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Simulation and generation of spectrum-compatible ground motions based on wavelet packet method

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ABSTRACT

This paper deals with the problem of generating spectrum-compatible artificial accelerograms for seismic dynamic analysis of engineering projects. A wavelet-packet-based, two-step procedure for the issue is proposed. The first step is to generate acceleration time history that could account for temporal and frequency non-stationarities of recorded ground motions. The second step is to decompose it into a desired number of wavelet packet vectors with high frequency resolution and non-overlapping frequency contents. Then each wavelet packet vector is scaled suitably and iteratively for the response spectrum of the simulated accelerogram to fit a specified design spectrum. The advantages of this procedure are that it can simulate user-specified acceleration time history with only 6 input parameters and the adjusted accelerogram has similar characteristics to the recorded one. The proposed procedure has been illustrated by simulating and modifying acceleration time history that are compatible with two different design spectrums for nuclear power plants. In addition, iterative efficiency of the method is investigated by simulating and adjusting acceleration time history for 100 successive times. The maximum relative error of the 76 period control points can reach 6% or below. Results show that the proposed method is effective and practical to generate and find spectrum-compatible ground motions with both stochastic and deterministic aspects.

1. Introduction

In seismic design, response of those major engineering structures, such as nuclear power plant, dam, big fluid reservoir, long-span bridges, ultra-tall buildings and so on, have to be analyzed carefully and completely when they are subjected to earthquake ground motions. Dynamic time history analysis is necessary for those structures and the selection of acceleration time history plays an important role in the process. Although response spectra method has been introduced for many years, it is still the most powerful tool and criterion for selecting design seismic ground motions in various structure code [1–3]. The spectra of selected acceleration time history must fit design response spectra within certain accuracy that is defined by these codes. These time histories are spectrum-compatible and are necessary to use for reasons that on the one hand, the seismic response history analysis resulting from spectrum-compatible time histories has lower dispersion and on the other hand, many regions in the world do not have sufficient ground motion records.

Calculation of response spectra from given time history is unique and simple, but obtaining a time history from given spectra is a more difficult inverse problem. Methods for this problem has been proposed by many researchers over the past three decades. The earlier research works have been reviewed by Ahmadi [4]. Most of the works transform the time history in the form of Fourier series and modify the amplitude and phase iteratively to fit the design spectra [5]. Although Fourier approach is straightforward and some attention was also paid on the non-stationarity of the amplitude with many envelope functions [6–8], it has two drawbacks [9]: First it does not have good convergence properties. Second, it alters the non-stationarity of time history if the shape of Fourier spectrum is changed significantly. Then, the relationship between response spectra and some other spectra, except for Fourier spectra, was used to generate synthetic motions directly. Kaul [10] introduced trigonometric series model to simulate an acceleration time history that has given power spectrum. Similar methods, such as in [11,12], used evolutionary power spectra to reflect frequency content of synthetic ground motions, which assumed that phase and phase-difference follow certain probability distribution [13]. Synthetic acceleration time history of the above methods can fit design response spectra within sufficient accuracy by further modification. However, the synthetic ground motions usually have significant difference in the waveform from the recorded ground motions [14], which will affect the response of

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structures in dynamic time history analysis.

Instead of directly simulating artificial ground motions from a pure mathematical perspective, some efforts are put into generating accelerograms that are closer to real ground motions, such as the features of full non-stationarity in time and frequency. Gupta and Joshi [15] generated spectrum-compatible accelerograms by selecting the phase angles of suitable real accelerogram and still following the trigonometric series model. Shrikhande and Gupta [16] characterized the seismic excitation through the spectrum compatible power spectral density function of an equivalent stationary motion. The progress is that the method considers the response to be non-stationary. Other efforts, using harmonic wavelet or wavelet transform, also improve the technique. Abrahamson [9] made modifications to Lilhanand and Tseng optimization procedure and presented an algorithm that can preserve the non-stationarity of the reference ground motion for a wide range of time histories [17]. The basic idea is to adjust the time history in the time domain by adding wavelets to the reference time history. Mukherjee and Gupta [18] proposed a wavelet-based procedure to decompose and scale recorded accelerogram directly without any artificial or simulated ground motions so that the scaled recordings keep their original characteristics. Spanos and Giaralis [19] introduced a harmonic wavelet-based approach, which generates artificial accelerograms and modifies them with field recorded accelerograms to achieve good matching of the signals' response spectra with GB 50,011-2001 design spectrum. Other wavelet-transform-based iterative schemes are also described by [20,21]. Relatively new time-frequency method like Hilbert–Huang Transform [22] and spectral-representation-based methodology [23] are also applied to retain the instantaneous frequency characteristics of ground motion records. These methods considered the time-invariant frequency contents to account for the situation, wherein non-linear systems respond quite differently to the ground motions with temporal variations.

