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A multi-modal analytical non-stationary spectral model for characterization and stochastic simulation of earthquake ground motions

Christos Vlachos [a], Konstantinos G. Papakonstantinou [b], George Deodatis [a,*]

[a] Department of Civil Engineering and Engineering Mechanics, Columbia University, New York, NY 10027, USA
[b] Department of Civil and Environmental Engineering, The Pennsylvania State University, University Park, PA 16802, USA

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ABSTRACT

A novel stochastic earthquake ground motion model is formulated in association with physically interpretable parameters that are capable of effectively characterizing the complex evolutionary nature of the phenomenon. A multi-modal, analytical, fully non-stationary spectral version of the Kanai–Tajimi model is introduced achieving a realistic description of the time-varying spectral energy distribution. The functional forms describing the temporal evolution of the model parameters can efficiently model highly non-stationary power spectral characteristics. The analysis space, where the analytical forms describing the evolution of the model parameters are established, is the energy domain instead of the typical use of the time domain. This space is used in conjunction with a newly defined energy-associated amplitude modulating function. The Spectral Representation Method can easily support the simulation of sample model realizations. A subset of the NGA database is selected in order to test the efficiency and versatility of the stochastic model. The complete selected database is thoroughly analyzed and sample observations of the model parameters are obtained by fitting the evolutionary model to its records. The natural variability of the entire set of seismic ground motions is depicted through the model parameters, and their resulting marginal probability distributions together with their estimated covariance structure effectively describe the evolutionary ground motion characteristics of the database and facilitate the characterization of the pertinent seismic risk. For illustration purposes, the developed evolutionary model is presented in detail for two example NGA seismic records together with their respective deterministic model parameter values.

1. Introduction

The rising interest in performance-based earthquake engineering coping with structural performance from the linear range to nonlinear to collapse [1], in parallel to modern code requirements, has enhanced the need for reliable, diverse and realistic earthquake acceleration motions [2]. The complex structural response is known to be highly dependent upon a proper characterization of the seismic motion, which inherently exhibits both magnitude and frequency non-stationarities. Among the consequences of the spectral non-stationarity is the moving resonance effect, e.g. [3,4]. Naturally, the availability of actual recorded seismic motions pertaining to certain earthquake scenarios can turn out to be quite limited or nonexistent. Therefore, engineers are frequently forced to scale the recorded motions and/or modify their spectral content [5]. This procedure, mainly motivated by necessity, is fraught with specific concerns regarding the resulting potentially unrealistic seismic ground motion representation.

One alternative to this process is to use simulated seismic waveforms with representative characteristics of possible earthquake ground motions at the site/region of interest. Apart from overcoming the record modification concerns, the description of the earthquake hazard in the form of simulated waveforms provides a meticulous characterization of the seismic risk related to structural systems, extending in large spatial domains, which cannot be achieved by the scaling of actual records. Furthermore, stochastic ground motion models can be straightforwardly implemented in stochastic dynamic analysis by using the abundance of refined methods in this field, e.g. [6–9].

The aim of this paper is to discuss this approach and propose a rigorous, as well as practical, scientific method to realize this simulation option. The existing models for the stochastic simulation of earthquake ground motions are classified in three main

* Corresponding author. Tel.: +1 212 854 9728.
E-mail address: deodatis@columbia.edu (G. Deodatis).

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categories. The first category, usually referred as 'source-based' models, comprises physical models that are heavily dependent on seismological principles and describe the fault rupture mechanism and resulting propagation of seismic waves, e.g. [10–14]. These models have significant potential for engineering practice but unfortunately have not yet reached a practical status for real engineering applications, since they require significant computational resources and thorough knowledge of a variety of seismological parameters describing the earthquake source and the seismic wave travel path. Another complication is that these models are typically experiencing difficulties capturing the local site response.

The second category consists of models developed to generate simulated waveforms either similar to a target seismic record, forming the 'site-based' model category, e.g. [15,16], or compatible to a designated response spectrum, constituting the 'spectrum-compatible' model category, e.g. [17,18]. Site-based models can effectively characterize the stochastic nature of the ground motion by fitting to a target seismic record obtained at a specified site and local soil conditions. Comprehensive formal literature reviews can be found in [16,19,20] describing different models, including those based on filtered white noise random processes [16,21–23], filtered Poisson processes [24,25], Auto-Regressive Moving-Average (ARMA) models [26–28], spectral representation of stochastic processes [6,15,20,29–31] and finally stochastic wave theory [32–36].

While the models of the above-mentioned category can exploit the techniques in the field of stochastic dynamics, which is a very significant attribute, they do not offer any other considerable advantage in comparison to the practice of selection/modification of actual records, since they cannot provide acceleration time-histories based on future earthquake scenarios and do not usually take into account the uncertainty of their model parameters, thus being unable to reflect the natural variability of the earthquake ground motions [18]. It is hence mainly for this reason that these models are not broadly used in current earthquake engineering practice and the much simpler procedure of record scaling is typically preferred.

