \Delta\omega]^{1/2}\cos(\omega_n\cdot t + \Phi_n) \tag{5}$$

in which $f_0(t)$ is the simulated process, $\omega_n = (n-1)\cdot\Delta\omega$, $n = 1, 2, \ \ldots, N$, are the discrete frequencies and Φ_n, $n = 1, 2, \ \ldots, N$, are the independent random phase angles uniformly distributed in the range of $[0, \quad 2\pi]$.

Generally, the EPSD of a realistic process can be estimated via wavelets [24]. The normalized wavelet transform $W(a,b)$ of a function $X(t)$ is defined as

$$W(a, b) = \frac{1}{\sqrt{|a|}}\int_{-\infty}^{+\infty} X(t)\cdot w^*\left(\frac{t-b}{a}\right)\mathrm{d}t \tag{6}$$

in which $w(t)$ is the mother wavelet function, a is the scale parameter and b is the time parameter. The asterisk denotes the complex conjugate. The kernel of wavelet transform (6) is the conjugation of the mother wavelet function with dilatation a and translation b. Spanos and Failla derived that [24], for a given scale parameter a_j, the EPSD $S_{ff}(\omega, t)$ of a realistic stochastic process $f(t)$ satisfied

$$E[W(a_j, b)^2] = 4\pi^2 a_j \int_{-\infty}^{+\infty} |F_w(\omega\cdot a_j)|^2\cdot S_{ff}(\omega, b)\cdot \mathrm{d}\omega \tag{7}$$

in which $F_w(\omega)$ was the Fourier transform of the mother wavelet function $w(t)$, as

$$F_w(\omega) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} w(t)\cdot e^{-i\omega t}\cdot \mathrm{d}t \tag{8}$$

The EPSD, $S_{ff}(\omega, t)$, could be estimated by solving integral Eq. (7).

In this article, the GHW are used in the EPSD estimation. The GHW function by time step $k/(n-m)$ is defined as

$$w_{m,n}\left(t - \frac{k}{n-m}\right) = \frac{\exp\left\{2\pi n i\left(t - \frac{k}{n-m}\right)\right\} - \exp\left\{2\pi m i\left(t - \frac{k}{n-m}\right)\right\}}{2\pi i(n-m)\left(t - \frac{k}{n-m}\right)} \tag{9}$$

in which m, n are the scale parameters of the GHW and k must be an integer. The dimensions of m, n are both Hz. The Fourier transform of Eq. (9) is [28]

$$F_{w_{m,n}}(\omega) = \begin{cases} \frac{1}{2\pi(n-m)}\exp\{-i\omega k/(n-m)\}, & 2\pi m \le \omega < 2\pi n \\ 0, & \text{elsewhere} \end{cases} \tag{10}$$

Fig. 1a presents the Fourier spectrum of a single GHW of level m, n. The Fourier spectra of the GHW of different levels are shown in Fig. 1b. As derived by Newland [28], the GHW coefficients $c_{m,n,k}$ of a function $X(t)$ are

$$c_{m,n,k} = (n-m)\cdot\int_{-\infty}^{+\infty} X(t)\cdot w^*_{m,n}\left(t - \frac{k}{n-m}\right)\mathrm{d}t \tag{11}$$

$$\tilde{c}_{m,n,k} = (n-m)\cdot\int_{-\infty}^{+\infty} X(t)\cdot w_{m,n}\left(t - \frac{k}{n-m}\right)\mathrm{d}t \tag{12}$$

and $X(t)$ can be expressed as

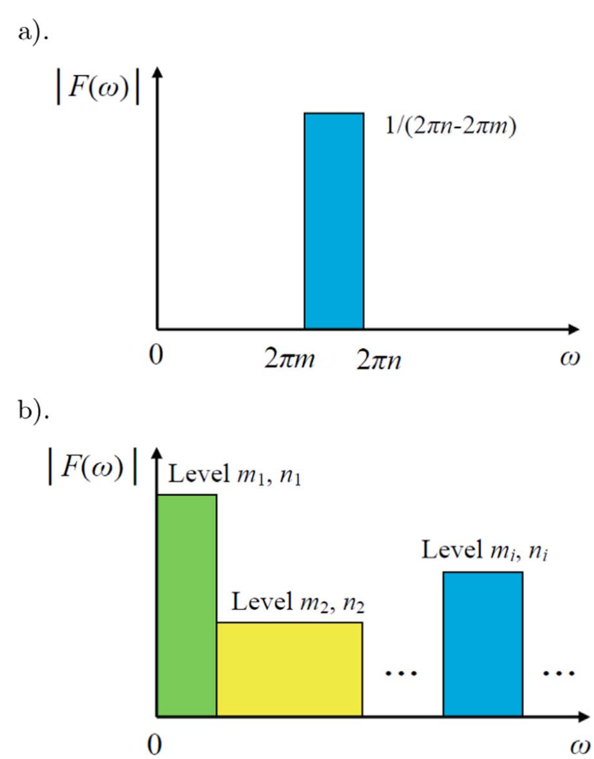

Fig. 1. Fourier amplitude spectra of a). a single GHW of level m, n and b). of the GHW of different levels.