As mentioned above, previous methods either neglect the time-frequency features of real ground motions or modified real ground motions directly to meet the requirement of spectrum compatibility. An alternative option is to first simulate ground motions and then adjust its frequency component to match a design spectrum. The purpose of the present study is to propose an approach of simulating and generating spectrum-compatible acceleration time histories that have similar characteristics with real ground motions. It has a basic process of: 1) generating artificial accelerogram that could accounts for time and frequency variations, 2) decomposing it into a finite number of non-overlapping frequency bands and 3) scaling them up/down iteratively so that the accelerogram is compatible with a specified design spectrum within certain accuracy.

In the present study, a wavelet-packet-based ground motion simulation model proposed by Yamamoto and Baker [24] is used and modified. This method combines seismology with engineering. It has been used to simulate those strong ground motions that have very close characteristics to recorded ones. Some modifications are made to this method to simulate, decompose, scale and reconstruct accelerograms. The advantages of the proposed method are that the initial simulated stochastic ground motions have time-frequency similarity with recorded ones and the decomposition has high resolution in frequency domain. The proposed method is illustrated by fitting two different design spectrum. For each spectrum, two acceleration time histories of different duration are generated and adjusted. In addition, an error study is conducted to investigate the iteration performance of the proposed method.

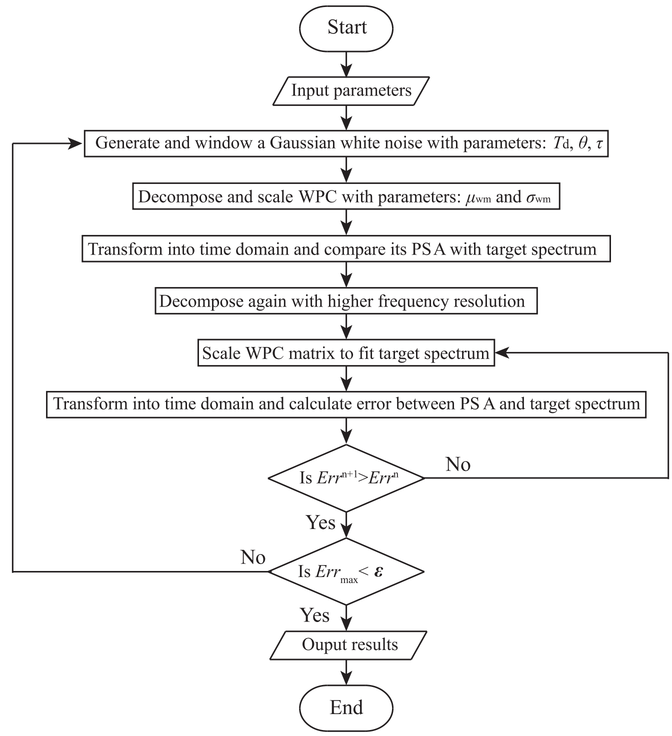

Fig. 1. Flow chart of the proposed methodology for generating and scaling spectrum-compatible ground motion vector processes.

2. Spectrum-compatible algorithm

In this section, we introduce the stochastic wavelet packet method of generating and adjusting random artificial accelerogram. The whole procedure is outlined in Fig. 1. It starts with some input parameters and then simulates an acceleration time history by wavelet-packet method. Then, like other methods, it will use an iterative process to fit target spectrum with relative errors. The whole process will be stopped when the error falls below an acceptable value ε. All the steps will be described in detail in the following parts of this section.

2.1. Wavelet packet

Recently, Yamamoto and Baker [24] proposed a stochastic model to simulate non-stationary ground motions using the wavelet packet transform, which decomposes an acceleration time history $x(t)$ into a collection of wavelet packets localized in time (t) and frequency (f) domain. The wavelet packet coefficients for each packet are defined as follows:

$$c^i_{j,k} = \int_{-\infty}^{\infty} x(t)\psi^i_{j,k}(t)dt \tag{1}$$

where $c^i_{j,k}$ is the wavelet packet that denotes the ith set of wavelet packets at the jth scale parameter and k is the translation parameter in time, and $\psi^i_{j,k}(t)$ is the wavelet packet function. Note that $\psi^i_{j,k}(t)$ is localized on the time and frequency axes, the wavelet packets can control energy distribution in time and frequency domains. Conversely, with certain wavelet packets, it is convenient to reconstruct a time series data from the wavelet packets using the inverse wavelet packet transform as follows:

$$x(t) = \sum_{i=1}^{2^j} \sum_{k=1}^{2^{N-j}} c^i_{j,k}\psi^i_{j,k}(t) \tag{2}$$

where 2^N is the number of data in the time series.