The stochastic ground motion model introduced in this paper belongs to the third category, which encompasses analytical 'site-based' stochastic ground motion models that are capable of parameterizing the earthquake ground motion and practically consider the inherent stochasticity in their model parameters in order to capture the natural variability of the seismic ground motions. Models of such kind are of a limited number, mainly because accessible databases with large amount of reliable seismic waveforms only recently became available. In one of the first attempts, Yeh and Wen in 1990 [23] revisited a model originally formulated by Grigoriu et al. in 1988 [29], resulting in a 13 parameter model that is characterized by an amplitude modulating function and a transformation of the time scale, the function of which is to modulate the frequency content of the well known stationary Kanai–Tajimi model [21,22]. Sabetta and Pugliese in 1996 [37] expressed the non-stationary spectral density of the ground motion with a lognormal spectral distribution at each time instant, followed by a lognormal envelope function that was taking into account the P and S waves arrival times. Pousse et. al in 2006 [38] revisited the model suggested by Sabetta and Pugliese [37] using a ω-square frequency model and a new amplitude modulating function. Stafford et al. in 2009 [39] developed a new energy-based envelope function, ignoring however the frequency non-stationarity of the ground motion. In 2008, Rezaeian and Der Kiureghian [16,40] developed a stochastic model based on a single degree of freedom linear oscillator, which served as a time-varying linear filter to describe the frequency non-stationarity of the seismic motion, and an amplitude modulating function. In their effort to formulate a relatively simple model that can be of practical use, they had to make some assumptions that are not always fully supported by actual data, such as the linear temporal variation of the ground motion's dominant frequency. Finally, in 2013, Yamamoto and Baker [41] presented a wavelet-based model, employing a total number of 13 parameters. The resulting model is the only one to date in this category capable of directly simulating ground motions based on multi-modal non-stationary spectral densities. A total number of 4 independent random variables are employed for each wavelet packet, quadrupling the simulation required variables as compared to other methods and making its use in the field of stochastic dynamics and its expansions towards simulation of spatially correlated seismic waveforms rather complicated.

This paper presents the formulation of a new stochastic earthquake ground motion model, characterized by physically interpretable parameters that are capable of effectively modeling the complex evolutionary nature of the phenomenon. The suggested model is based on a novel multi-modal, analytical, non-stationary spectral version of the well-known Kanai–Tajimi (K–T) model [21,22]. The frequency and amplitude modulated Kanai–Tajimi model was first introduced by Deodatis and Shinozuka in 1988 [26], while Lin and Yong suggested a more restrictive form, employing the theory of random pulse trains, that same year [25]. The model presented in this work is the first fully analytical model to date that is capable of directly and efficiently describing multi-modal evolutionary power spectral densities. The evolutionary K–T model analyzed in this paper is bimodal, without any loss of generality regarding the number of modes that can be modeled and/or their modeling procedure. The newly introduced bimodal K–T model and the developed functional forms that can describe the temporal evolution of its parameters are presented in the next sections and are capable of representing strongly non-stationary spectral densities. The analysis space, where the analytical forms describing the evolution of the model parameters are established, is the energy domain, instead of the typical use of the time domain. This is followed by the introduction of a newly defined energy-associated amplitude modulating function. The analytical form of the suggested model facilitates the simulation of sample realizations by the Spectral Representation Method (SRM) [6,15,42,43], which is based on the evolutionary spectral theory of Priestley [44,45]. The SRM is of particular interest in the fields of random vibrations and stochastic dynamics, and it also has the capacity to accommodate the spatial variation of the simulated ground motions [6,42,46,47].

The formulation of the new bimodal evolutionary Kanai–Tajimi model is presented in the following sections. The parametric forms necessary for the description of the time-varying model parameters are provided, together with the energy domain description that serves as the selected analysis space. A subset of the NGA strong motion database [48,49] is selected in order to test the capabilities and versatility of the proposed stochastic model. The used database is thoroughly analyzed and sample observations of the model parameters are obtained by fitting the evolutionary model to its records. The natural variability of the database seismic ground motions is depicted through the model parameters and their resulting marginal probability distributions together with their estimated covariance structure, effectively describe the evolutionary characteristics of the database seismic motions and facilitate the characterization of the pertinent seismic risk. The necessity of post-processing the model's sample realizations is highlighted and a simple filtering process is suggested. Detailed sample fits of the time-varying model parameters are presented for illustration purposes with respect to two example NGA seismic records and their respective deterministic model parameter values are provided as well. Sample acceleration realizations are also shown, together with derived velocity and displacement time-histories and elastic response spectra realizations pertaining to the two seismic record examples.